THE ECONOMICS OF A TRANSFORMER DESIGNED WITH A LOW CURRENT, RESISTANCE BRIDGING LTC AND SERIES TRANSFORMER VERSUS A HIGH CURRENT, REACTANCE BRIDGING LTC AND NO SERIES TRANSFORMER

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Executive Summary

A transformer designed with a low current, resistance bridging load tap changer and a series transformer can yield a lower cost total transformer design while enhancing performance. Series transformers are about the same cost as preventive autotransformers, so this is not an added cost. Regulating windings and cabling for higher current tap changer designs are significantly more expensive. True transformer cost optimization can be achieved with the use of a series transformer but may not be achievable without one where the volts-per-turn is defined by the LTC step voltage. Contact life is as much a function of how the tap changer is incorporated into the design of the transformer as it is a function of the tap changer itself. Transformers designed with a high current, reactance bridging LTC can be more expensive to build than a transformer designed with a low current, resistance bridging LTC and a series transformer.

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I^2T Energy Switched

Contact erosion is primarily a function of the energy switched. This is typically calculated as I2T.

Let’s compare a 600A LTC to a 2500A LTC:

6002 A x 6ms = 2,160 A2sec

25002 A x 6ms = 37,500 A2sec

37,500 / 2,160 = 17.4 times larger contact erosion forces at work

If the 600A tap change has a booster/series transformer that steps down the current in the LTC to 250A, then the I2T is 2502 A x 6ms = 375 A2sec

25002 A x 6ms = 37,500 A2sec

37,500 / 375 = 100 times larger contact erosion forces at work

In the calculations above, the switching times were assumed to be the same. It is likely that the arcing times for the higher current, arcing-in-oil reactance bridging LTC are longer, making the result even larger. The conclusion to be drawn here is that high current LTCs have much larger arcing energy and will create much more carbon in the oil if the LTC is an arcing-in-oil type of switch. This is probably the primary reason that high current, arcing-in-oil LTCs are no longer made in the USA (only high current, vacuum LTCs are manufactured in the USA).

Because of this significant difference in switched energy, the carbon particles produced by the arc in oil are much smaller for the lower current resistance LTCs. These very fine particles tend to stay suspended in the oil versus the much larger carbon particles / strings that can form in the higher current tap changers. When carbon strings form, they can fall and bridge two contacts or a contact-to–ground, causing a problem. The smaller particles of the low current tap changer don’t cause these types of problems and are easily removed with on-line oil filtration at low flow rates. Carbon particles in a high current tap changer may need to be removed quickly requiring a high flow rate oil filter system.

Series Transformer Cost vs. Preventative Autotransformer Cost

The 600A UZD LTC is typically used in conjunction with a series/booster transformer, see FIG. 1 at right. The series transformer is used to reduce the line current to the LTC so that an LTC can be applied in a circuit where the line current is higher than the rating of the LTC.

***FIG. 1** - Transformer designed with a series transformer (at right end) for use with 600A resistance bridging load tap changer.*

Example:

LTC rated current = 600A
Line current = 1200A
Turns ratio of series transformer = 2:1
Current through the LTC = 600A

All load tap changers are designed for make-before-break type of switching so that the circuit isn't opened during the tap change operation. That means that at one point during the tap change, you have to bridge two contacts at different voltages. Because the resistance of the few turns in the regulating winding is likely to be in the milliohm range and the step voltage of 5/8% may be 50V, the circulating current can easily exceed 1,000A. Therefore, additional impedance is added to the circuit to limit the circulating currents to a reasonable value. Either a resistor or reactor will work for this function.

The UZD® model LTC uses a resistor as the bridging impedance device. Reactance LTCs on the market today use a reactor (preventive auto) as the bridging impedance device. A difference to be noted is that the preventive auto is sized to carry rated current continuously so that the bridging position is a permanent operating position, therefore less stationary contacts are needed in the reactance bridging LTC (typically eight). In the UZD, the resistor is only in the circuit during the tap change (total tap changing time of about 70 milliseconds) so the UZD has 16 stationary contacts plus neutral contacts.

The size of a series transformer used to reduce current to the LTC would be the same percentage of the maximum nameplate MVA as the percentage of regulation. For example, a 50 MVA max NP rating transformer with ±10% regulation would require a series transformer sized at 5 MVA. The core of the series transformer is basically not energized at neutral tap position and the excitation of the series transformer core goes up with tap position such that maximum sound level and losses would occur at either tap extreme. For transformers with reduced sound levels, it is possible to design the booster transformer with lower flux density to avoid compromising the sound level reduction of the transformer's main core.

Reactance bridging LTCs always have a preventive auto (reactor) to limit the circulating current at the bridging positions, see FIG. 2 at left. A preventive auto (PA) is sized as 1.25% of the max NP MVA and in this example would be 625 KVA. PAs have a gapped core and operate with the core saturated. The core of the PA is fully excited only in the odd (bridging) tap positions. Therefore, the sound level and the losses will be highest on the odd tap positions.

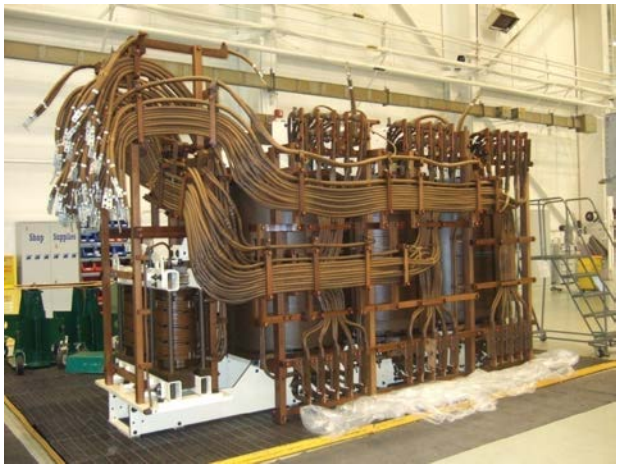

FIG. 2 *- Transformer designed with a preventive auto transformer for use with 2,500A reactance bridging load tap changer.*

The losses of a series transformer versus the losses of a PA are similar. Losses occur at different tap positions so evaluating these differences can be tricky. Some make the evaluation by averaging the losses at neutral and 15 raise so that the effects of a series transformer and PA are included. Please note that some transformers using reactance bridging tap changers have both a PA and a series transformer.

A reactance bridging tap changer will always have a PA and may also have a series transformer, see FIG. 3 at right. A resistance bridging tap changer will never have a PA and may have a series transformer. In the case of a low current LTC like the UZD®, it will typically have a series transformer.

The cost to build a series transformer will likely be higher than the cost to build a PA due to the typically larger size of a series transformer compared to a PA. This difference in cost could amount to several thousand dollars depending on transformer size and percentage of regulation. However, both of these devices are usually mounted inside the main tank, typically at one end of the main core and coil assembly. This location requires that the main tank be extended to accommodate these devices, adding extra tank steel and oil. The quantity of these extra materials will be similar.

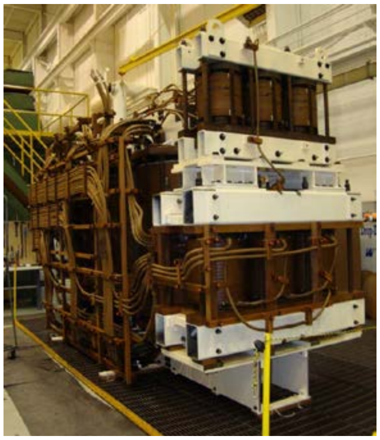

FIG. 3 - Transformer designed with reactance bridging LTC with preventive auto (on top) and series transformer (on bottom).

Cabling Cost Including Losses, Labor and Through Put Time

In any LTC transformer, there are cables that connect the regulating voltage (RV) / tap winding to the tap changer (see FIG. 1 and 2 on pages 3 and 4 respectively). The location of the LTC will influence the length of these cables. For on-tank, compartment type LTCs such as the UZD®, this could be on the side wall (segment 1) or transformer end wall (segments 2 or 4). The current passing through these cables will create a flux field around the cable which can link magnetically to the steel tank wall or core clamp and induce eddy currents in these parts, generating heat and additional kW of load loss.

In the case of the UZD®, these cables would be sized for 600 amps max. Each conductor of the multi-start RV winding would be connected to the next conductor in the RV winding by means of a cable running from the top of the first conductor to the bottom of the second conductor, from the top of the second conductor to the bottom of the third, etc. for 16 loops. On each of these cable loops there is a crimped T connection. A cable is run from this T connection to the LTC. The selector switch in the LTC determines how many of the conductors in the RV winding are connected in series. Therefore, in the worst case condition for the UZD®, there would be 600A x 16 loops = 9,600 amps of current flowing near the tank wall. More typically, though, the current is reduced by th turns ratio of the series transformer— to get 500,000 operations, the current would typically be 250 amps for 250 amps x 16 loops = 4,000 amps flowing next to the tank wall. For higher current reactance bridging LTCs, there would only be eight loops instead of 16 (doubling of contact duty via bridging positions with PA in circuit). Therefore, assuming a 2,500 amp LTC, the worst case condition would be 2,500 amps x 8 loops or 20,000 amps of current flowing near the tank wall.

If the LTC is mounted on the side of the transformer, these cables are shorter. If the LTC is mounted on the end wall of the tank, the cables will be much longer. The higher current LTCs are typically larger and usually mounted on the end walls of the transformer, so they will have longer cable runs.

There is an alternative way around this high current cable issue. That is to make a two layer (radial) RV winding where half of the conductors are in one layer (inner) and wound in one direction and the other half of the conductors are in the other layer (outer) and wound in the opposite direction. These loops would be connected to each other at the tops and bottoms of the RV winding and a cable connected there to run to the LTC. In this design, only the cable attached to the stationary contact selected in the LTC will carry current so much less current flows in cables next to the tank wall. However, the radial real estate used for the two layer RV winding is expensive. Let’s say it costs $1,000/mm radially and this winding scheme takes an additional 15mm for a $15,000 higher cost.

Now let's look at the cost of higher current cables. If the UZD is designed with 250 amp cables and the higher current LTC is wired with 2,500 amp cables you can see that the cost of the cable alone will be around 10 times higher. Additionally, the weight of 10 times more conductor is quite heavy and will require a much larger support structure which adds more cost. On top of that is the labor cost to cut, crimp and wrap all the additional cabling. It is unlikely that a single cable would be used for the high current application. It would likely be multiple cables in parallel. This involves cutting, routing, crimping and wrapping many more cables. This extra labor is in the critical path of transformer production and is difficult to put significantly more manpower on as the workers would all need to be in about the same place at the same time. The reality is that *these high current designs take a day or two longer to build and increase the work-in-process inventory costs and reduce the number of transformers that can be produced in that factory*. Reduced volume represents lost opportunity cost to the manufacturer.

Power Class vs. Distribution Class Preventive Auto and Series Transformer

It may be tempting to build either of these transformers (series transformer or preventive autotransformer) using distribution class, rectangular core and coil technology. This is a mistake. Distribution transformers have a significantly higher failure rate than do power transformers. This difference is acceptable based on the application. A distribution transformer has far fewer customers connected to it so the consequences of losing the transformer are less. However, if a distribution transformer is applied in a power transformer, the distribution transformer is now the weak link and the reliability of the power transformer is only as high as the weak link distribution transformer. A suggestion for customer specification is as follows:

> *The preventive auto and series transformer shall be of the same construction as the main core and coil assembly, specifically round core with circular disc and helical windings.*

RV Winding Cost Including Increase in Mean Turn Diameter of Other Windings and Increase in Core Window Opening

Load Tap Changing transformers typically have a separate regulating voltage (RV) winding to hold all of the turns necessary to supply voltage to each of the stationary taps in the LTC. An example of an RV winding is shown in FIG. 4 to the right.

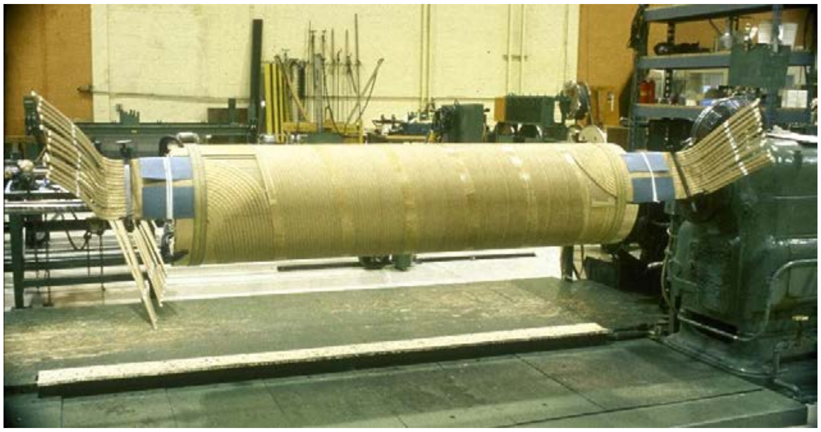

FIG. 4 - Typical regulated voltage (RV) winding for a 600A, resistance bridging LTC.

If an RV winding is designed to carry 2,500A versus 600A, it will need 2,500 / 600 or a 4.17 times larger cross sectional area of copper to carry the higher current. This will likely increase the radial dimension of this winding (see FIG. 5 at right). The cost of radial "real estate" in a transformer is in the range of $1000/mm so an increase in radial build of this winding is expensive. If an extra 10mm is required in radial build, this could cost an extra $10,000. If the RV, typically the innermost winding, increases in diameter, the LV and HV windings outside of the RV must also increase in diameter. This means the length of copper wire to go around the core is longer and at the same ohms per foot of wire, the resistance will go up, consequently the load losses will go up. This effect can be offset by increasing the copper area, but that increases cost and also increases the diameter of the winding.

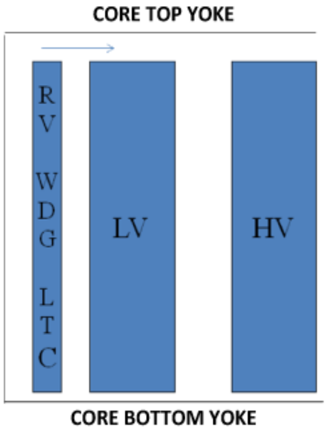

FIG. 5

If the diameter of the windings increases, the window opening in the core must also increase (see FIG. 6 at right).
The core window is the distance between core legs that the windings must fit within (in a core form transformer). This increase in window opening will increase the length of the top and bottom core yokes and add cost and extra no-load losses.

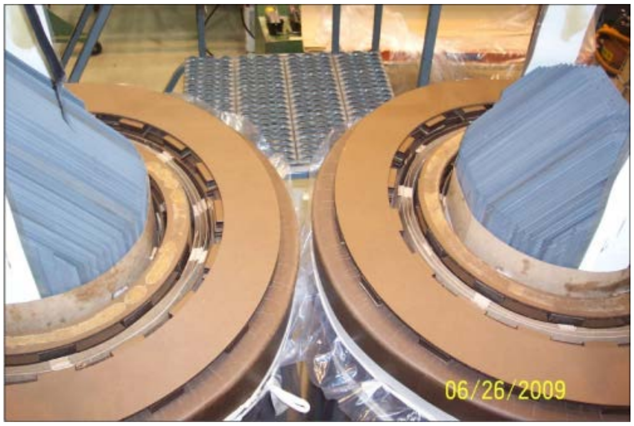

FIG. 6

If the RV is designed to carry more current, it will likely generate more heat due to I2R losses. This extra heat may lead to increasing the size of the cooling ducts around the RV winding which increases the radial build of the winding, increasing cost as described above. Also these extra kilowatts of heat, plus the extra no-load losses mentioned in the previous paragraph, may require adding extra external cooling capacity in the form of radiators and/or fans, all of which add cost.

Optimized Main Core and Coil Assembly Costs

There are 33 variables in a transformer that are all interrelated. If you change one of these attributes, one or some or all of the other variables will change. Transformer design engineers today typically utilize a computer optimization program that takes into account specified parameters such as MVA, HV kV, HV BIL, LV kV, LV BIL, % impedance, sound level, temperature rise guarantee, no-load loss evaluation, load loss evaluation, etc. They then work within that program to design a transformer, calculate its losses and multiply those losses by the evaluation

$/kw and calculate the cost of copper, core steel, plate steel, oil, insulation, labor, etc. to arrive at an evaluated price plus losses number. The program will then change a significant parameter like core diameter and calculate the new price and loss value. This process is repeated until an optimal design is found for quotation purposes. At the very heart of this optimization is Volts per Turn.

Let’s take an example transformer with a 12.47 kV wye connected LV winding with LTC of ±10% regulation in 16-5/8% steps. Where = 7,200 v line to ground. Taking of 1% of this is 7,200V x 0.00625 = 45V per step. Therefore, the volts per turn in the main core and coil have to be fixed at 45 V/T or some multiple of this. You could design at 22.5 V/T and have two turns of conductor in the RV winding around the core to generate the 45 volts needed for the of 1% step voltage. Or you could design to 90 V/T and use a reactive bridging tap change so that the center tap of the PA gives 45 volts, etc.

In this example the V/T has been fixed by the voltage needed to meet the LTC step voltage. If the optimum V/T is different than that required for the LTC step voltage, the cost and losses of the main core and coil assembly have not been truly optimized. If a series transformer is used in the LTC circuit, the design engineer can decouple the V/T in the main core and coil from the turns in the RV winding by changing the turns ratio in the series transformer and the number of turns in the RV winding. *Since there is ten times more material in the main core and coil than in the series transformer, there can be a significant beneficial effect on the optimized cost by using a series transformer. A load tap changing transformer without a series transformer may not be fully cost optimized.*

Even vs. Uneven Steps in the LTC

If a transformer is designed, for example, with 102 turns in the LV winding and ±10% LTC, you would need 10.2 turns in the RV winding, divided by 8 for a reactive bridging design or divided by 16 for a resistance bridging design. You cannot have 0.2 turns. You can have 10 turns or 11 turns but not 10.2 turns. In this example, one would probably round down to 10 turns. In a reactive bridging LTC without a series transformer, you would need 8 loops in the RV winding but 10 turns doesn’t divide evenly into 8 loops. So, two of the loops would have these extra turns included which would cause uneven steps in the LTC and result in higher sound levels at these taps with higher than normal turns/tap.

A transformer designed with a series transformer in the LTC circuit will use the turns ratio of the series transformer to accomplish even voltage steps on all tap positions. FIG. 7, on the next page, shows the voltages as they would appear on a transformer nameplate with an additional column added on the right showing the “error” in voltage or the deviation from what a 5/8% step would be in a transformer without a series transformer.

12,470Y/7200 Volt Rated secondary +/- 16 - 5/8% steps

	NAME PLATE VOLTAGE	ACTUAL VOLTAGE	VOLTAGE ERROR
16R	13720	13720	100.00%
15R	13640	13658	100.13%
14R	13560	13595	100.26%
13R	13480	13470	99.93%
12R	13410	13345	99.52%
11R	13330	13283	99.65%
10R	13250	13220	99.77%
9R	13170	13158	99.91%
8R	13090	13095	100.04%
7R	13020	13033	100.10%
6R	12940	12970	100.23%
5R	12860	12845	99.88%
4R	12780	12720	99.53%
3R	12700	12658	99.67%
2R	12630	12595	99.72%
1R	12550	12533	99.86%
N	12470	12470	100.00%
1L	12390	12408	100.15%
2L	12310	12345	100.28%
3L	12240	12283	100.35%
4L	12160	12220	100.49%
5L	12080	12095	100.12%
6L	12000	11970	99.75%
7L	11920	11908	99.90%
8L	11850	11845	99.96%
9L	11770	11783	100.11%
10L	11690	11720	100.26%
11L	11610	11658	100.41%
12L	11530	11595	100.56%
13L	11460	11470	100.09%
14L	11380	11345	99.69%
15L	11300	11283	99.85%
16L	11220	11220	100.00%

FIG. 7

Contact Life

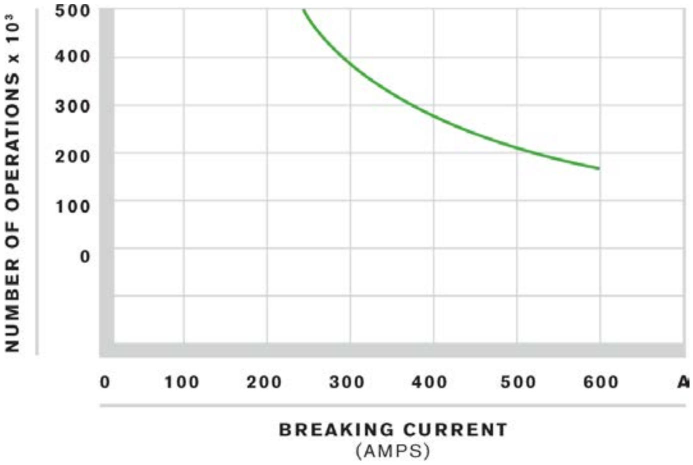

FIG. 8

The arcing contacts in a load tap changer erode with tap changer operations. This erosion is primarily a function of the number of operations, the current the transformer is carrying at the time of these tap changes and the switching time of the tap changer. Changes in loading and power factor (phase angle) significantly affect transformer voltage regulation. As transformer load increases or the phase angle moves away from unity power factor, the regulation increases (output voltage or bus voltage drops). LTCs are specified to compensate for this voltage regulation effect.

LTCs typically have a contact life curve (see FIG. 8 above which shows estimated contact life in number of operations vs. current switched for the UZD®). Most customers desire to have the contacts last the life of the transformer without need for changing. If the contact life varies significantly with current, the transformer designer will want to apply the LTC such that the maximum nameplate current or average current is low enough to yield the desired contact life. This can be done with a series transformer. If a transformer has 1,200 amps line current, a series transformer with a turns ratio of 2:1 would reduce the line current to 600 amps so that a 600 amp LTC could be used. If the desired contact life is achieved at 250 amps in the LTC (see example contact life curve below), the transformer designer would need to increase the turns ratio of the series transformer to 1,200 / 250 or 4.8:1. Thus, how a tap changer performs can be a function of how it is applied in the transformer design as well as a function of the tap changer itself.