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Optimal Placement of Load or no Load Regulator Across a Transformer. Reduction of Copper Losses

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Abstract : In this article, we present an optimal and reliable approach of the placement of a regulator, with or without load across a transformer. The approach consists in placing the regulator at the secondary of the transformer in order to minimize the copper losses it causes. In fact, the regulator incorporated in the power transformer in order to improve the voltage profile of the electric network increases the copper losses. The usual solution, which consists of placing the regulators on the transformer's side where the current is lower, helps to reduce the effects of electric arc without resolving the problem of copper losses that it creates. Copper losses are however higher if the regulator is placed at the primary of the transformer. The main objective of this paper is to show that these losses could be minimized. The approach is tested on a five nodes network, and on the Congolese interconnected electricity grid were simulation results obtained justify our claims.

***Keywords* -** Optimal placement, power transformer, load or no load regulators, effect of hysteresis, degradation phenomenon, regulatory taps, copper losses, ideal transformer.

I. Introduction

The use of transformers in power grids posses many problems among which the effect of hysteresis is one of the major one. This effect which has as origin the flow of electric current across the transformer's windings leads to losses across its copper and iron components. Electrical networks are highly embedded with power transformers some of which are load or no load regulated. The regulators are incorporated in the transformer windings for voltage regulation in order to improve the capacity of the power transmission in networks. The placement of load regulators across power transformers brings new problems such as the electric arc that accompanies the passage of current from one tap to another, on the one hand, and an increase in the copper losses on the other hand.

In fact, electric arcs destroy the taps and can equally cause fire. Meanwhile, during the usage of load regulators, it is the number of turns that increases, thus increasing the resistance at the primary or secondary, and of course increasing the transmission losses. The use of perfectly treated mineral and synthetic oils in transformer tanks does stop the hysteresis problem in power transformers even if the main role of using these oils is to cool the transformers.

About the electric arcs that occur during the flow of current from one tap to another, the classical tendency consists of incorporating the load regulator on the side with low current in order to minimize its effects [12,13,14,15]. Actually, the load regulator (electromagnetic contactor) is submerged in mineral and synthetic oils contained in a reservoir so as to suffocate the electric arcs that are susceptible to damage the taps and the transformers [14, 15, and 16]. However, the increase of copper losses caused by load or no load regulators still remains a major challenge. Copper losses contribute to the expansion of the hysteresis effect and in doing so; degrade the transformers as for example oil ageing and loss of its insulating properties. These losses are however very high no matter on which side of the transformer the regulators is placed.

However in this study, our approach is essentially to minimize the copper losses caused by load or no load regulators as power flows across transformers in grids. In order to minimize the rate of degradation in such transformers, it is necessary to compare the losses dissipated in the windings without the regulator, and when it is incorporated first of the all at the primary and then at the secondary of the transformer. In this study, we have examined two possibilities for placing load regulators. Losses are calculated for the transformer with regulator at the primary and at the secondary windings. These losses are compared with the losses in the transformer without regulator.

This study is divided into five sections consisting of generalities on the transformer with load or no load regulator, the proposed approach, simulations results and conclusions.

II. Generalities on transformer with load or no load regulator

II.1 Principle of load or no load regulator

It is often necessary to adjust the number of windings of transformers in order to regulate the voltage of the network. In fact a transformer with a capacity for voltage regulation has many taps as shown in Figure 1.

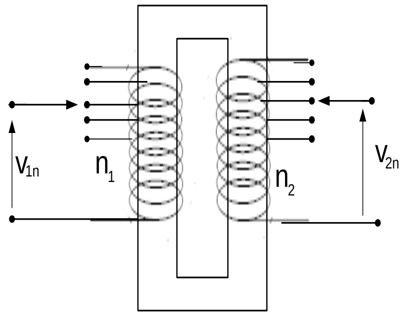


Fig.1: Diagram showing a transformer with load regulation

In some transformers, tap-changing is done by manually changing the number of turns when the apparatus is out of service. However, in most modern transformers, tap-changing can be done under load, that is without the interruption of the current through the winding. This is why this apparatus is called a load regulator. It is made up of a contactor conceived to attenuate the production of electric arcs susceptible to damage the contacts and an electric motor to move its contacts

Load regulators can be manually controlled (remote controlled by the operator from the control center) or automatically (feedback system) [14, 15, 16]. The taps which generally have the values of 10%, 7.5%, 5%, 2.5%, 1.5%, -1.5%, -2.5%, -5%, -7.5% and -10%, define the regulatory level of the voltage to be attained across the transformer.

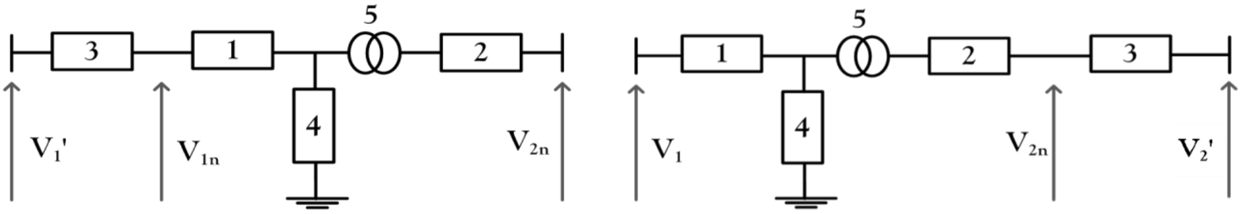
II.2 Developped models of transformer with load or no load regulator

These models are represented by the different resistive, inductive elements and an ideal transformer as shown in Figure 2 [1,4,6].

The numbers and letters in figure are defined as:

V_{1n} and V_{2n} represent respectively nominal voltages at the primary and at the secondary of the transformer.

V_1' and V_2' represent respectively the voltages at the primary and at the secondary of the transformer when the regulator is present.



a) When the regulator is placed at the primary b) When the regulator is placed at the secondary

Fig. 2: Transformer model

1 represents the complex impedance of the primary winding: $z_1 = r_1 + ix_1$;

2 represents the complex impedance of the secondary winding: $z_2 = r_2 + ix_2$;

3 represents the additional complex impedance brought by the insertion of the load regulator : $z' = r' + ix'$;

4 represents the magnetizing complex impedance $z_\mu = r_\mu + ix_\mu$;

5 symbolizes an ideal transformer

II.3 Simplified model of the transformer with load or no load regulator

The parameters of the transformer are expressed here in the per unit system (pu); in order to transform the initial voltage ratio $n_p : n_s$ to a unitary voltage ratio $1:1$. This helps to obtain a simplified model having the short-circuit admittance Y_{CC} in series with an ideal transformer. All of them are connected between the primary and the secondary nodes and are enough to completely describe the performance of the two windings transformer.

However, the mechanism for varying the number of turns of the windings and therefore varying voltage on one or the other terminal of the transformer is not represented. The reason is that it does not constitute an impedance element that could influence the results. The magnetizing admittance is neglected because the study is essentially on copper losses and also because its value is (infinite and so magnetizing current could be neglected).

We finally consider the load regulator as a voltage source injecting a small variable voltage (addition or subtraction) in phase with the voltage of the winding in which it is inserted.

The final model of the transformer is represented in Figure 3 with tap ratios $T:1$ or $1:T$ at the primary and at the secondary respectively [6,10].

a) When the regulator is at the primary b) When the regulator is at the secondary

Fig.3: Simplifies model of the transformer

Here we define the following:

1 Is the short-circuit complex admittance of the transformer $Y_{CC} = \frac{1}{Z_{CC}} = G_{CC} + iB_{CC}$;

2 is the ideal transformer.

Looking at the model obtained the link between the primary and the secondary currents of the ideal transformer could be established as follows:

Model a: The regulator at the primary

It is known that: $\frac{|V|}{|V_s|} = \frac{T}{1}$ and $\frac{T}{1} = \frac{|I_s|}{|I_p|}$

And the input currents of the transformer are:

$$I_p = Y_{CC}(V_p - V) = Y_{CC}(V_p - TV_S) = Y_{CC}V_p - Y_{CC}TV_S \quad (1)$$

$$I_s = -TI_p = -TY_{CC}(V_p - TV_S) = -Y_{CC}TV_p + Y_{CC}T^2V_S \quad (2)$$

Combining equations (1) and (2), the following equation of currents across the transformer in matrix form is obtained:

$$\begin{pmatrix} I_p \\ I_s \end{pmatrix} = \begin{pmatrix} Y_{CC} & -TY_{CC} \\ -TY_{CC} & T^2Y_{CC} \end{pmatrix} \begin{pmatrix} V_p \\ V_s \end{pmatrix} \quad (3)$$

Model b: The regulator at the secondary

It is known that: $\frac{|V|}{|V_s|} = \frac{1}{T}$ and $\frac{1}{T} = \frac{|I_s|}{|I_p|}$

By analogy the input and the output currents of the transformer are:

$$I_p = Y_{CC}V_p - \frac{1}{T}Y_{CC}V_S \quad (4)$$

$$I_s = -\frac{1}{T}Y_{CC}V_p + \frac{1}{T^2}Y_{CC}V_S \quad (5)$$

Combining equations (4) and (5), the following matrix equation of currents is obtained

$$\begin{pmatrix} I_p \\ I_s \end{pmatrix} = \begin{pmatrix} Y_{CC} & -\frac{1}{T}Y_{CC} \\ -\frac{1}{T}Y_{CC} & \frac{1}{T^2}Y_{CC} \end{pmatrix} \begin{pmatrix} V_p \\ V_s \end{pmatrix} \quad (6)$$

III. Proposed approach

Generally, copper losses could be expressed in two different ways: namely, by the sum of losses in all branches of the transformer or by the sum of active powers at its nodes (primary and secondary).

Here, the method of calculation of losses by summing the power at the transformer's nodes is used. Therefore, the copper losses are deduced from the equations of input and output active powers of the transformer. For the same tap position of the regulator, the losses are determined when placed at the primary and at the secondary of the transformer respectively.

III.1. Load or no load regulator placed at the primary

The power equation at the input of the transformer could be written as [6] and [10]: $S_p = V_p I_p{}^*$.

After further expansion and separation into active and reactive powers:

$$P_p = V_p{}^2G_{CC} - TV_pV_s[G_{CC}\cos(\theta_p - \theta_s) + B_{CC}\sin(\theta_p - \theta_s)] \quad (7)$$

$$Q_p = -V_p{}^2B_{CC} - TV_pV_s[G_{CC}\sin(\theta_p - \theta_s) - B_{CC}\cos(\theta_p - \theta_s)] \quad (8)$$

At the secondary windings we have: $S_s = V_s I_s{}^*$.

After further expansion and separation into active and reactive powers:

$$P_s = T^2V_s{}^2G_{CC} - TV_pV_s[G_{CC}\cos(\theta_s - \theta_p) + B_{CC}\sin(\theta_s - \theta_p)] \quad (9)$$

$$Q_s = -T^2V_s{}^2B_{CC} - TV_pV_s[G_{CC}\sin(\theta_s - \theta_p) - B_{CC}\cos(\theta_s - \theta_p)] \quad (10)$$

Copper losses in the transformer are the sum of active powers at its nodes. Thus:

$$\Delta P_p = P_p + P_s = (V_p{}^2 + T^2V_s{}^2)G_{CC} - 2TV_pV_sG_{CC}\sin(\theta_p - \theta_s) \quad (11)$$

III.2. Load or no load regulator placed at the secondary

Taking into consideration the same hypothesis as in (§2.1), the active and reactive powers at the primary of the transformer are:

$$P_p' = V_p{}^2G_{CC} - \frac{1}{T}V_pV_s[G_{CC}\cos(\theta_p - \theta_s) + B_{CC}\sin(\theta_p - \theta_s)] \quad (12)$$

$$Q_p' = -V_p{}^2B_{CC} - \frac{1}{T}V_pV_s[G_{CC}\sin(\theta_p - \theta_s) - B_{CC}\cos(\theta_p - \theta_s)] \quad (13)$$

Similarly, the expressions of the active and reactive powers at the secondary of the transformer are:

$$P_s' = \frac{1}{T^2}V_s{}^2G_{CC} - \frac{1}{T}V_pV_s[G_{CC}\cos(\theta_p - \theta_s) + B_{CC}\sin(\theta_p - \theta_s)] \quad (14)$$

$$Q'_s = -\frac{1}{T^2}{V_s}^2 B_{CC} - \frac{1}{T}V_pV_s\left[G_{CC}\sin(\theta_p - \theta_s) - BCCcos\theta p{-}\theta s \right. \qquad (15)$$

As before, the copper losses in the transformer are:

$$\Delta P_p = {P_p}' + {P_s}' = \left({V_p}^2 + \frac{1}{T^2}{V_p}^2\right)G_{CC} - 2\frac{1}{T}V_pV_sG_{CC}\cos(\theta_p - \theta_s) \qquad (16)$$

The formulas (11) to (16) are programmed in Matlab to determine the copper losses in the transformer and to see at which side they are lower.

IV. Test

In order to validate our work, we have firstly applied our theory on an electrical network of five (5) nodes and seven (7) branches [6]. The transformer is inserted successively between nodes 3 and 6, and 4 and 6. Each insertion leads to the creation of a supplementary node to separate the transformer and the line.

The network is shown in figure 4. In view of the nonlinearity of load flow equations, we will use the Newton-Raphson iteration algorithm to evaluate the load flow by taking into account the transformer with load regulator.

The algorithm is implemented in MATLAB. The simulation results are shown in Table 1 and Table 2.

From the tables, it is clear that the load regulator placed at the transformer's secondary reduce copper losses and this reduction is more important when the power through the transformer is important.

V. Application

The approach was applied to the Congolese interconnected electricity network. This network is made up of thirty (30) real nodes and three (3) imaginary nodes for simulation purposes; twenty-three (23) transmission lines; five (5) transformers in series with the transmission lines. Three (3) of these transformers are three-windings. The remaining two are two-winding transformers. These transformers have been modeled as transmission lines.

In this study, we have chosen the transformer placed between nodes 24 and 28, across which the load regulator is incorporated, because it occupies a strategic position in that its secondary is connected to a transmission line of 170 Km a distance requiring voltage control. The entire network is perfectly modeled not just for the present study, but for other applications. The Congolese interconnected electricity network is represented in Fig. 4, with all parameters in pu.

VI. Simulation results

The simulation results are presented in the table of Appendix 1. Table 1 presents the apparent power losses in the transformer and the ratio of apparent power losses when the regulator is inserted at the primary. It also presents similar results with the regulator in the secondary of the transformer. Table 2 presents just the copper losses. These results indicate that when the load or no load regulator is placed at the secondary, copper losses are reduced. Have you take into account the voltage level?

VI. Conclusion

The approach presented in this study has been on the optimal placement of the load or no load regulator across the power transformer. This placement has optimized the joule losses in the transformer and thus minimizing the joule effect. From the tables of Appendix 1, the apparent powers lost in the transformer are evaluated as: $\Delta S = 0.0004 + j0.009$, in the case of the transformer without the regulator ; $\Delta S_p = 0.0569 + j1.3069$, when the regulator is inserted at the primary of the power transformer. $\Delta S_s = 0.0184 + j0.4219$ when the regulator is inserted at the secondary of the power transformer.

The ratio of the apparent power lost in the transformer with the regulator at the primary with respect to that without the regulator is 145. This shows that the insertion of the regulator at the primary of the transformer increases the apparent power lost by 145 times; while for the insertion of the regulator at the secondary, this ratio is 47 times. Therefore the insertion of the regulator lost in the transformer by 3.2 times with respect to the case where it is inserted at the primary.

The copper losses when the regulator is placed at the primary is evaluated at 0.0567; while losses when the regulator is placed at the secondary is evaluated at 0.0184. The respective ratios to the no-load losses are 142 and 46 for insertion of the regulator at the primary and at the secondary of the transformer. Therefore, the insertion of the regulator at the secondary reduces the copper losses in the transformer by 3.08 times with respect to the case where it is inserted at the primary.

This shows that considerable reduction of losses in large grids with several regulating transformers can be achieved by placing tap-changing regulators at the secondary rather than at the primary windings. Technically, a gain of 3.83 MW is obtained for just one transformer, a considerable amount of power for a small network like the Congolese one. Where a large number of households could be electrified by that amount

A secondary benefit from a technical standpoint is a reduction in the rate of transformer degradation used by the hysteresis effect. Also, this reduction of copper losses leads to additional improvements in the available capacity.

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APPENDIX 1

Nodes	Losses with regulator at the primary (pu)		Losses with regulator at the secondary (pu)		Ratio
	$\Delta P + j\Delta Q$	ΔS_p	$\Delta P + j\Delta Q$	ΔS_s	$\frac{\Delta S_p}{\Delta S_s}$
$3-6$	$0.0154 + 5.1500i$	5.15	$0.0150 + 5.0091i$	5	1.03
$4-6$	0.0541+18.0188i	18.02	$0.0137 + 4.5564i$	4.564	4

Tableau 1 : Simulations results - Comparison of apparent losses.

Nodes	Losses with regulator at the primary (pu)	Losses with regulator at the secondary (pu)	Ratio
	ΔP_p	ΔP_s	$\frac{\Delta S_p}{\Delta S_s}$
$3-6$	0.0154	0.0150	1.03
$4-6$	0.0541	0.0137	3.95

Tableau 2 : Simulations results - Comparison of copper losses.

APPENDIX 2

Nodes	Losses without regulator (pu)		Losses with regulator at the primary (pu)		Losses with regulator at the secondary (pu)		Ratio	
	$\Delta P + j\Delta Q$	ΔS	$\Delta P + j\Delta Q$	ΔS_p	$\Delta P + j\Delta Q$	ΔS_s	$\frac{\Delta S_p}{\Delta S}$	$\frac{\Delta S_s}{\Delta S}$
$24-28$	$0.0004 + j0.009$	0.00901	$0.0569 + j1.3069$	1.308	$0.0184 + j0.4219$	0.4223	145	47

Table 1: Simulation results - Comparison of apparent losses.

Nodes	Losses without regulator (pu)	Losses with regulator at the primary (pu)	Losses with regulator at the secondary (pu)	Ratio	
	ΔP	ΔP_p	ΔP_s	$\frac{\Delta P_p}{\Delta P}$	$\frac{\Delta P_s}{\Delta P}$
$24-28$	0.0004	0.0569	0.0184	142	46

Table 2 : Simulation results - Comparison of copper losses.

APPENDIX 3

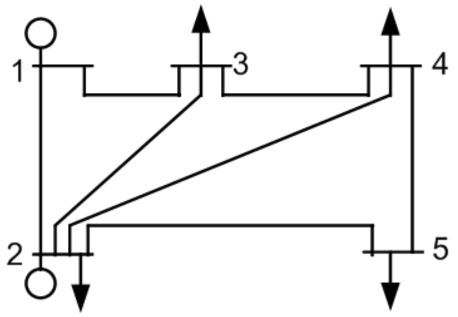

Figure 4: Five nodes test-network

<u>APPENDIX 4</u>

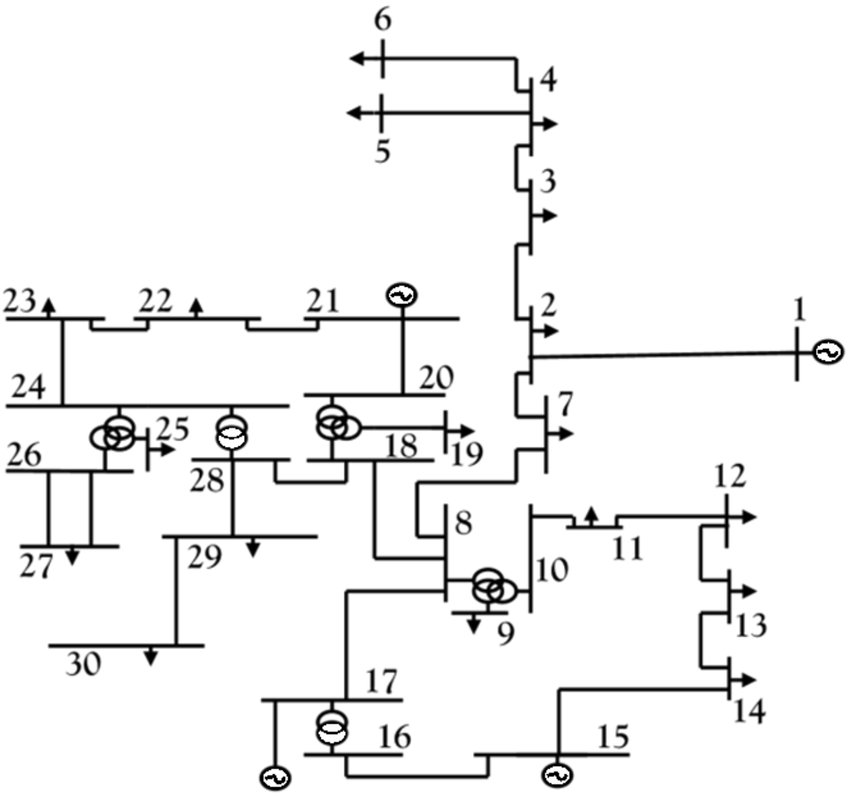

Figure 5: Thirty nodes–Congolese interconnected electrify network