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Impact of Harmonic Disturbances on the Lifespan of a Domestic Station in the City of Niamey

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Abstract: Electrical energy is transported to consumers by means of electrical networks that are a set of infrastructures allowing the transport and distribution of this energy flow. Among these infrastructures, the MV/LV (Medium Voltage to Low Voltage) distribution transformer is one of the key elements in the distribution chain. The lifetime of transformer stations is estimated to be around 20 years under nominal operation. The aim of this scientific work is to evaluate the influence of harmonic disturbances on the lifetime of a domestic substation (Tree-Phase) in the city of Niamey. This article has made it possible to obtain on the three phase a higher temperature of the hot spot in the presence of harmonics than that recorded in the regime without harmonics (e g. 58.84°C against 57.79°C). The impact in terms of loss of life of the electrical transformer was determined to be 206.32 seconds against 178.59 seconds on phase 1. In addition, the results obtained following the evaluation of lifespan in fundamental regime have concluded that the transformer is not overloaded, but the loads placed between its terminals are unbalanced. The consequence of this imbalance will cause premature ageing of the insulating papers at the level of windings wich supply the overloaded phases. On the other hand, under harmonic conditions, currents with harmonics at the transformer terminals contribute to the ageing of the transformer.

Keywords: Diagnostics, Harmonic, Electrical Transformer, Hot Spot Temperature, Lifetime

1. Introduction

The quality of electrical energy is a complex and diversified subject because it requires an adequate sizing of all components of the electrical chain [1]. This energy is distributed to consumers by means of electrical networks, which are a set of infrastructures allowing the distribution of energy flow (electricity). Among these infrastructures, the MV/LV (Medium Voltage to Low Voltage) distribution transformer is one of the key elements.

This transformer lasts about 180,000 hours (more than 20 years) [2, 3]. However, Niger's electricity grid is managed in a rudimentary way, which is why we generally observe technical losses of transformers [4]. In addition to causes, electrical disturbances are factors that affect the good condition of electrical infrastructure.

Electrical disturbances act on the operating temperature of the transformer called "hot spot temperature". This is the indicator of transformer aging [5, 6]. This is why, in this article, it will be a question of evaluating the impact of harmonic disturbances on the life of the transformer. This evaluation will be made on one of the electrical substations of the city of Niamey.

2. Review of the Electrical Disturbances That Accelerate the Aging of the Transformer

Electrical disturbances are phenomena that affect the quality of electrical energy, the most common that are harmful to the life of the transformer are: overloads, imbalances, short circuit and harmonic currents [5, 7]. Electrical insulation is the lifeblood of electrical transformer technology. The malfunction of this element influences proportionally on the state of the transformer, this can lead to a stop of the electrical distribution to subscribers [6].

2.1. Methods for Evaluating the Service Life of the Electrical Transformer

Electrical insulation can be considered as the heart of the transformer: if it is insufficient, the direct consequence is the electrical failure [8].

The life of a transformer depends on the life of the winding insulation papers. The lifespan of these insulating papers depends on the quality of the oil, operating temperature and load [9].

The methodology described by the IEC and IEEE standard, to calculate the loss of life (or reduction of life) of insulating papers, is carried out in three steps:

Evaluation of the temperature of the hot spot;

Evaluation of the aging rate (or aging acceleration factors) of insulating papers;

Evaluation of the reduction of the life (or loss of lifespan) of insulation papers [10].

2.2. Temperature of the Hot Spot Impact on Electrical Transformers

Several studies have described procedures for assessing the loss of life of transformers. The IEC and IEEE standard specify a procedure for evaluating the service life of electrical transformers.

Equation (1) calculates the temperature of the hot spot [2].

$$\theta H = \theta A + \Delta\theta TO + \Delta\theta H \quad (1)$$

with:

θH: Hot spot temperature.

θA: Average ambient temperature.

$\Delta\theta TO$: Deviation of oil temperature from ambient temperature.

$\Delta\theta H$: Deviation of hot spot temperature from oil temperature.

This equation creates an interdependence of a transformer's life at oil temperature and nominal operating temperature. It also determines the aging rate. Indeed, the calculation of the aging acceleration factor is done according to the type of insulating paper.

2.3. Deviation of Oil Temperature from Ambient Temperature

The increase in the oil temperature compared to the ambient temperature for any load current is calculated as a function of the load current of the transformer. It is given by equation (2) [11, 3]:

$$\Delta\theta_{TO} = \Delta\theta_{TO,R}\left[\frac{K^2R+1}{R+1}\right]^n \quad (2)$$

$\Delta\theta_{TO,R}$: Deviation of oil temperature from ambient temperature when the transformer is at rated load;

K: Ratio between available load current and rated load current;

A: Ratio between nominal load loss and vacuum loss.

Equation (3) represents the temperature difference when the transformer load changes several times, over a time interval [3, 11]:

$$\Delta\theta_{TO} = (\Delta\theta_{TO,u} - \Delta\theta_{TO,i})\left[1 - e^{-(\frac{t}{\tau_{TO}})}\right] + \Delta\theta_{TO,i} \quad (3)$$

With :

$\Delta\theta_{TO,i} = \Delta\theta_{TO,R}\left[\frac{K_i^2R+1}{R+1}\right]^n$: First deviation of the oil temperature from the ambient temperature;

t: duration of the charge;

τ_{TO}: The time constant of the oil.

The determination of $\Delta\theta_{TO,u}$ (last deviation of oil temperature from ambient temperature) is similar to that of $\Delta\theta_{TO,i}$. K_i shall be replaced by K_u which is the ratio between the current of the last load and that of the nominal load.

The difference of the temperature of the hot spot from the oil temperature for any load current is calculated as a function of the load current of the transformer by equation (4) [3, 11]:

$$\Delta\theta_H = \Delta\theta_{H,R}K^{2m} \quad (4)$$

With:

K: Ratio between available load current and rated load current;

$\Delta\theta_{H,R} = \Delta\theta_{H/A,R} - \Delta\theta_{TO,R}$: Deviation of the temperature of the hot spot (at the nominal load) from the oil temperature;

$\Delta\theta_{H/A,R}$: Deviation of the temperature of the hot spot (at the nominal load) from the ambient temperature;

Equation (5) is used to calculate the temperature difference of the hot spot from the oil temperature, when the transformer load changes several times over a time interval [3, 11]:

$$\Delta\theta_H = \left(\Delta\theta_{H,u} - \Delta\theta_{H,i}\right)\left[1 - e^{-\frac{t}{\tau_w}}\right] + \Delta\theta_{H,i} \quad (5)$$

With :

$\Delta\theta_{H,i} = \Delta\theta_{H,R}K_i^{2m}$: First gap;

$\Delta\theta_{H,u} = \Delta\theta_{H,R}K_u^{2m}$: Last gap.

τ_ω : Time constant of windings.

NB:

It is assumed $\Delta\theta_{H/A,R}$ is equal to :

80°C for an average increase in hot spot temperature to 65°C.

65°C for an average increase in hot spot temperature to 55°C.

The exponents n and m are given in Table 1, depending on the cooling mode of the transformer [11].

Table 1. *Values of exponents m and n by type and transformer cooling mode.*

Cooling mode	m	n
ONAN	0,8	0,8
ONAF	0,8	0,9
Not directly OFAF or OFWF	0,8	0,9
Direct ODAF or ODWF	1,0	1,0

Evaluation of the aging acceleration factor of insulating papers.

The calculation of the aging acceleration factor is done according to the type of insulating paper. Indeed, there are:

1. insulating papers used by the IEEE (IEEE std C57-91) Load Guide (Submersible Transformers), which have a certain resistance to thermal imperfections with a reference temperature of up to 110°C. These insulators are called "thermally improved paper" and their aging acceleration factor is given by equation (6) [3, 11].

$$F_{aa} = \exp\left(\frac{15000}{273+110} - \frac{15000}{\theta_H+273}\right) \quad (6)$$

2. insulating papers used by the IEC Load Guide (IEC 354-1991), which have less resistance to thermal imperfections compared to those used by IEEE load guides. Their reference temperature is 98°C. These insulators are called "thermally unimproved paper" and their aging acceleration factor is given by equation (7) [12].

$$v = 2^{(\theta_H-98)/6} \quad (7)$$

The following table summarizes this calculation phase.

Table 2. *Acceleration factor according to the type of insulating paper.*

Standard	Insulating papers	Factor accelerating aging
IEEE std C57-91	Thermally improved (reference temperature at 110 degrees)	$F_{aa} = \exp\left(\frac{15000}{273+110} - \frac{15000}{\theta_H+273}\right)$
CEI 354-1991	Thermally not improved (reference temperature)	$F_{aa} = 2^{(\theta_H-98)/6}$

From the aging acceleration factor, it is possible to determine the reduction in the service life (or loss of life) of a transformer, over any time interval, is an integration of the aging acceleration factor over this time interval. It translates into the following general formula [3, 13]:

$$LOL_h = \int k.dt;\ \text{avec}\ k = \begin{cases} F_{aa} \\ \text{ou} \\ v \end{cases} \quad (8)$$

As Faa and V do not depend on time: LOLH = k. t
with:

LOL (Loss Of Life): loss of lifespan

The percentage of the reduction in the life of insulating papers is defined by equation (3) [3, 14]:

$$LOL_p(\%) = \frac{F_{aa} x t x 100}{\text{Life of insulating duration}} \quad (9)$$

The electrical characteristics of the transformer of the distribution substation are given in Table 3.

Table 3. *Electrical characteristics of the distribution transformer.*

Electrical characteristics		Values
Rated power		1000 kVA
Nominal voltage	Primary side	20 kV
	Secondary side	410 V
Nominal Current	Primary side	28,9 A
	Secondary side	1408 A
Short-circuit voltage		6%
Nominal frequency		50 Hz
Windings		Aluminum
Coupling		Dyn11 (in triangle-star)
Standard reference		CEI 60076 / NFC 52- 112-1
Hermetic filling		Yes
Cooling type		ONAN

3. Result and Interpretation

As mentioned above, it is exactly a question of evaluating the lifespan of a domestic station under permanent load. Figure 1 illustrates the profile of the currents called by these loads. A first observation is the fluctuation of consumption. This fluctuation is explained by the variation in activities during the day. In addition, the supply lines are not evenly distributed, this probably causes an imbalance of currents. Lines 1, 2 and 3 correspond to the secondary coils of the MV/LV transformer.

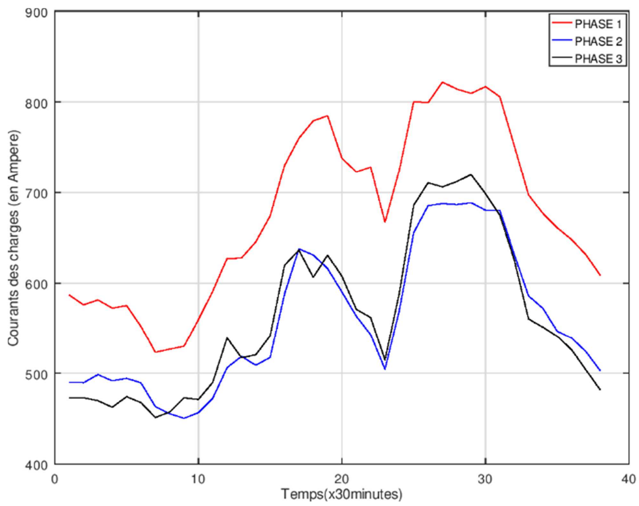

Figure 1. *Load current fundamental regime.*

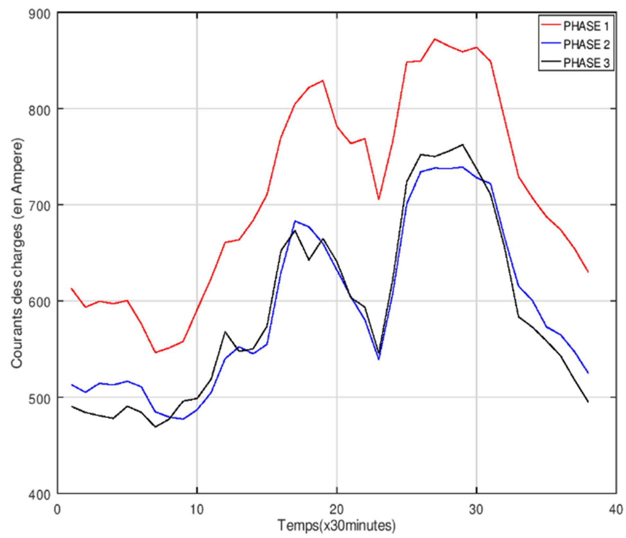

Figure 2. *Load current in harmonic regime.*

The temperature profiles of the hot spot also undergo the same behavior as the charging currents, i e. the greater the charging current, the higher the temperature of the corresponding coil. The aging acceleration factor (or aging rate) depends on the type of insulating paper in the transformer windings.

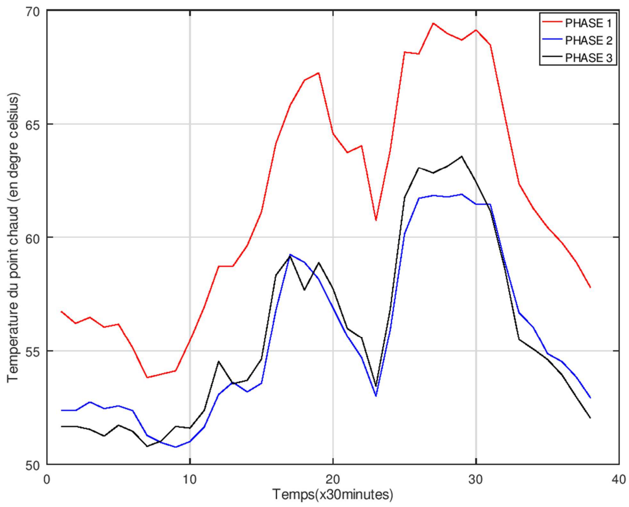

Figure 3. *Evolution of the temperature of the hot spot in fundamental regime.*

From what is related from the previous figures, we cannot neglect the impact of non-linear loads on the transformer in domestic environment.

As a result, these harmonic currents contribute to the acceleration of aging of the insulating papers of the windings. The curves (2) of Figure 3 represent the aging rates, in regime without harmonic and in regime with harmonic.

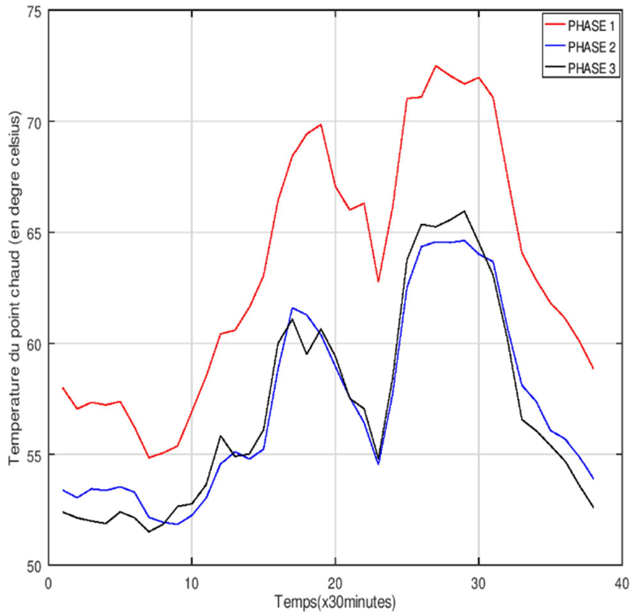

Figure 4. *Evolution of the temperature of the hot spot in harmonic regime.*

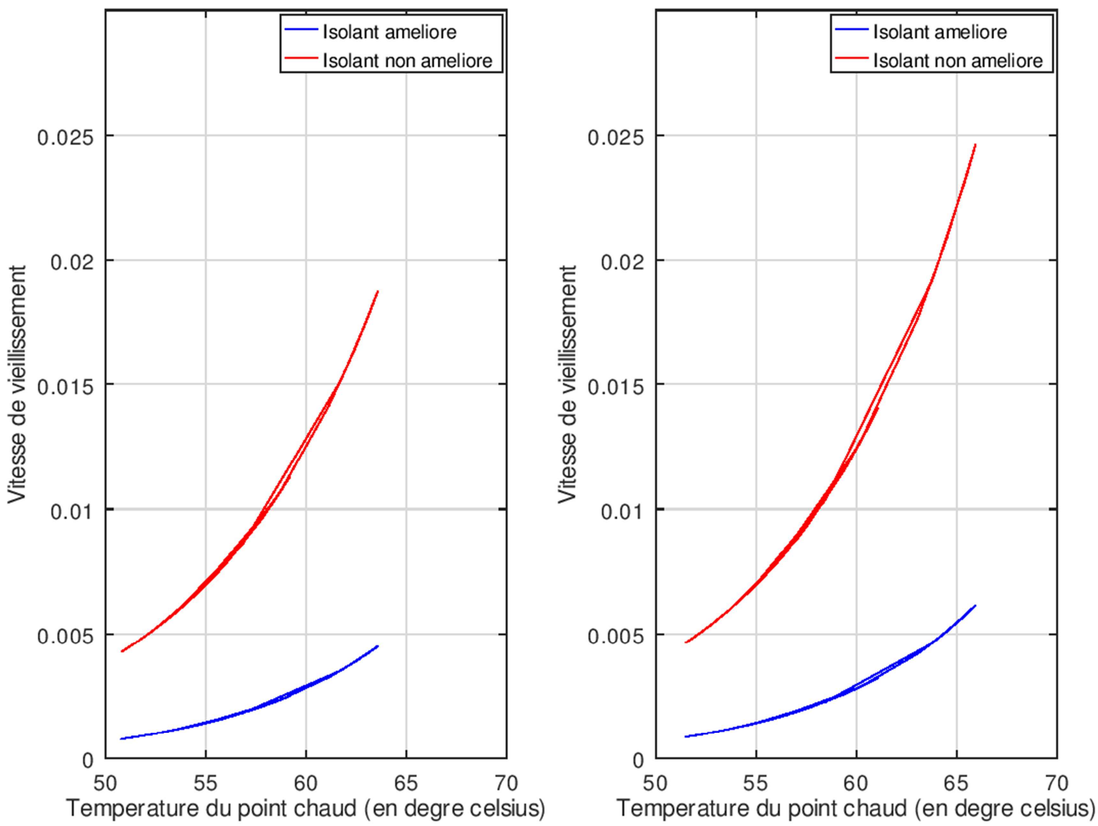

Figure 5. *Temperature impact without harmonic and with harmonic.*

In short, the estimated lost life regression and the temperature level of the hot spot under this stress is summarized in the following table:

Table 4. *Summary table of the two results.*

Phenomena	Hot spot temperature in 24 hours (°C)		Lost lifespan in 24 hours (S)	
Regimes	**Fundamental**	**Harmonic**	**Fundamental**	**Harmonic**
Phase 1	57,79	58.84	178,59	206,32
Phase 2	52,92	53,89	90,72	103,94
Phase 3	52,03	52,60	79,92	86,66

4. Conclusion

The evaluation of the lifespan of the transformer is a very important step in the management of the electrical energy distribution network. Indeed, a specific study on the KALLEY-EST distribution substation was carried out over a period of 24 hours, under two regimes (without harmonic and with harmonic). The results led to the conclusion that harmonics accelerate the technological loss of transformers. Definitely, the losses of the life by 24 hours, in harmonic regime, are highlighted on the three phases, respectively 206.32 S; 103.94 S and 86.66 S. These results show the need to set up a device facilitating the prediction of the state of transformations in order to avoid stopping the supply of electrical energy.

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