Feasibility Study of an in-Tank Oil Purification for an Operating Transformer (Case of the ZYD50 Purifier of Frontier Mine)

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Abstract: ***This article is devoted to the feasibility study of an in-tank oil treatment of an operating transformer. This study has been performed with Frontier mine's ZYD 50 purifier. This purifier operates via filtration, drying and vacuum degassing at a temperature T ranging from 20℃ to 80 ℃ with a flow rate of 50 litres per minute. During our study, an identification of the constraints that may occur during a purification of an in-tank oil operating transformer was performed. As a result, the temperature and oil level control of the in-tank oil transformer were found to be the key constraints. Thus, in order to guarantee a safe purification for the transformer within its environment, as recommended bythe IEC60422 standards, we have chosen an HYDAC oil cooler, written a Sequential Function Chart (SFC) for the automation and the safety of the oil purification process. This research makes possible for industry and public sector, the purification of a transformer while connected to the network in order to keep the power supply a vailable while increasing the transformer life.***

Keywords: Purification, ZYD Purifier, Transformer Oil, Operating Transformer, Constraints.

1. Introduction

Power transformers are a key element of the electrical distribution networks due to their ability to convert the input voltage to different levels depending on the requirements. Also, transformers are quite expensive pieces of equipment in terms of capital expenditure, they usually represent about 60% of the total cost for substations (FOFANA, HEMMATJOU, and FARZANEH, 2010). This is the reason why their lifetime must be extended to the maximum in order not to spend huge amounts of money for replacing them over the years.

Oil-filled transformers are the most widely used in electrical distribution. The oil ensures both electrical insulation and heat transfer (ROUSE, 1998 cited in PERRIER, 2005). On the other hand, there are several parameters that reduce the transformers' lifetime by causing the quality degradation inside the transformer's tank. Amongst these parameters there are electrical constraints, thermal constraints and environmental constraints that cause the oil to lose the required quality in order to maintain the transformer's insulation and cooling (PERRIER, 2005). The transformer's paper insulation quality decreases depending on the severity of these constraints as well as the operating time (LOISELLE, 2013, p.18). When the oil quality is seriously reduced, it is recommended to isolate the transformer in order to purify the in-tank oil due to the risks of breakdown and possible explosion becoming high.

Additionally, power transformer oil purification is often only performed during the reduced downtimes for planned infrastructure maintenance. This is a common practice in the industrial sector, including at Frontier SA. This does not avail enough time for an effective purification of the oil.

Therefore, the main objective of this research is to study the feasibility of performing an oil purification of a transformer while in operation (with normal load), using a ZYD 50 purifier, in order to increase its availability and lifetime. This study refers to the IEC standards recommended safety measures for an operating transformer as well as its environment during an in-tank oil purification.

2. Methodology

In order to better understand our scope, we should ask ourselves the following question: What constraints could we encounter during an in-tank oil purification of an operating transformer?

Firstly, during the energy conversion process within active parts of a transformer, the losses are partly wasted in the form of heat (CLAERHOUT, 2001, p. 52). Therefore, in order to better fulfil one of its functions, that of being a coolant, the average temperature of the oil must be lower than that of the active parts so that it remains a heat "receiver" and allows an easy cooling by convection through transformer fins.

Additionally, the purification of an operating transformer's in-tank oil is aimed to extract impurities (solid particles, moisture and dissolved gases) while the transformer is loaded. During the process, the oil temperature varies between 20℃ and 80℃inside the purifier in order to reduce its moisture content (CHONGQING ZHONGNENG, no date).

At Frontier mine, the site transformers' primary voltage is 33kV and is therefore lower than 72.5 kV. This classifies them as part of category C according to the IEC 60422. The alarm and the trip thresholds for the transformer tank thermometer are generally set to 60 ℃ and 80℃. As a result, in order to be able to purify the oil without causing the activation of the alarm or even the trip of the transformer protection devices we must stay well away from the alarm threshold. The first constraint which is the heating of the oil during the purification process is hence defined.

Secondly, in order to purify the oil, the ZYD 50 purifier regularly sucks a constant quantity of the in-tank transformer oil at a flow rate of 50 litres per minute, processes it, then discharges it back to the transformer tank (CHONGQING ZHONGNENG, no date). Thus, the second constraint is the probable unsafe decrease of the oil level in the transformer tank.

Therefore, in order to purify the in-tank oil of an operating transformer while ensuring the safety of the transformer and its environment, it will be necessary to constantly monitor certain parameters of the oil in the transformer tank. This is obviously:

- The oil temperature inside the transformer tank by considering its temperature alarm threshold.
- The level of the oil in the transformer tank.

Despite these different constraints, controls can be implemented in order to be able to perform a completely safe purification. Therefore, we are going to size and select a heat exchanger capable of cooling the oil discharged from the purifier and also write a Sequential Function Chart for an automated monitoring of the oil temperature and level inside the transformer tank.

2.1. Sizing of the heat exchanger

The heat exchanger must be able to reduce the maximum temperature of the outlet oil to 40℃. The two fluids in a heat exchanger are physically separated from each other using a mass-transfer-proof wall that is a permeable as possible to heat transfer. Therefore, as a hypothesis of calculation, we suppose that all the energy lost by the hot fluid is totally gained by the cold fluid (BONTEMPS et al, 1994, p. 2).

The power P of the heat exchanger is given by the followed formula:

$$P = qc \times (Ti - To) \quad (2.1)$$

With qc being the calorific flow of the fluid, Ti the temperature of the fluid at the inlet of the heat exchanger and To the temperature of the fluid at the outlet of the heat exchanger.

$$\mathrm{qc} = \mathrm{qm} \times \mathrm{Cp} \quad (2.2)$$

With qm being the mass flow rate of the fluid passing through the heat exchanger and Cp the specific heat of the fluid.

The mass flow of the fluid can be determined by the followed expression:

$$\mathrm{qm} = \rho \times \mathrm{qv} \quad (2.3)$$

With ρ the density of the fluid and qv its volumetric flow rate.

By introducing the equations 2.2 and 2.3 into the equation 2.1, the power P of the heat exchanger becomes:

$$P = \rho \times \mathrm{qv} \times Cp \times (Ti - To)$$

During our experiment we noticed that the outlet temperature of the oil during the purification varies between 50 ℃ and 60℃. However, we will be considering extreme cases where the outlet oil temperature reaches 80 ℃ and we expect the heat exchanger to cool it down to 40℃. The oil density and average specific heat are 863.7 kg/m^3 and 1.91 kJ/kgK (NYNAS, 2013).

Using the data provided previously, we can calculate the power P of the heat exchanger as follows:

$$P = 863.7 \times \frac{0.05}{60} \times 1{,}91 \times 40 = 55\ kW$$

The heat exchanger is characterized by a specific cooling capacity P' expressed as follows, with Ta the ambient temperature [9]:

$$P' = \frac{P}{Ti - Ta} \quad (2.4)$$

With Ta the ambient temperature of the air.

This gives: $P' = \frac{55}{80-30} = 1{,}1\ kW/K$

We can also calculate the air flow required for the oil cooling using the equation 2.5 expressing the heat balance of the heat exchanger.

We have determined the necessary power of the heat exchanger to cool the oil from 80 ℃ to 40 ℃ for a flow rate of 50 litres per minute. In order toper form the selection, it is necessary to decide on the technology to be used by the heat exchanger.

Since this applies to a transformer purifier, the heat exchanger must be easy to move, and the cooling fluid must be cheap and readily available. This leads us to choose the air as the second (cooling) fluid ofthe heat exchanger. Thus, a cross flow heat exchanger would suit us.

At the inlet of the heat exchanger the air is blown at ambient temperature ($T2i = 30$℃).The outlet temperature of the air T2o must then be specified. Considering that the distance travelled by the air in a cross flow exchanger is short, the difference between its inlet and outlet temperatures must be realistically small. Therefore, we do expect an outlet air temperature T2oof 40℃. The heat exchanger heat balance is given by:

$$qc1 \times (T1i - T1o) = qc2 \times (T2i - T2o) \quad (2.5)$$

Since the left side of the equation was previously calculated above, the equation becomes:

$$55 = qm2 \times 1.006 \times (T2i - T2o)$$

$$qm2 = \frac{55}{10.06} = 5.46\ kg/s \text{ and}$$

$$qv2 = \frac{5.5}{1{,}204} = 4.53\ m^3/s \text{ or } 16326 m^3/h$$

For an air flow rate of 5.5 kg/s , an outlet oil temperature of approximately 39.8℃is obtained. This is very close to the desired temperature (40℃).

2.2. Oil level during purification

The oil flow rate is the same at both the inlet and outlet of the purification machine. During the purification process, the purifier sucks some oil while discharging some other oil at the same time. This implies that the oil level in the tank remains constant during the purification. That can be explained using the mathematical model of the purifier-tank system, during the purification process, as follows:

$$A\frac{dL}{dt} = Qi - Qo \quad (2.6)$$

With A the area of the tank, L is the oil level in the tank, Qi the inlet volumetric flow and Qo the outlet volumetric flow supplying the tank.

Based on the expression 2.6, if the inlet volumetric flow *Qi* and the outlet volumetric flow supplying the tank *Qo* are equal, the variation of the oil level in the transformer tank with respect to the time $\frac{dL}{dt}$ is practically zero. However, as previously mentioned, the level only drops at the very first suction sequence, while there is an inlet but no outlet flow.

2.3. Automation and Safety

In order to have a safe oil purification system of an operating transformer using the ZYD 50purifier, the system must be automated. Ourthought is to implement an automated safety system that can constantly control the level and the temperature of the oil in the transformer tank.

2.3.1. Principle of automation

In case of any abnormal condition during the purification, a Programmable Logic Controller (PLC) must be able to stop the purifier and the cooler's motor while isolating the transformer tank at the same time.

The excepted abnormalities which may occur during the purification include:

- An overheating of the oil in the transformer tank;
- A critical drop in oil level inside the transformer tank.

2.3.2. Inputs and Outputs to the Programmable Logic Controller

In this section, the various required inputs and outputs to the controller as well as their importance inautomating the purifier, cooler and transformer tank operation are specified and described.

2.3.2.1. Programmable Logic Controller's Outputs

Outputs include actuators, pre-actuators and indication lights. Actuatorswill be controlled via solenoid valves. These would be fully open or fully close and will therefore depend on digital outputs from the PLC output card. Their role will be interrupting or allowing the passage of oil into interconnection pipes from and to the tank.

LEDs (light-emitting diodes) will be used for warning and displaying sequences status.These will be reinforced with audible alarms in some instances. All of them will be activated and deactivate used digital outputs too.

The following are the required digital outputs, with their function (see Figure 2.1):

- ***KMP contactor:*** *Switches the purifier ON or OFF;*
- ***KMC contactor****: Switches the cooler ON or OFF;*
- ***ON/OFF Valves (VIT, VOT,VIP and VOP)****: Serve to interrupt the inlet and/oroutlet flows of oil into the transformer tank in the event of any abnormality;*
- ***Orange LED:*** *Indicates the opening of the valves;*
- ***Green LED:*** *Indicates that the transformer is ready for purification;*
- ***Red LED:*** *Indicates when the purifier is in operation;*
- ***Alarm - AS1****:Warns when the oil level in the transformer tank is lower than 95%;*
- ***Alarm- AS2:****Warns when the oil temperature in the transformer tank is above55℃ ;*
- ***Alarm - AS3:*** *Warns when the oil temperature at cooler's outlet is above 45℃.*

2.3.2.2. Programmable Logic Controller's Inputs

Inputs include sensors and push buttons. Those will send signals to the PLC input card. The following are the required digital inputs, with their function (see Figure 2.1):

- ***Oil level sensor (TLTS):*** *Continuously measures the oil level in the transformer tank.*
- ***Temperature sensors (2):*** *Continuously measure the oil temperature inside the tank for the transformer **(TTTS)** and at the outlet of the heat exchanger **(TCS).***
- ***Solenoid Valves Limit Switches (VITS-O, VITS-C, VOTS-O, VOTS-C,VIPS-O, VIPS-C, VOPS-O and VOPS-C):*** *Each solenoid valve is equipped with limit switches.*
- ***Start pushbutton (PBS):*** *Starts the purification.*
- ***Reset Push Button (PBR):*** *Stops the purification.*
- ***Valves Push button (PBV):*** *Opensall the valves at once.*

Figure 2.1shows the in-tank oil purification system of an operating transformer with the different sensors and actuators.

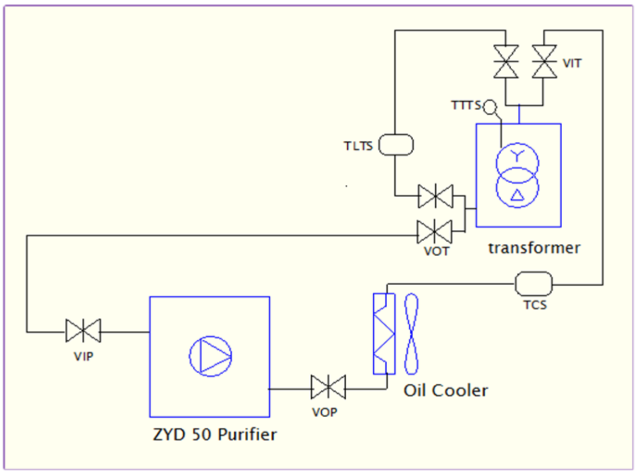


Figure 2.1: Oil purification system for an operating transformer

2.3.3. Automation using a Sequential Function Chart

As previously raised, our oil purification system requires some automation to ensure a continuously safe in-tank transformer oil purification while operating. Further to identifying the required inputs and outputs, we came-up with a Sequential Function Chart which describes how the process would be automated through different sequences as presented on Figure 2.2. The below SFC uses different tags for specific sequences, command and status. These are explained below:

Run Purifier ***(Rpur);*** *Stop Purifier****(Spur)****;Run Cooler* ***(Rcool)****;Stop Cooler* ***(Scool)****;Close Transformer Inlet Valve****(CVIT)****; Close Transformer Outlet Valve* ***(CVOT)****;Open Transformer Inlet Valve****(OVIT)****;Open Transformer Outlet Valve* ***(OVOT)****; Close Purifier Inlet Valve****(CVIP)****; Close Purifier Outlet Valve* ***(CVOP)****;OpenPurifier Inlet Valve****(OVIP)****;Open Purifier Outlet Valve* ***(OVOP)****;Switch ON Green LED* ***(LgreenLED)****; SwitchOFF Green LED(* ***TgreenLED)****;Switch ONOrange LED(* ***LorangeLED)****; SwitchOFFOrange LED****(TorangeLED)****;Switch ONRed LED****(LredLED)****;SwitchOFF Red LED****(TredLED)****; Activate Alarm 1* ***(Aalarm 1)****; DeactivateAlarm 1* ***(Dalarm 1)****;ActivateAlarm 2* ***(Aalarm 2)****;DeactivateAlarm 2* ***(Dalarm 2)****; ActivateAlarm 3* ***(Aalarm 3)****;DeactivateAlarm 3****(Dalarm 3)****).*

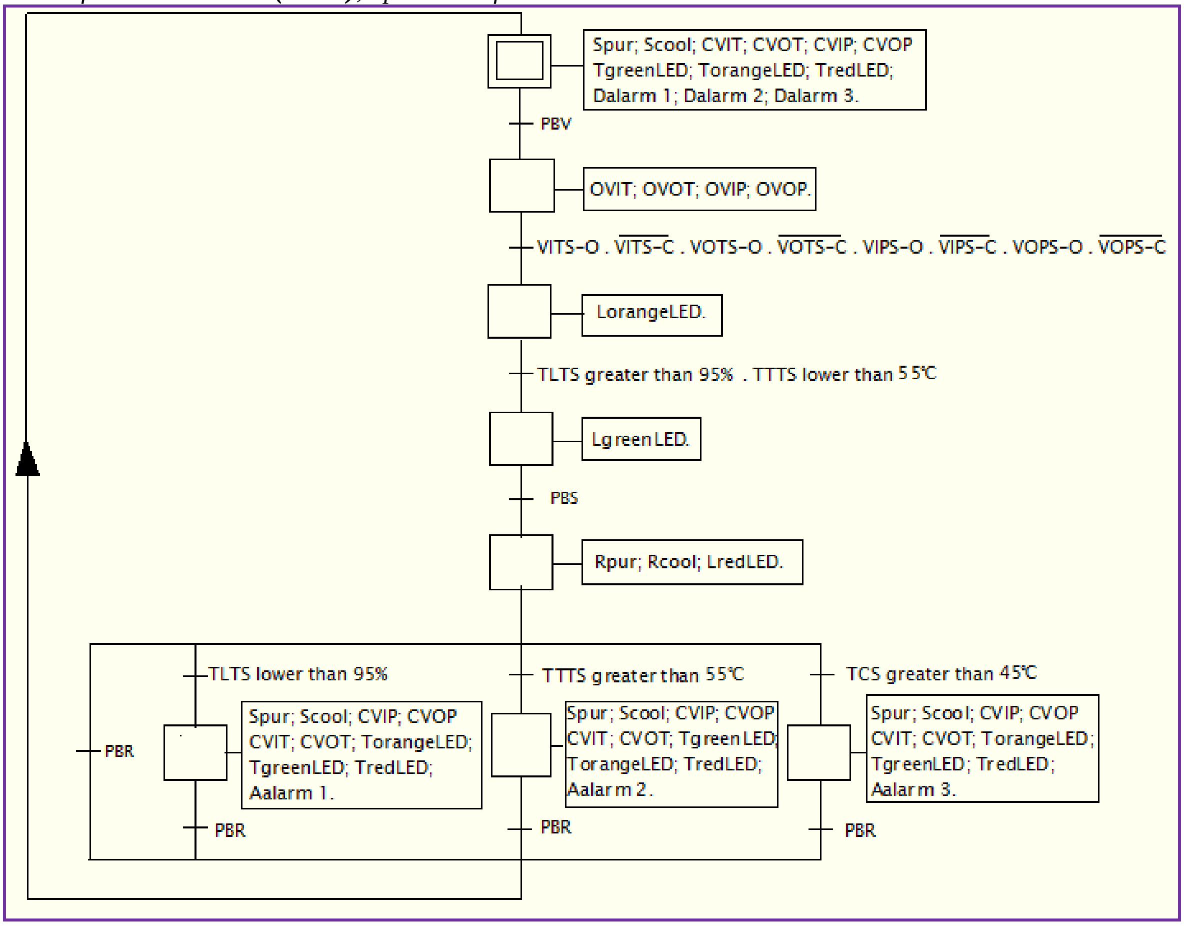


Figure 2.2: SFC for the safe automation of the purification system

3. Outcome and Discussion

Following our calculations, we sized the oil cooler to 55kW and an air flow of 4.53m^3/s. This is expected to cool our oil, at a flow of 50 l/s by maintained a different in temperature of 40 ℃ between the inlet and outlet. Figure 3.1presents specifications of the cooler offered by HYDAC for our application. The pressure drop Dpin such a heat exchanger are said to be 21,000Pa. Then, it is necessary to predict the new discharge head **Hd'** of our purification system after connecting it to the heat exchanger.

$$\mathbf{Hd' = Hd - Dp^m}$$

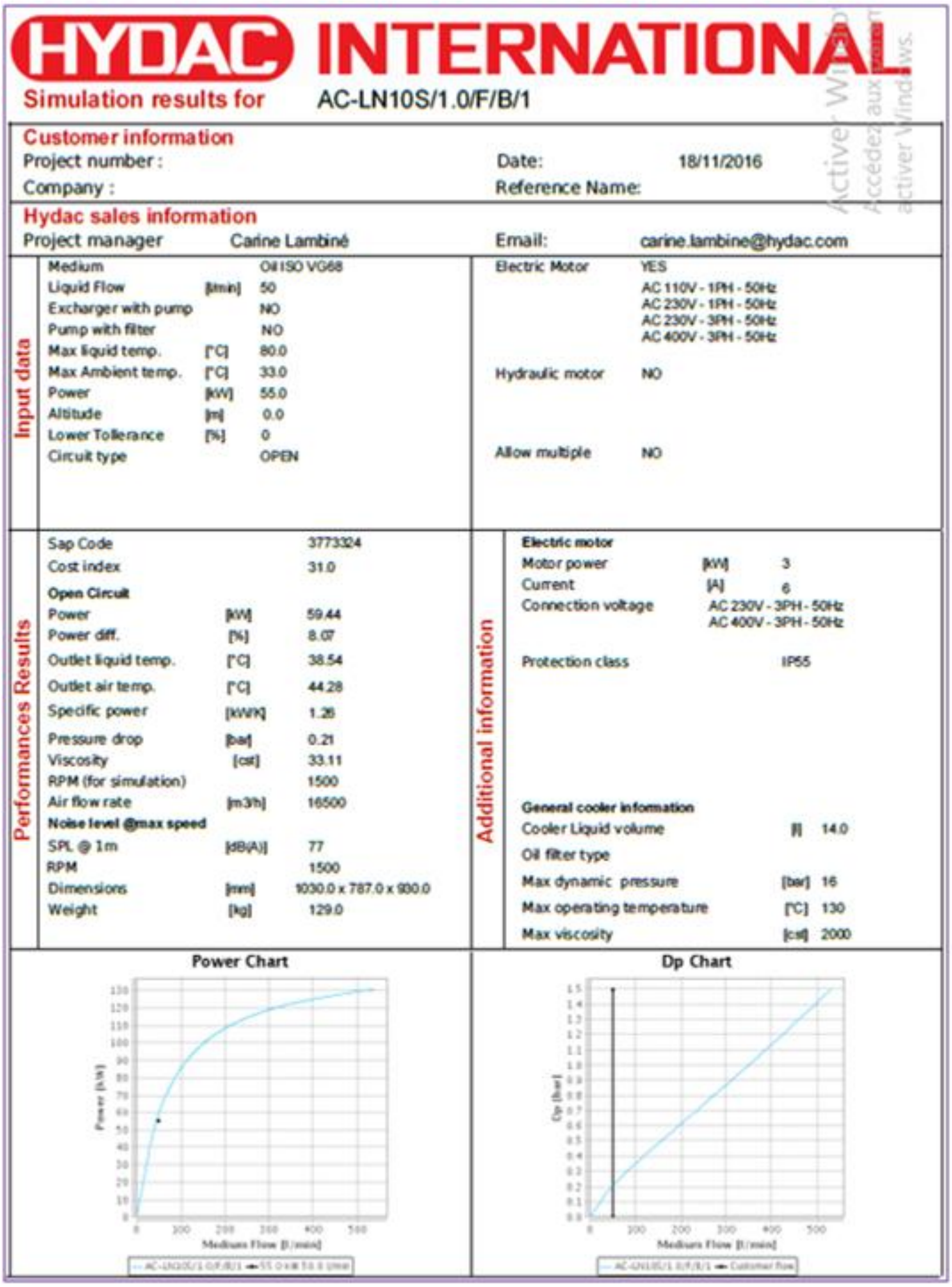
With ***H*** the discharge head of the purifier without the heat exchanger (5 meters) and $\mathbf{Dp^m}$**,** the head loss within the heat exchanger in meters.

By dividing Dp by the density of the transformer oil which is 8472.897 N/m³, we obtain about 2.48 meters; which is the pressure drop inside the heat exchanger $\boldsymbol{Dp^m}$.

So, $Hd' = 5 - 2.48 = 2.52\ m$

With such a result, the maximum head between the purifier's pump and the transformer oil supply point must be approximately 2.5 meters.

The SFC hence established uses 12Digital inputs and two analog Inputs (for the outlet cooler's temperature and transformer oil level) and 10 digital outputs. These could be converted into Digital Inputs by rather using temperature and level switches. By doing so, a basic PLC such as the Siemens LOGO 230 RC with two DM8 230R expansion modules could safely automate such a purification system.



HYDAC INTERNATIONAL

Simulation results for AC-LN10S/1.0/F/B/1

Customer information

Project number: | Date: 18/11/2016

Company: | Reference Name:

Hydac sales information

Project manager: Carine Lambiné | Email: carine.lambine@hydac.com

Input data

Medium		Oil ISO VG68	Electric Motor	YES
Liquid Flow	[l/min]	50		AC 110V - 1PH - 50Hz AC 230V - 1PH - 50Hz AC 230V - 3PH - 50Hz AC 400V - 3PH - 50Hz
Exchanger with pump		NO		
Pump with filter		NO		
Max liquid temp.	[°C]	80.0		
Max Ambient temp.	[°C]	33.0	Hydraulic motor	NO
Power	[kW]	55.0		
Altitude	[m]	0.0		
Lower Tollerance	[%]	0		
Circuit type		OPEN	Allow multiple	NO

Performances Results

Sap Code		3773324
Cost index		31.0
Open Circuit		
Power	[kW]	59.44
Power diff.	[%]	8.07
Outlet liquid temp.	[°C]	38.54
Outlet air temp.	[°C]	44.28
Specific power	[kW/K]	1.26
Pressure drop	[bar]	0.21
Viscosity	[cst]	33.11
RPM (for simulation)		1500
Air flow rate	[m3/h]	16500
Noise level @max speed		
SPL @ 1m	[dB(A)]	77
RPM		1500
Dimensions	[mm]	1030.0 x 787.0 x 930.0
Weight	[kg]	129.0

Additional information

Electric motor		
Motor power	[kW]	3
Current	[A]	6
Connection voltage		AC 230V - 3PH - 50Hz AC 400V - 3PH - 50Hz
Protection class		IP55
General cooler information		
Cooler Liquid volume	[l]	14.0
Oil filter type		
Max dynamic pressure	[bar]	16
Max operating temperature	[°C]	130
Max viscosity	[cst]	2000

Figure 3.1: HYDAC proposed cooler specifications

4. Conclusion

This feasibility study of in-tank oil purification for an operating transformer, aims to actively address some of the most important oil quality issues for power transformers. These particularly apply to the moisture content, viscosity, acid content and even more, that influence the oil dielectric strength and heat-transfer capacity. These oil characteristics are capable of reducing transformers' lifetime. In this regard, common practice for in-tank oil purification for power transformers as well as the IEC standards for oil maintenance where used as a basis during our field experiments.

The IEC 60422 standards recommend strict safety measures for an on-load transformer oil purification. These measures aim to prevent harms to the workers and the environment but also avoid any damages to the equipment itself (IEC, 2013).

To this end, we carried out a constraints' analysis of an in-tank oil purification of a transformer connected to the network with the ZYD 50 purifier.

Our first finding was the risk of overheating the oil during the purification process resulting in the rise in temperature for the transformer itself. In order to overcome this, a proper cooler must be placed at the outlet of the purifier. This cooler should be a cross flow air-oil heat exchanger with a minimum power of 55 kW for an oil flow of 50 litres per minute. However, the use of such a heat exchanger leads to a 2.48 meters loss in discharge head for the purification system.

Our second finding was that of a possible unsafe reduction in oil level inside the transformer tank. However, this only happens at the initial suction sequence and thereafter, the level remains constant as the inlet and outlet flows would be equal during the purification process. Such a reduction in level at the process start could only be of a concern for very small transformers.

Lastly, in order to ensure that the above process takes place in a continuously safe manner, we have decided to automate the steps and sequences. This involves equipment starting and stopping as well as valves opening and closing; with sequences being stopped in case any abnormalities occur. To this end, a Sequential Function Chart was designed and would allow such an automated safety system to be controlled using as basic as the Siemens LOGO 230 RC PLC with two DM8 230R expansion modules.

References

[1] BONTEMPS, A., GARRIGUE, A., GOUBIER, C., HUETZ, J., MARVILLET, C., MERCIER, P.& VIDIL, R. (1994). Echangeurs de chaleur, définitions et architecture générale, (pp. 1-2). Techniques de l'ingénieur.Available at www.techniques-ingenieur.fr, accessed on 10 july 2016.

[2] CHONGQING ZHONGNENG (no date). ZYD-50 Double stage Vacuum Transformer Oil Purifier. Technical specification. Availableatwww.zhongnengcq.cn,accessed on 10 Avril 2016.

[3] CLAERHOUT, L. (2001).Electricité (volume 4), (pp. 52-60).Centre de Recherche Pédagogiques, Kinshasa.

[4] FOFANA, I., HEMMATJOU H., and FARZANEH M. (2010). Low temperature and moisture effects on polarization and depolarization currents of oil-paper insulation, vol. 80, (pp. 91-97). Electric Power Systems Research.

[5] IEC 60422. (2013). Mineral insulating oils in electrical equipment – Supervision and maintenance guidance (ed. 4).

[6] LOISELLE, L. (2013). Influence des produits de dégradations sur la stabilité thermique et diélectrique des fluides isolants des transformateurs de puissance, (p. 18 – 84). Mémoire pour l'obtention d'un diplôme de maitrise, université de Québec.Available at www.constellation.uqac.ca,accessed on 12 July 2016.

[7] NYNAS AB. (2003). Mineral Oil: technical and Safety data sheet. Product data sheet. Available at www.edenoil.co.uk,accessed on 01 March 2020.

[8] PERRIER, C. (2005). Études des huiles et des mélanges à base d'huile minérale pour transformateurs de puissance – recherche d'un mélange optimal. Autre. Doctoral thesis (archives of HAL), Ecole Centrale de Lyon. Available at www.tel.archives-ouvertes.fr,accessed on 15 February 2020.

[9] ROUSSE T.O. (1998), Mineral insulating oil in transformers,vol 14, n°3, (pp. 6-16).IEEE Electrical Insulation Magazine. cited in PERRIER, C. (2005). Études des huiles et des mélanges à base d'huile minérale pour transformateurs de puissance – recherche d'un mélange optimal. Autre. Doctoral thesis (archives of HAL), Ecole Centrale de Lyon.