Literature Study on Condition of Tertiary of Interbus Transformer and Alternative Protection

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***Abstract*—Interbus Transformer (IBT) plays important role in the reliability of power system interconnecting two different voltage levels thus enable the power interchange. Failure in the IBTs' bushings, will instantly lead to the power interruption and outage. Normally, IBTs are constructed of three windings with primary and secondary in wye and the tertiary in delta. The primary and secondary are loaded, with tertiary mostly unloaded and provide the isolating system due to the unbalance from the other two windings. Operating bushings above the nominal voltage tends to reduce the operating cycle. Displacement of absolute reference from phase to phase voltage thus will raise the applied voltage exceeds the nominal voltage. Theoretically, applying operating voltage of 1.571 x U_0 to the tertiary bushing continuously is likely to reduce the life time of bushing to approximately 2.5 years. Online monitoring technique is introduced to monitor the changes in the bushings due to the degradation of insulation quality. Literature study focusing on the ideal condition of a bushing against the real loading cycle in operation also considered to estimate the insulation degradation mechanism. This study put more efforts in analyzing the bushing condition as the function of loading pattern and the applied voltage. Bushing online monitoring data are attached as well to describe the occurrences inside the bushing. At the end of this study, options on the protection scheme are described with fault analysis.**

***Index Terms*—tertiary bushing, partial discharge, expected life time, protection scheme**

I. Introduction

Generally the existence of tertiary windings in transformer enable the path to the current circulation in the winding itself when the unbalanced conditions occur both in normal operation or fault circumstances. Tertiary windings enhanced the more compact, simple and economics design of transformers. Practically, the tertiary windings play roles as [1]:

- To reduce triple harmonic of output voltage thereby stabilizing potential of the neutral point.
- To suppress third harmonic current.
- To provide path of circulation current in unbalance condition.
- To reduce the system zero sequence impedance in effective earthing where solid earthing is not provided.
- To supply the auxiliary loads.

In PLN it is a common practice to utilize the single phase single bank interbus transformers (IBTs) for 500kV, with few of three phase single bank IBT. Total of 135 unit of IBTs are in operation at voltage level of 500/150kV with tertiary winding to deliver the power from 500kV to 150kV power grid with detail as Table I [2].

TABLE I. Type and Number of Interbus Transformer

No.	Interbus Transformer	Tertiary Earthing	Total
1.	Three phase single bank	Solid	3
2.	Single phase single bank	Solid	26
3.	Single phase single bank	Floating	18

During the operation, several failures and damages on were recorded. Table II shows the event recorded during period of 2008 up to 2013 on IBTs 500/150kV. The failure of IBT results in unexpected large area blackout and huge losses of economics and social potential in the community. It is necessary to continuously observe the condition of IBTs and run a life cycle estimation to avoid the occurrence of this unexpected event so the future action can be precisely planned in precaution.

TABLE II. IBTs Failure Statistics in Java Bali System

No.	IBT Identity	Year of Operation	Year of Failure	Cause
1.	CW1 ph R	1996	2009	Bushing
2.	KB1 ph T	1994	2009	Secondary Bushing
3.	CB2 ph R	2012	2012	Tertiary Bushing
4.	CW2 ph S	1996	2013	Tertiary Bushing

II. Bushing and Its Standards

Referred to IEC 60137 [3], bushing is defined as device the enables one or several conductors to pass through a partition such as a wall or a tank, and insulates the conductors from it. Bushings experience the highest stress compared to other parts of a transformer. Part of bushing that suffered the highest potential gradient is part that close to the enclosure/tank of the transformer or parts that is directly earthed.

The contribution of bushings failure to the transformer damaged range from 12.3%-20% according to CIGRE 1983 statistic. This statistic is higher in PLN as describe in Table II above.

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A. *Tertiary Winding Connection*

The IBTs 500/150/66kV in PLN are commonly connected in delta for the tertiary winding and solidly earthed as shown in Fig. 1 and Fig. 2. The rated voltage of tertiary winding is 66kV.

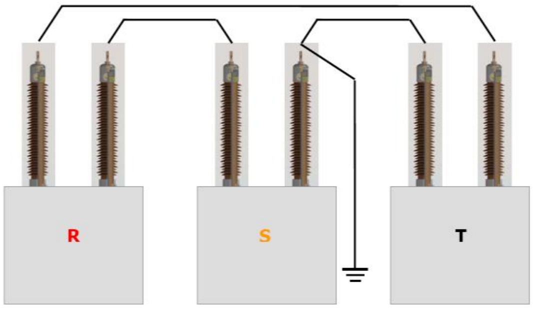

Figure 1. Tertiary connected in Delta in IBTs.

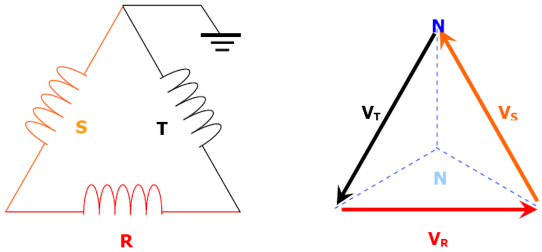

Figure 2. Equivalent circuit and the vector.

In vector analysis, the tertiary winding can be redrawn in the following equivalent circuit. In the unearthed delta circuit, the phase-to-phase voltages of each phase are 66kV without phase-to-earth reference. The 66kV is the relative voltage between phases. No absolute reference in this connection. The apparent reference as if the neutral point is in the center of the delta, shown in the blue dash line. When the connection between phase S and T is drawn solidly earthed, then the absolute reference is now appear and the apparent neutral point displace to the connection point between phase S and T. The relative voltage of 66kV at phase S and T now turn to be the absolute voltage.

B. *Bushing Specification*

Most of the bushings assembled to the tertiary winding are rated at 72.5kV with the specification as shown in Table III.

TABLE III. SPECIFICATION OF TERTIARY BUSHING

No.	Item	Remark
1.	Type	Not mentioned
2.	Highest voltage (Um)	72.5kV
3.	Maximum phase to earth voltage	42kV
4.	Bushing Dry Power frequency voltage withstand (AC)	155kV
5.	Transformer Power frequency voltage withstand (AC)	140kV
6.	Lightning Impulse withstand voltage (BIL)	325kV
7.	Rated current (Ir)	800/1000/1250/1600/2500/3150A
8.	AD Arcing distance (min.)	600mm
9.	Standard creepage distance	1820mm

C. *Online Bushing Monitoring*

Online bushing monitoring installed in IBT is a Dynamic Rating type DTM-6 (see Fig. 3). The monitored parameters are:

- Temperature
- Bushing power factor
- Bushing capacitance
- Bushing partial discharge

Figure 3. Test/Potential tap of bushing and installed DTM-6.

The principle of DTM-6 is sum the currents measured from the bushing via the test/potential tap (Table III). This sum of current method calculates relative variance of capacitance and power factor of each bushing.

The online bushing monitoring data were taken from DTM-6 installed at on IBT 500/150/66kV at CW SS, Jakarta, with the following measurement on two bushings of each phase of tertiary winding:

- Channel 7 (CH07) TV1 Bushing phase R (Tertiary)
- Channel 8 (CH08) TV1 Bushing phase S (Tertiary)
- Channel 9 (CH09) TV1 Bushing phase T (Tertiary)
- Channel 10 (CH010) TV2 Bushing phase R (Tertiary)
- Channel 11 (CH011) TV2 Bushing phase S (Tertiary)
- Channel 12 (CH012) TV2 Bushing phase T (Tertiary)

The measurement data on primary and secondary winding will not be concerned further since this study focus on the tertiary winding.

III. DATA AND LITERATURE STUDY

Due to the lack of supporting data from the routine maintenance and online monitoring prior to 2012, this project is focused on the literature study with the empiric and some theoretical approach. Data from online monitoring measurements are applied as comparison variable whether there are changes in diagnostic parameters.

A. *Online Monitoring*

The bushing online monitoring data is achieved from DTM-6 recorder with observed parameter:

- Imbalanced current
- Tan δ and capacitance of bushing
- Changes of load current, temperature, humidity as reference
- Partial discharge

Fig. 4 shows the record of Tan δ parameter taken in the period of June 18th-20th, 2013. Areas marked with yellow, green and red respectively show the abnormalities measurement of Tan δ phase R, S and T.

The abnormality of bushing is associated to the phase due to unbalanced current encountering related area. Unbalanced current was 1.87% and 28.69°, which is below the critical value of 3% [4].

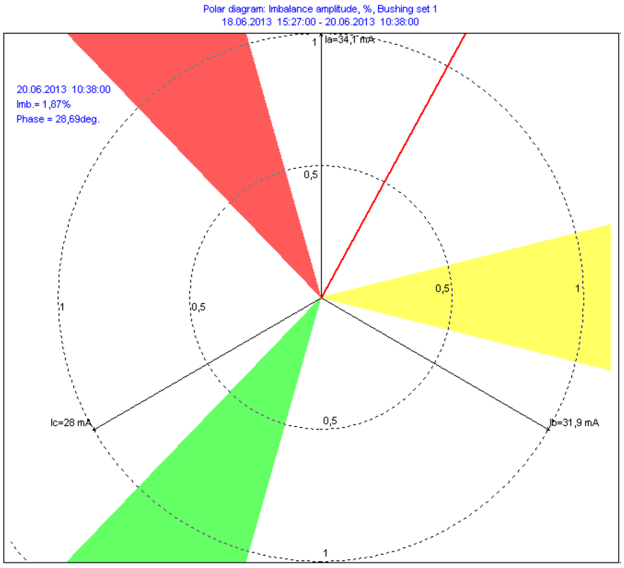

Figure 4. Tan δ online monitoring.

Fig. 5 shows record of capacitance parameter taken from the same period as the Tan δ parameter. Lines marked with yellow, green, red, purple and blue respectively show capacitance measurement of bushing tertiary phase R, S and T, the temperature and humidity of the ambient condition. There were not significant changes associated to the deviation of temperature and humidity. The capacitance parameters show relatively stable reading at 411pF, 383pF and 338pF each phases.

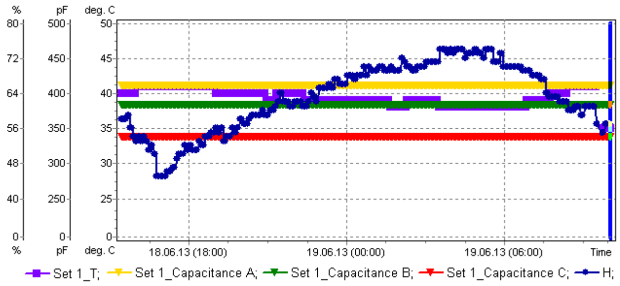

Figure 5. Capacitance online monitoring.

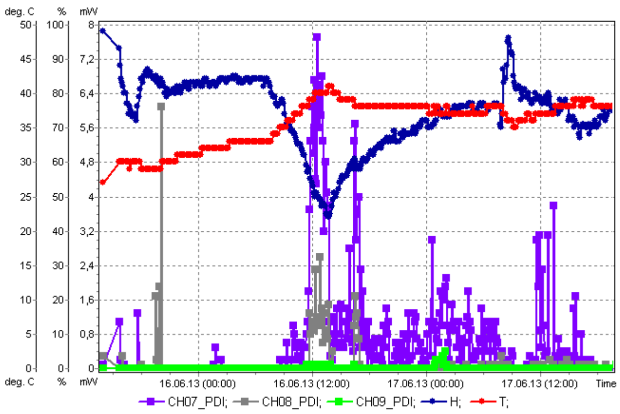

Figure 6. PD online monitoring on tertiary bushings 3.1.

Fig. 6 shows the record of PD activities during longer period on tertiary bushings 3.1. Lines marked by purple, grey, green, blue and red respectively refer to bushing 3.1 phase R, S, T and measurement of humidity and temperature of ambient condition of these bushings.

At certain time interval, bushing 3.1 at phase R shows significant PD activities compare with the other bushings. The lowest PD activities was recorded at bushing T. instead of to display the quantitative measurement, PD activity records show the existence of PD activity itself in the associated bushing.

Fig. 7 shows the record of PD activities on tertiary bushings 3.2. Lines mark by brown, yellow, black, blue and red respectively refer to bushing 3.2 phase R, S, T, humidity and temperature of ambient condition surround the bushings. Bushing phase T consistently shows the PD activity with the highest occurrence among the other two bushings.

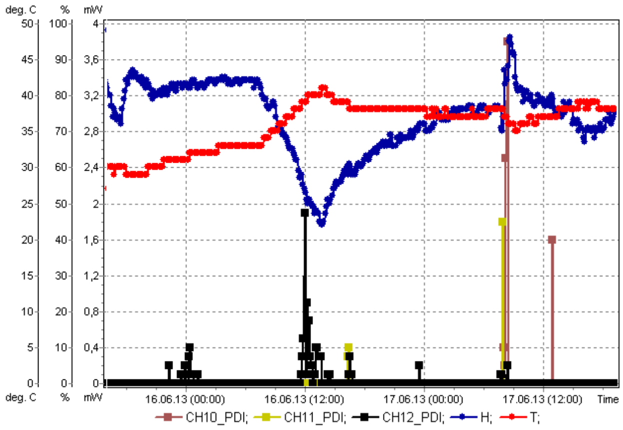

Figure 7. PD online monitoring on tertiary bushings 3.2.

B. Literature Review

In general, high voltage equipments are designed to be able to perform well under rated operation voltage in life time between 30 up to 50 years. Testing prior to the operation against the over voltage circumstances were conducted referred to the testing specification included the lightning and switching impulse, AC and DC voltage which are combined with the heat cycles, load cycles, mechanical loads etc.

To meet the requirements of HV equipment specifications and to achieve the uniform specifications, HV system is standardized as:

- U, is a phase to phase voltage, which determine the system voltage of equipments,
- U_m, is maximum phase to phase voltage which can be applied during a relatively long time, generally U_m ranges from 5 up to 15% higher than U,
- U_0, is rated phase to earth voltage, hence

$$U_0 = \frac{U}{\sqrt{3}}.$$

U_0 is an important value for the testing specification of which the testing voltage is referred to the multiple of U0. The period of testing voltage applied to is associated to the expected life time of HV equipment as shown in Table IV [5].

TABLE IV. TESTING VOLTAGE AGAINST THE EXPECTED LIFE TIME

No.	Testing Voltage [x U_0]	Expected Life Time
1.	1.0	30-50 years
2.	2.0	42 days
3.	3.0	1 day
4.	4.5	1 minute

Testing at $4.5xU_0$ for 1 minute is categorized as high potential testing with relatively short time duration compared to other HV equipment testing. The testing purpose is to trigger harmless defect to insulation dielectric at lower testing voltage, however it is necessary to be considered that this testing cannot assure the operational life time up to the designated cycle. The endurance testing is more recommended at $3xU_0$ for 24 hours [5].

Based on the testing review and calculation approaches, with the assumption of the designated life time of bushing is 50 years, the estimation of life time of bushing can be evaluate with the following equation:

$$\text{bushing\_life\_time} = \frac{k}{U^n_{\text{applied}}}$$

where *k* is the bushing designated life time constant, and *n* is coefficient of bushing life time as function of applied/operational voltage.

In Fig. 8, the bushing expected life time as function of applied voltage is shown in blue line. For the tertiary bushing connected in delta and earthed at connection between phase S and T, the bushing experiences 66kV phase to earth voltage despite of 66kV phase to phase voltages. The maximum phase to earth voltage as in the specification of bushing is 42kV (Table III).

With the continuous applied voltage at bushing phase S and T is $1.571xU_0$, the expected time is estimated as 130 days (n = 11.093). If the manufacturer applied the safety margin of 1.2 to the bushing design, then the expected life time will rise to 2.5 years. Theoretically expected life time for the continuous applied voltage $1.57xU_0$ can reach more than 2.5 year, whilst in reality the life time can exceed far beyond 2.5 years or even less depends on many conditions of the bushings.

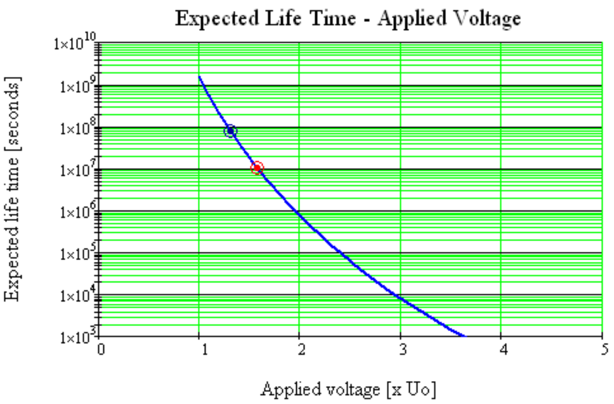

Figure 8. Expected life time of bushing as function of applied voltage.

IV. TERTIARY WINDING DELTA CONNECTION PROTECTION SCHEME

Earthing of delta winding will raise the voltage reference at the related bushings from phase to phase to be phase to earth and give more stress to the bushing insulation. C1 component of bushing will suffer the higher voltage which results in the increment of the dielectric losses, the thermal effect and the temperature.

Special investigation carried out on drawn out bushings due to the tan δ of the insulation oil exceeding the normal value has shown these bushings met the requirement of routine testing as well as the new bushing testing [6]. Based on the report paper presented in CIGRE session 2002, the failure in bushing may be introduced as the following [7]:

- Degradation of the oil and formation of oil products
- Deposits of semi-conductive sediment on the surface under effect of electrical filed
- Distortion of electrical field
- Surface discharges, gas evolution and flashover.

Earthing on point of delta will shift the phase-to-phase reference to phase-to-earth furthermore; the applied voltage to the bushings will exceed the rated voltage and introduces complex result to the accelerated ageing of the bushing life time.

A. Directly Earthed Protection Scheme

Directly earthing on delta winding enables simple protection scheme to the winding against the internal fault involving the ground/earth. An overcurrent relay fed from CT measuring the earthing connection from delta is sufficient to protect the delta winding. The other aspect shall be considered is the specification of bushings if it is intended to be directly earthed at one point.

B. Floating/Not Earthed Protection Scheme

Option to maintain the life time of tertiary bushing after directly earthed is removing the earthing and isolate the bushing to shift the phase-to-earth reference to phase-to-phase reference as the specification of the bushings.

From the simulation of single phase to ground fault at tertiary winding connected in delta with infeed from 500kV and 150kV sides and 0 ohm fault resistance, there is no fault current in the tertiary winding, the voltage at faulted bushing will decrease and the healthy bushings will increase as high as the phase-to-phase voltage [7]. The symmetrical analysis shows there is zero sequence voltage.

The installation of Potential Transformers at each phase and applying the unbalance voltage protection scheme will clearly discriminate the single phase to ground fault in the not earthed delta. The current protection scheme unable to operate due to the changes of current is not sufficient to be detected by the current based relays.

There are two protection schemes can be applied for the floating delta connection:

1) Overvoltage protection scheme

This scheme requires three Potential Transformers (PTs) connected in YNyn0 and three overvoltage relays. The principle of this scheme is to detect any unbalance voltage as shown in Fig. 9. Since the floating delta is subjected to the voltage balance, this scheme provides more sensitivity in the single phase to ground fault even involving high resistance.

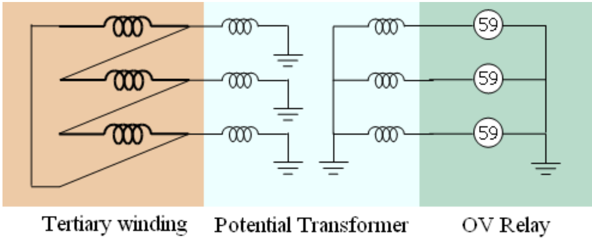

Figure 9. Overvoltage protection scheme.

2) Zero sequence voltage protection scheme or known as the neutral displacement voltage scheme

This scheme requires three Potential Transformers (PTs) connected in YNd and a voltage relay. The principle of this scheme is to detect any residual voltage from the open delta side as the unbalance voltage from the wye side of PT as shown in Fig. 10. This scheme provides more security but less sensitivity.

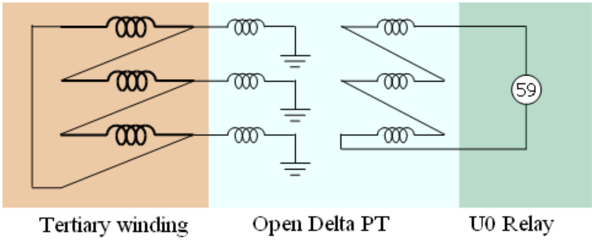

Figure 10. Zero sequence voltage protection scheme.

V. Conclusion and Further Discussion

A. Conclusion

Online bushing monitoring on tertiary bushing at 500/150/66kV IBT connected in delta which is solidly earthed at connection point between phase S and T has shown the partial discharge activities.

Theoretically, applying the operating voltage exceed the rated U0 to the tertiary bushing increase the risk of the bushing to fail.

Tertiary bushing connected in delta which is solidly earthed has benefits in anticipating the occurrence of internal faults, however removing the earthing of delta will compensate the life time of the bushing due to the voltage reference.

For the tertiary winding connected in delta, the removing of earthing at one point of delta shall be completed by the proper protection scheme.

B. Further Discussion

More detail data on the bushing are required to have a comprehensive description of bushing condition.

The economics of rated voltage of U0 consideration as the specification of bushings and the earthing scheme of tertiary winding connected in delta shall be investigate later.

Further research shall be carried out to investigate other IBTs which are in operation with the tertiary winding connected in delta and solidly earthed despite the tertiary bushing has been calculated theoretically to reach the end of lifetime but still remain in operation until this moment.

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