Online Monitoring of Transformers with Digital Fault Recorder Signals: Case Studies from Indonesian System

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***Abstract*— This paper presents application of online monitoring concept, based on fundamental frequency signals, developed at ABB Corporate Research, Sweden. Using ordinary voltage and current signals available in station control room, one can estimate the turn ratio, magnetizing current, short-circuit impedance and power loss. For the case studies presented in this paper, digitized voltage and current signals of two transformers were recorded by Digital Fault Recorders (DFR) under steady state conditions. The two transformers investigated in this study are installed in Indonesia: 500/150 kV 250 MVA at Suralaya station and 500/168/71.5 kV 500 MVA at Cilegon station. As per the results from these two cases, the proposed online monitoring method has demonstrated comparable change detection accuracy (sensitivity) to the corresponding off-line tolerance limits stipulated by IEC and IEEE Standard.**

***Index Terms*—On-line monitoring, power transformer, turn ratio, magnetizing current, short-circuit impedance, power loss**

I. Introduction

POWER transformers are one of the most important and expensive equipment of a power system. Their reliability can directly affect the safe running and the reliability of the whole power system. Online monitoring and diagnosing power transformer incipient fault conditions is becoming increasingly popular and capable of avoiding catastrophic failures and to take remedial actions in time like planned maintenance. Indonesia's transmission system with a 32857 MW peak demand[1], reported in July 2015, requires a high reliability of its power transformers in order to keep the power network up and running round the clock. Fig. 1 shows how the transformers in Indonesian grids failed in the period of 2008-2015 and most transformers failed due to winding related issues. In this context, proper detection of power transformer condition in advance assures planned power transformer outages and can be repaired timely which can prevent further damages to the transformers. Nowadays, most of online monitoring solutions use secondary indicator like dissolve gasses, temperatures, partial discharge, etc., which require special sensors and dedicated online monitoring systems installed close to or on the transformer.

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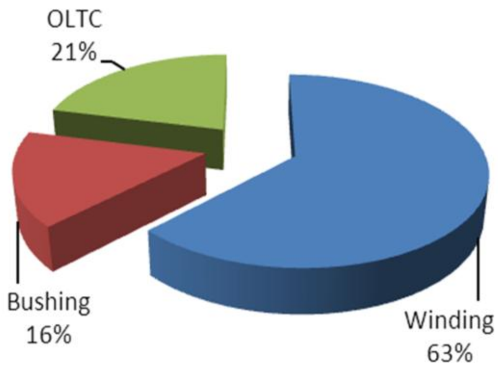

Fig. 1. Indonesia's transformer failure statistics in the period of 2008-2015, triggered by its main components.

These equipment need high demand of environmental withstand ability and costly installation process. Moreover they cannot assess the turn ratio, magnetization current, short-circuit impedance and power loss while the transformer is in service. Application of monitoring turn ratio, magnetizing current, short-circuit impedance, power loss will give information about any incipient condition of turn-to-turn fault, core defects, winding deformation, core and winding losses issue inside the transformer respectively.

E. Arry et al [2][3] has reported their research results on the estimation of the short-circuit impedance and power loss for online monitoring purposes, but the error caused by magnetizing current need to be compensated by applying a correction factor based on a prior no-load magnetizing current measurement, which has to be done during a factory test. On the other hand, online monitoring of turn ratio has not yet been seen in the literatures. D.K Xu et al [4] has verified the original method proposed in [2] with different loading conditions of a transformer. However, it still needs no-load current measured in the field which is not practical as CTs are highly inaccurate in measuring currents below 10 % of the rated current and no-load current of a transformer is usually below 1 %.

The proposed monitoring concept basically uses the fundamental frequency signal: current and voltage signals from primary and secondary sides. This concept does not in most cases require any special hardware or sensor for data acquisition. It uses the same digitized voltage and current signal monitored by the digital fault recorder or any data acquisition unit in the substation.

II. Online Monitoring of Transformer by Fundamental Frequency Signal: Transformer Explorer

A. Transformer Explorer Concept

Transformer Explorer is a concept developed by ABB Corporate Research in Sweden[5], which uses the signals from ordinary voltage and current sensors installed on a transformer in service to estimate and monitor the most central transformer parameters: short-circuit impedance, turn ratio, magnetizing current and power loss. Those parameters are hereafter referred to as the transformer fundamental quantities. From the simple transformer model as shown in Fig. 2, it is possible to deduce the transformer ratio and the short-circuit impedance by linear fitting the measured quantities such as ordinary voltages and currents of high voltage side and low voltage side of a transformer as a function of the load current. The power loss can be estimated by the difference between power in and out of the transformer during it is in service.

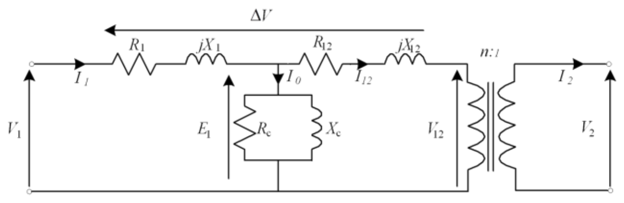

Fig. 2. Transformer basic circuit refer to the primary side.

In this model, R_1 and R_{12} represent active power losses in the windings and R_c represent core losses, while X_1, X_{12} and X_c represent leakage reactance of primary and secondary winding and magnetizing reactance respectively. *n* is the ratio of the number of turns in a higher voltage winding to that of the lower voltage winding. For all practical purposes, when the transformer is on open-circuit or no-load, its voltage and turns ratios can be considered equal and it is measured during transformer offline testing. Referring to the model, there is a linear relationship between primary and secondary currents, which is given by equation (1).

$$I_1 = I_{12} + I_0 = \frac{I_2}{n} + I_0 \qquad (1)$$

The sum of two series impedance ($R_1 + jX_1$ and $R_{12} + jX_{12}$) is called short-circuit impedance(Z_w), which is usually estimated offline by a short-circuit test as the ratio between the applied voltage and the current drawn. This test is used to detect winding displacements/deformations that may have occurred since the factory test which also determines the copper loss or load loss in the transformer. The resistance and reactance in the magnetizing branch can be determined by no-load test during which only magnetizing current I_0 is flowing through the transformer. The IEEE standard for transformer off line test recommends tolerance limits of 0.5 % for the turn ratio and ~3.0 % for the short-circuit impedance measurement[6].

Voltage drop ΔV is caused by the load current ($I_{12} = I_2/n$) and magnetizing current I_0 which flows through the primary and secondary impedances. ΔV of a loaded transformer is dominated by the load current because I_0 is quite small as < 1 % of rated current for large power transformer. However, under light load conditions, voltage drop created by magnetizing current shares a significant portion and with assumption that magnetizing current remains the same at higher load, we can see a linear relationship between ΔV and load current, of which the gradient represents the short-circuit impedance (Z_w) as shown in equation (2).

$$\Delta V = I_1 Z_1 + I_{12} Z_{12} = (I_{12} + I_0) Z_1 + + I_{12} Z_{12}$$
$$V_1 - nV_2 = (Z_1 + Z_{12}) I_{12} + Z_1 I_0$$
$$V_1 - nV_2 = (Z_1 + Z_{12}) \frac{I_2}{n} + Z_1 I_0$$
$$V_1 - nV_2 = Z_w \frac{I_2}{n} + Z_1 I_0 \qquad (2)$$

The power loss can be estimated from the difference of power in and out of the transformer, which is shown in equation (3). The active power loss can be obtained from the real part of apparent power loss. This method can be used during normal transformer operation and can be easily extended to the three phase case.

$$S_{loss} = S_{in} - S_{out} = V_1 I_1^* - V_2 I_2^* \qquad (3)$$

B. Linear Fits

There are two basic equations (1) and (2) are of the form of $\mathbf{y} = \mathbf{ax} + \mathbf{b}$, where **a** and **b** represent the transformer parameters. So from a data set consisting of **y** and **x** will yield the transformer parameters. Table I shows the description of symbols representing each linear equations.

Table I. Transformer parameters used in linear fits.

Equation	x	y	a	b
Turn ratio	I_2	I_1	$\frac{1}{n}$	I_0
Short-circuit impedance	$\frac{I_2}{n}$	$V_1 - nV_2$	Z_w	$Z_1 I_0$

The equation that can be used to determine **a** and **b** from a number of **k** −data of **x** and **y** can be written in matrix from as shown in equation (4). With many number of measurements available, it becomes a linear regression problem or over determined system of linear equations. Equation (4) was solved with ordinary least square method in Matlab.

$$\begin{bmatrix} y^0 \\ y^1 \\ \vdots \\ y^k \end{bmatrix} = [a] \begin{bmatrix} x^0 \\ x^1 \\ \vdots \\ x^k \end{bmatrix} + [b]$$

$$\begin{bmatrix} y^0 \\ y^1 \\ \vdots \\ y^k \end{bmatrix} = \begin{bmatrix} x^0 & 1 \\ x^1 & 1 \\ \vdots & \vdots \\ x^k & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} \rightarrow \begin{bmatrix} x^0 & 1 \\ x^1 & 1 \\ \vdots & \vdots \\ x^k & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} y^0 \\ y^1 \\ \vdots \\ y^k \end{bmatrix} = \begin{bmatrix} a \\ b \end{bmatrix} \qquad (4)$$

As the turn ratio and impedance are dependent on the tap position, before applying the linear fitting procedure, one has to classify the data points into different taps.

1) Turn Ratio and Magnetizing Current

As already mentioned, equation (1) provides the turn ratio and magnetizing current as the gradient and the intercept of the linear fit of primary current vs the secondary current. The turn ratio fit will give two important transformer parameters: the turn ratio and magnetizing current, where the turn ratio can be compared with the nameplate value if the tap position is taken into account. Result of turn ratio will usually have small imaginary component since the sensors are never perfectly balanced so this imaginary component can be taken as a mismatch between primary and secondary side CTs. For the comparison, the nominal turn ratio for each tap position can be calculated according to equation (5).

$$n_{tap} = \frac{HV_{nominal}}{LV_{nominal}} * (1 - ((tap - tap_{nominal}) * tapstep)) \qquad (5)$$

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The magnetizing current for transformers is usually less than 1 % of nominal current and generally not determined with any great precision. Because the ordinary current measurement is not practical by any means as CTs are highly inaccurate measuring currents below 10 % of the rated current.

Significant deviations from nameplate values of the turn ratio can be due to a turn-to-turn fault in the transformer as this fault will lessen the turn ratio. This kind of fault is rare and difficult to detect by conventional protection system unless it has develop into more serious and costly to repair fault such as phase to ground fault. A short-circuit of a few turn of the winding will give rise to a heavy fault current or large circulating current flow in the short-circuited loop, but the terminal current will be very small because of the high ratio of transformation between the whole winding and the short-circuit turns. Hence the estimation of turn ratio is developed to detect this incipient fault.

Magnetizing current that we get from the turn ratio fit as the intercept, **b**, can be used generally to know if there is any issue in the core of the transformer. We can compare the result with the nameplate as the reference or any factory test result. A conducting path across the laminated structures of the core can permit sufficient eddy-current to flow which cause serious overheating. If any portion of the core insulation becomes defective, the resultant heating may reach a magnitude sufficient to damage the winding. In an oil-immersed transformer, core heating sufficient to cause winding insulation damage will also cause breakdown of oil with an accompanying evolution of gas. This gas will escape to the conservator, and is used to operate a mechanical relay.

A change in the voltage also has an effect to the magnetizing currents. An increased voltage level should result in an increased magnetizing current and vice versa.

2) Short-Circuit Impedance

To perform the short-circuit impedance fit we use the equation below.

$$V_1 - nV_2 = Z_w \frac{I_2}{n} + Z_1 I_0 \qquad (2)$$

Short-circuit impedance Z_w is the slope of the fit and the real and imaginary part will show the winding resistance and reactance of the transformer respectively. The data of short-circuit impedance can be shown on the plot between voltage drop as the y axis and load current as the x axis. We can compare the result of winding reactance with the winding reactance that shown on the nameplate. Winding reactance in our result is in ohm referred to HV side and winding reactance on the nameplate is in percent that we can convert to ohm referred to HV side. Knowing the reactance at the nominal tap, the values for the other taps can be calculated from equation (6).

$$X_{tap} = X_{nom} * (1 - ((tap - tap_{nominal}) * tapstep))^2 \qquad (6)$$

Where X_{tap} and X_{nom} are the reactance at any tap position and nominal value respectively. tap, $tap_{nominal}$, and tapstep are the specified tap, nominal tap and step between each tap respectively. Reactance will give information about any change due to displacement/deformation of windings, therefore it is recommended to perform this estimation after any through fault current occurred on the transformer and compare to the previous values.

Winding resistance will be shown in the real part of short-circuit impedance fit. The result of winding resistance can be compared with the factory test protocol or onsite offline testing because the quantity is not given on the nameplate. It is usually very small, a few percent of the reactance. Resistance of short-circuit impedance can show us about the condition of tap-changer contact issue or any losses inside the transformer.

3) Power Loss

To estimate the power loss one can use equation (3). However, power loss estimated in this way is very sensitive to instrument transformer ratio errors, that it could even lead to negative losses. Comparison of estimated power loss with the value of expected power loss from factory acceptance test is possible only if appropriate sensor error corrections are applied. The IEC standard recommends 10 % of total losses for acceptable tolerance limit of power losses measurement [7].

III. Signal Acquisition

The signals appropriate for transformer fundamental quantities estimation are usually available in the devices that measure the voltage and current of a power transformer, which can be either from metering and protection class instrument transformers. These devices could be metering, numerical relay protection (IEDs) or digital fault recorder (DFR), which are commonly installed together with a transformer installation. To estimate the transformer fundamental quantities, one should be in steady state conditions which mean voltage and current phases have to be obtained from steady waveforms without disturbances.

In Indonesian transmission system, there are Digital Fault Recorders (DFR) installed at every 500 kV stations to record voltage and current signals of primary equipment, feeders, busbars, etc., which play an important role in deeper analysis of disturbances or faults. This also helps the load dispatch operator to make fast decisions by analyzing the type and location of the fault. It was found that these DFRs record required signals, i.e. all the primary and secondary voltage and current signals. As shown in Fig 3, a DFR gets HV and LV side voltages from the metering class capacitive voltage transformers (CVTs) and all current signals from current clamps attached to the secondary circuit of protection class current transformers (CTs). This is the first time the Transformer Explorer concept is tested with signals from instrument transformers belonging to two different accuracy classes: namely metering class voltage and protection class current measurements. This means, the low accuracy (protection class) currents may have significant amplitude and angle errors compared to voltages.

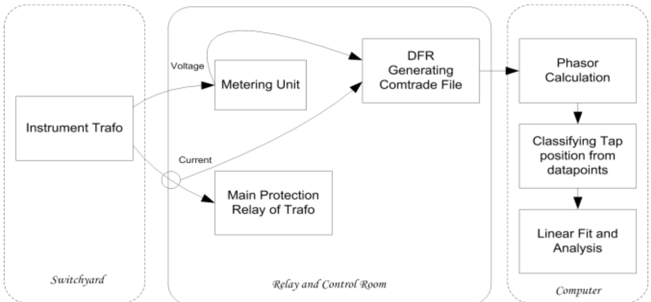

Fig. 3. Block diagram showing signal acquisition and Transformer Explorer calculations.

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The DFRs at the two stations, where the signals were recorded, have 6400 S/s sampling rate and 2.5 s long waveforms were recorded by manual remote triggering option provided by the equipment software. Using the Comtrade waveform files generated by the DFR, we calculate the amplitude and phase angle of all the voltage and current signals. Then data is classified as per tap position by using current ratio ($n \cong \left|\frac{I_2}{I_1}\right|$) or compensated voltage ratio ($n \cong \left|\frac{V_1-(Znom*I_1)}{V_2}\right|$). After that, data belonging to each tap is used to estimate the transformer parameters.

IV. Accuracy and Uncertainty

There are two component of error for any measurement: systematic errors and random errors. Systematic errors are errors that are introduced by an inexactness of the used sensors which is predictable and typically remains constant over time. Thus the systematic errors mainly contribute to the absolute accuracy, which is the degree of closeness of measured value to the true value of the quantity. In the context of transformer fundamental quantities estimation, absolute accuracy is the degree of closeness of estimated value compared to its nominal value mentioned on the nameplate or value from a factory acceptance test result. An improvement of absolute accuracy would require using more exact sensors, either replacing the existing ones or an individual calibration of these. Instrument transformers and the current clamps that are used by the DFR for recording voltages and currents belong to a certain accuracy class (indicating the maximum error of that class), which eventually decide the absolute accuracy of the estimated quantities.

Random errors are the errors that lead to measurable values being inconsistent or vary when repeated measures of quantity are taken. Random errors are unpredictable and mostly caused by the noise or any other rapidly changing condition and tend to be stochastic with normal distribution when the individual random errors are summed. Thus the random errors are lower detectable limit for changes in the estimation with a certain uncertainty of measurement.

In the context of Transformer Explorer estimations, we define the absolute accuracy and uncertainty. Having determined a line fit from a reasonable number of $(\mathbf{x}, \mathbf{y})$ pairs, one may study the deviation or difference of each pair to the fit: $\delta_y = |y - (ax + b)|$. If the fit is correctly made, δ_y should average to zero and the standard deviation of it can be used as the indicator of sensor noise influence. The noise influence in the intercept of the fit, parameter **b**, will be of the same size as the standard deviation of δ_y. Then for the slope of the fit, parameter $\boldsymbol{a}$, an estimate of the uncertainty from the noise in **y** can be derived as

$$\delta_a = \frac{\sigma_y}{max(x)-min(x)} \quad (7)$$

Where δ_a and σ_y are the uncertainty of the slope and standard deviation of δ_y respectively. It becomes obvious that data in a wide range gives a better estimate of the slope. The uncertainty which is presented as percentage compared to the slope of the fit can be derived as

$$\delta_a \; in \, \% = \frac{\delta_a}{a} \times 100\% \quad (8)$$

In case of power loss, we use the standard deviation of y with the full load total loss on nameplate refer to the HV rated side current which derived as

$$\delta_{powerloss} = \frac{\sigma_y}{total\ loss} \quad (9)$$

The percentage absolute accuracy is calculated as follows:

$$\left|\frac{a_{estimation}-a_{tap}}{a_{tap}}\right| \times 100\% \quad (10)$$

Where $a_{\text{estimation}}$ is the slope of the turn ratio and short-circuit impedance fits that we have estimated and a_{tap} is the nominal value for the relevant tap-position.

V. Case Studies

Transformer Explorer concept is exemplified by the analysis of signals from two transformers in Indonesian power system. It has already mentioned that voltage and current signals were acquired from DFRs installed at those two stations.

A. Transformer 1: 500/150 kV, 250 MVA, YNyn0d11 at Suralaya Station

This is a three phase transformer which is located at Suralaya station to deliver power from 500 kV backbone systems to lower voltage 150 kV systems that has been loaded around 38-76 % of its rated power (power factor 0.62-0.93) during the signal recording period. On the nameplates of both HV and LV side CTs, the accuracy class is stated as 1 % and for the CVTs as 0.5 %. The YNynd11 vector group of this transformer allows us to directly use the measured signal as winding currents and voltages. The tertiary winding of this transformer connected in delta is inside the tank and one of the corners of the delta winding is brought out of the tank and earthed. There is no voltage or current measurement available on the tertiary winding. This transformer has a tap changer consisting of 15 taps (5 being the nominal) with 1.25 % tap step. Fig. 4 and Fig. 5 show turn ratio fit and impedance fit of one of the tap (tap 8) respectively.

The summary of the estimated turn ratio, magnetizing current and short-circuit impedance are presented in Table II, along with available nameplate values. The estimated turn ratio exhibits a very small uncertainty (the max value is 0.17 %) and a good absolute accuracy (the max value is 0.50 %) as well compared to the nominal value.

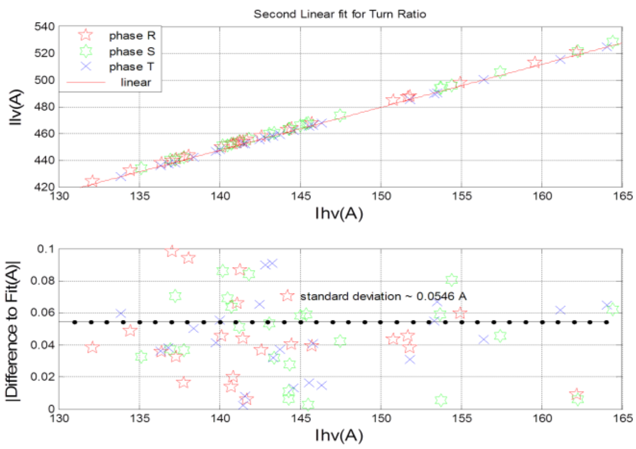

Fig. 4. Turn ratio fit (plot of LV current vs HV current). Lower figure shows the fit deviations or difference to the turn ratio linear fit (δ_y).

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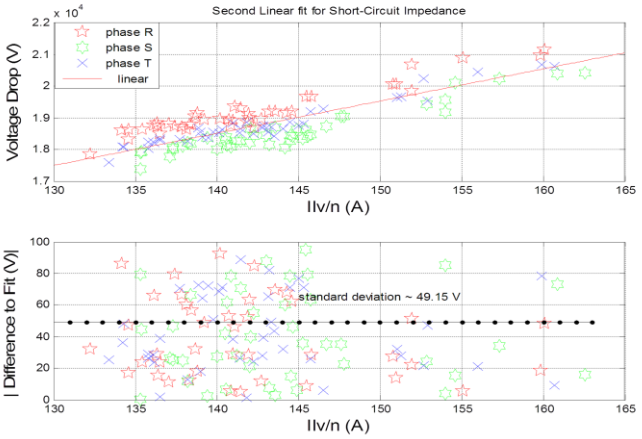

Fig. 5. Short-circuit impedance fit (plot of voltage drop vs LV current). Lower figure shows the fit deviations or difference to the short-circuit impedance linear fit (δ_y).

Table II. Estimated turn ratio, magnetizing current and short-circuit impedance per phase with corresponding uncertainty of the fits and absolute accuracy to the nominal.

Phase	Turn Ratio	Uncertainty (%)	Absolute Accuracy (%)	Magnetization Current (A)	Impedance (Ω)	Uncertainty (%)	Absolute Accuracy (%)
R	**3.2179**	**0.17**	**0.29**	**0.45∠ -84.3°**	**11+ 106.5i**	**1.53**	**3.75**
S	**3.2246**	**0.16**	**0.50**	**0.56∠-170.2°**	**11 + 105.4i**	**1.54**	**2.65**
T	**3.2096**	**0.17**	**0.04**	**0.76∠48.7°**	**10 + 105.8i**	**1.53**	**3.1**
Nameplate Value	3.2083			Not mentioned on nameplate	102.65i		

In case of short-circuit impedance, reactance exhibits a lower absolute accuracy (the max value is 3.75%) compared to the nominal value, which was observed at other field installations [5]. This can be due to different CT and VT accuracy classes, installation of secondary sensors for DFR or possibly the influence of long wires (usually 100 meters) in the secondary circuit of instrument transformers. Maximum uncertainty in the reactance estimation is 1.54 %. Lower uncertainty in turn ratio and impedance estimation means that one can detect changes in those parameters complying with the tolerance limits stipulated by IEEE. However winding resistance (real part of the estimated impedance) shows a very high value compared to a typical HV winding resistance which is usually small (about 1Ω) or a few percent of winding reactance. This could most probably due to a slight relative phase angle error in the acquired signals, which is quiet possible as currents and voltages have protection and metering accuracy respectively. The same effect is seen for other taps as well.

The estimation of power loss is shown on Fig. 6. Here estimated power loss has a significantly high scatter of data, which is about 0.2465 MW. In percentage the detectable change of estimated power loss to the full load power loss (assuming 1 % loss, i.e. 2.5 MW loss of rated 250 MVA) is about 9.86 %.

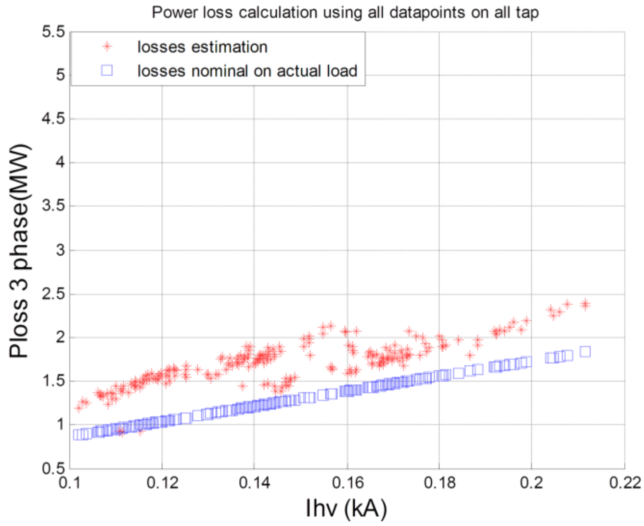

Fig. 6. Total power loss compared to the nominal losses for the same load current.

B. *Transformer 2: 500/168/71.5 kV, 500 MVA, YNyn0d1, at Cilegon Station*

Fig.7 Picture of one phase of the transformer at Cilegon Station.

This transformer bank consists of three single phase transformers, and one of the units is shown on Fig.7. Each one is rated at 166.7 MVA and 500 MVA, 500/168/71.5 kV when connected in YNyn0d1 vector group. This transformer has been loaded to 8.8 – 40 % of its rated power. Because of power system demand, most of the time it is loaded with reactive power (p.f. from 0.02 to 0.8). The power flow through this transformer is bidirectional depending on the demand. Both power directions can be used to estimate fundamental quantities, but the data should be classified according to the power direction. Signal acquisition system is as the same as in the previous case and has the same accuracy class of instrument transformers.

Similar to the first case, the estimated turn ratio values for tap 7 shown in Table III are very close to the nominal values, having an absolute accuracy of about 0.48 %. The maximum uncertainty of the turn ratio estimation is about 0.16 %. The absolute accuracy and uncertainty of the short-circuit impedance are close to the first case of about 3.42 % and 0.73 % respectively. Fig. 8 depicts the turn ratio and impedance estimated for each tap position as seen in the

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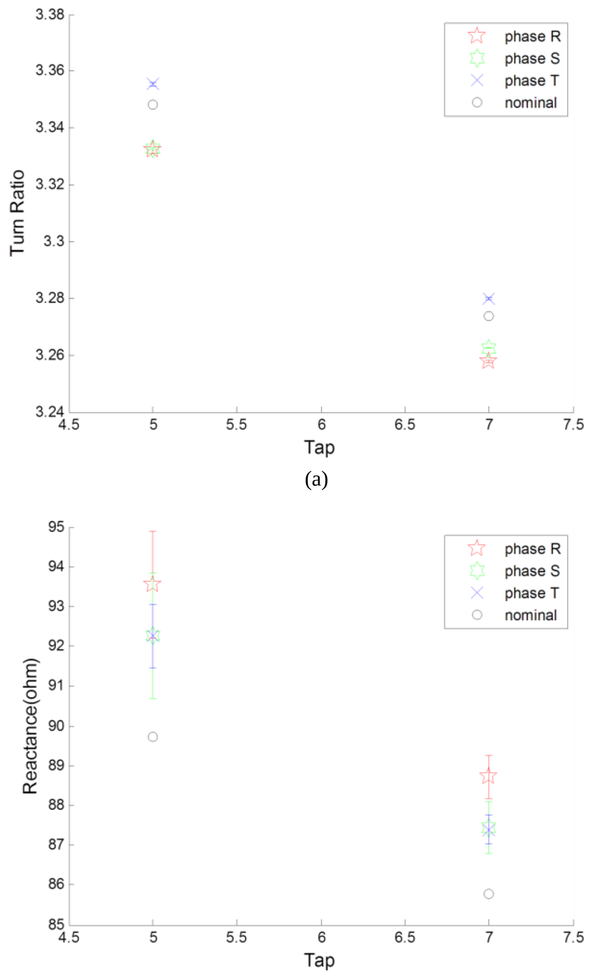
recording period, where the absolute accuracy of turn ratio and reactance is similar for every tap position because of constant systematical errors primarily due to instrument transformer ratio errors. Winding resistance shows the same issue observed in the first case, which can be due to the same reason explain in the previous section.

Table III. Estimated turn ratio, magnetizing current and short-circuit impedance per phase with corresponding uncertainty of the fits and absolute accuracy to the nominal.

Phase	Turn Ratio	Uncertainty (%)	Absolute Accuracy (%)	Magnetization Current (A)	Impedance (Ω)	Uncertainty (%)	Absolute Accuracy (%)
R	**3.2578**	**0.16**	**0.48**	**0.54∠76.6°**	**9.8 +88.7i**	**0.6**	**3.42**
S	**3.2625**	**0.12**	**0.34**	**0.68 ∠-114.3°**	**10.6 +87.4i**	**0.73**	**1.93**
T	**3.2798**	**0.11**	**0.18**	**0.17∠42°**	**9.1 +87.3i**	**0.41**	**1.87**
Nameplate Value	3.2738	-	-	0.346	85.7890i	-	-



(a)

(b)

Fig. 8. Plot of turn ratio (a) and reactance (b) per phase as a function of tap position. Error bars are the uncertainties of estimated value at each tap.

The estimation of power loss is similar to the first case. Standard deviation of the power loss estimation is about 0.4059 MW, so in percentage the detectable change compared to the full load power loss (1.3461 MW) is about 30.2 %. This is much higher than that of observed at other field installations [5]. The reason could be manifold: higher random noise, unsteady signals, system fluctuations, etc.

VI. Summary and Conclusion

Estimation of the most central parameters of a transformer (turn ratio, magnetizing current, short-circuit impedance and power loss) by means of in-service fundamental frequency signals is demonstrated. Without an outage, current and voltage signals were acquired through existing digital fault recorder for the analysis. It has been applied on two Indonesia's transformers and the uncertainty of the estimated parameters is low enough to detect changes within the tolerance limit of stipulated for corresponding off-line measurements (see Table IV).

Table IV. Summary of sensitivities and absolute accuracy of the estimated parameters for each case. Offline limits are given as a comparison[6-7].

Parameter	Case 1 (Transformer at Suralaya)		Case 2 (Transformer at Cilegon)		Offline Limits (%)
	Sensitivities (%)	Absolute Accuracy (%)	Sensitivities (%)	Absolute Accuracy (%)	
Turnratio	0.17	0.51	0.16	0.48	0.5
Impedance	1.54	3.75	0.73	3.42	~3
Power Loss	9.86	-	30.2	-	10*

*10% of the full load total loss

Despite the low accuracy class of existing CTs in the stations, a fairly good absolute accuracy compared to the nameplate values have been obtained, which indicates that monitored transformers are in good condition.

The proposed method does not require any hardware or sensor installations. It utilizes the available voltage and current signals monitored and recorded by existing digital fault recorders installed at the stations. However obtaining signals from instrument transformers belonging to two very different accuracy classes (protection and metering in this case) may influence the estimated parameters. Unrealistic high value of the estimated winding resistance at both locations could most probably be due to a few degrees of angle error in the protection class current signals compared to the metering class voltage signals. Hence, it is advisable to use signals either from metering or protection platforms, not from both.

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