Influence of Zero-Sequence Removal on Transformer Fundamental Quantity Monitoring

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***Abstract* —This paper presents results of a simulation study to quantify the effect of zero sequence removal on the accuracy of transformer fundamental quantities estimated from ordinary voltage and current signals by linear fitting selected quantities as a function of loads. Unbalanced system conditions and asymmetrical loads are some of the common causes of zero sequence. Flow of zero sequence across a transformer is dependent on the winding configuration of the transformer and the system grounding conditions. As all possible combinations of winding and grounding configurations, and appearance of zero sequence cannot in practice be tested, in this study, a series of PSCAD model simulations was performed based on a typical power system with two transformers, transmission lines, industrial and domestic loads. The transformers were configured in different vector groups (Y-Y, Y-Δ) and grounding states to replicate commonly encountered scenarios. System and load imbalances were created by asymmetrical loads on the transmission side and asymmetrical reactive power compensation on the consumer side respectively. The results indicates that the zero sequence removal result in good accuracy compare to estimation with zero sequence irrespective of the winding and grounding configurations.**

***Index Terms* — Zero-Sequence, Turn Ratio, Impedance, PSCAD, Transformer**

I. INTRODUCTION

Power transformers are one of the expensive and important equipment in power transmission and distribution networks. In order to avoid sudden transformer failures causing outages and collateral damages, early detection of the symptoms of such faults is necessary, so that planned maintenance and remedial measures can be carried out. There are number of methods available to assess the condition of a transformer both off-line and on-line. Due to the inherent advantage of round the clock service and early fault detection capability, on-line monitoring has attracted vast interest especially during last two decades and a number of solutions have been proposed and put into practice worldwide.

An on-line method to monitor the value of most central transformer parameters from current and voltage transformer signals installed on transformer in service was presented before. Using a simple transformer model it is possible to deduce the transformation ratio and total winding impedance by linear fitting selected quantities as a function of loads. This concept is named as Transformer Explorer [1].

In the proposed quantity estimation, winding voltages and currents are necessary, and often the zero sequence is dropped during the transformation process of signals from the measured line voltages and currents. It is also preferred to exclude the zero sequence current and voltages as their appearance in the primary and secondary sides is dependent on earthed neutral points and presence of a delta winding [2-4]. Unbalanced system conditions and asymmetrical loads are some of the common cause of zero sequence. The fact that a power network being unbalanced can also be due to a transformer fault (e.g. change of short circuit impedance due to a winding buckling) itself which is to be detected by the Transformer Explorer. In such a case zero sequence removal may have a negative effect on the ability to detect the fault (sensitivity), which is one of the key questions answered in the presented results.

In this paper we modelled a typical power system with different configurations of transformers and some imbalances scenarios that create zero sequence on voltage and current signals. These signals are analyzed using Transformer Explorer to estimate turn ratio and short-circuit impedance in order to see how the zero sequence removal could affect the sensitivity of the propose methods.

II. PRINCIPLE OF ON-LINE MEASUREMENT OF TURN RATIO AND IMPEDANCE

A. *Equivalent Circuit and Transformer Fundamental Quantity*

The transformer fundamental quantities can basically be derived from the equivalent circuit of a two winding transformer model presented in Fig. 1.

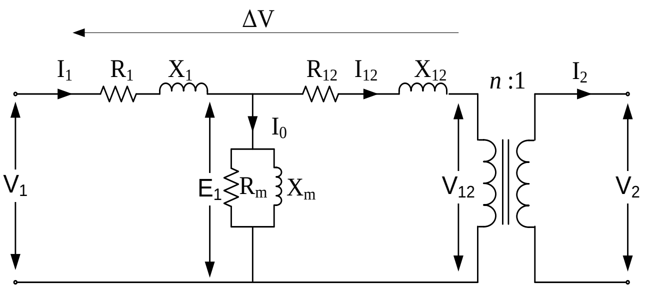

Fig. 1. Equivalent circuit of a two winding transformer referred to the primary side.

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The meanings of the symbols used in Fig. 1 are given below:

n:1 : Transformer ratio.
R_1, X_1 : Primary resistance, leakage reactance.
R_{12}, X_{12} : Secondary resistance, leakage reactance referred to primary side.
V_1, V_2 : Primary, secondary voltages.
I_1, I_2 : Primary, secondary currents.
V_{12}, I_{12} : Secondary voltage, current referred to primary side.
R_m, X_m : core loss resistance, magnetizing reactance.

From Fig 1, the primary current I_1 has two components, one is magnetizing component I_o and the other is load component ($I_{12}= I_2/n$). R_m represents core losses and X_m represents magnetizing reactance. These magnetizing current I_o and load current I_{12} cause a voltage drop ΔV in transformer. ΔV can be written as

$$\Delta V = V_1 - V_{12} = V_1 - n.V_2 \quad (1)$$
$$\Delta V = (R_1 + jX_1 + R_{12} + jX_{12}).\frac{I_2}{n} + I_o.(R_1 + jX_1) \quad (2)$$
$$\Delta V = Z_w.\frac{I_2}{n} + I_o.Z_1 \quad (3)$$

Where Z_w is the total short circuit impedance which is $(R_1 + jX_1 + R_{12} + jX_{12})$. Normally ΔV of a loaded transformer is dominated by load current I_{12} and I_0 is typically < 1 % for large power transformer. However, under light load conditions, voltage drop created by the magnetizing current shares a significant portion of ΔV. With an assumption that magnetizing current (I_0) remains fairly the same at higher load currents. The relationship between primary and secondary currents is linear and can be written as

$$I_1 = \frac{I_2}{n} + I_o \quad (4)$$

From equation (4), we can estimate the turn ratio (n) that is usually measured off-line as the no-load voltage ratio. These two basic values: Turn Ratio (n) and short-circuit impedance (Z_w) are hereafter be referred to as the Transformer fundamental quantities.

B. *Calculation of Fundamental Quantity*

The fundamental quantities are obtained by linear fitting one parameter against the load current. Equations (3) and (4) are of the form y = ax + b, where a and b represent the transformer quantities. Thus a linear fit of a data set consisting of x and y pairs will yield the transformer quantities. Table I shows the meaning of the symbols for the two different equations.

Table I. Line fit entities for transformer properties.

Equation	x	y	a	b
(1) Impedance	I_2/n	V_1 - n.V_2	Z_w	Z_1 I_0
(2) Turn Raito	I_2	I_1	1/n	I_0

The voltage and current signals, V_1, V_2, I_1 and I_2 are collected through a data acquisition system, Intelligent Electronic Devices (IED), Digital Fault Recorder (DFR) or in this case are generated from Comtrade recorder in PSCAD simulation.

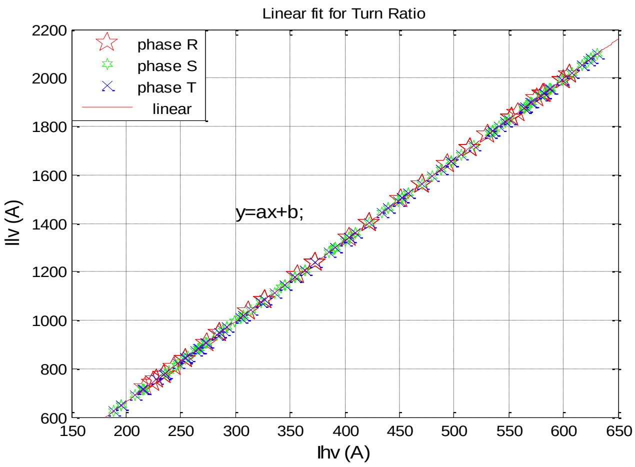

Fig. 2. Turn Ratio Fit (plot of LV current vs HV Current).

As shown in Fig. 2, Linear fit for turn ratio from current signals that we get from a data set (120 data points), one of the scenario using transformer configuration Y-Y with solidly grounded neutral.

C. *Symmetrical Component Transformation and Zero-sequence Removal*

A system of three unbalanced three-phase systems can be resolved in the following three symmetrical components:

- Positive Sequence: A balanced three-phase system with the same phase sequence as the original sequence.
- Negative sequence: A balanced three-phase system with the opposite phase sequence as the original sequence.
- Zero Sequence: Three phasors that are equal in magnitude and phase.

The voltage and current signals that we obtained consist of these three symmetrical components. To transform these signals into positive, negative and zero sequence, we need a *unit phasor* (or operator) that will rotate another phasor by 120° in the counterclockwise direction. The letter 'α' is used to designate such a complex operator of unit magnitude with an angle of 120^0. It is defined by

$$\alpha = 1\angle 120^o = e^{j120^o} = -\frac{1}{2} + j\,\frac{\sqrt{3}}{2} \quad (5)$$

The three phase voltage and current signals that we measure can be written in terms of sequence components in the form of following matrix equation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{a2} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad (7)$$

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Due to the fact that the zero sequence impedance is in most cases not the same as the positive/negative sequence counterparts and it depends on earthed neutral points and presence of a delta winding. Sometimes it is necessary to remove the zero sequence current and voltage, which can be performed as followed:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{a2} \end{bmatrix} - \begin{bmatrix} k1 \\ k1 \\ k1 \end{bmatrix} [V_{ao}] \tag{8}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} - \begin{bmatrix} k1 \\ k1 \\ k1 \end{bmatrix} [I_{ao}] \tag{9}$$

Where,
V_{ao} *and* I_{ao} are the zero sequence voltage and current.
K_1 is a setting parameter which can have values 1 or 0 and are set by the end user in order to enable or disable the zero sequence voltage and current reduction.

III. THE SIMULATION MODEL OF POWER SYSTEM AND TRANSFORMER

A. *Simulation Setup*

The total system modelled in PSCAD software is shown in Fig. 4. There are two transformers with ratings 500/150 kV, 500 MVA and 150/20 kV, 60 MVA. In both secondary sides, there are industrial load and domestic loads. Reactive power compensation or capacitor banks are connected to 20 kV side with a capacity 6 MVAR.

In order to create an imbalance system and load, the load model and capacitor banks are created per phase and represented by variable resistance, inductance and capacitance as shown in Fig. 3.

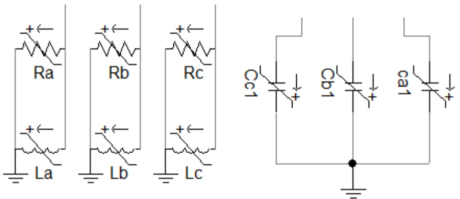


Fig. 3. Load and capacitor banks modelled as variable resistance, inductance and capacitance.

For the characteristics of industrial load, we assumed a constant consumption of 100 MW/phase connected to 150 kV. The variable loads are set to fluctuate with time having a peak value of 50 MW/phase on 150 kV side and 12 MW/phase on 20 kV side. The base power factor for the system is 0.85.

Using equation (10) and (11) we can estimate associated resistance and inductance for given power (P + jQ).

$$P = \frac{{V_{L-N}}^2}{R} \tag{10}$$

$$Q = P\sqrt{\frac{1}{\cos\varphi^2} - 1} = \frac{{V_{L-N}}^2}{\omega L} \tag{11}$$

A three-phase transformer is modelled in PSCAD as three identical single-phase transformers. From these single-phase transformers, it is possible to create different winding configurations depending on the power, voltage or special needs required to simulate the system [5]. The technical data of each transformer is presented in Table II.

Table II. Data for transformers.

Transformer	T1	T2
Voltage (kV)	500 / 150	150/20
Power (MVA)	500	60
Base Frequency (Hz)	50	50
Leakage Reactance (pu)	0.125	0.1232
No Load losses (pu)	0.0001	0.0001
Copper Losses (pu)	0.0005	0.0005
Magnetizing Current (%)	0.5	0.5

As shown in Fig. 4, voltage and current signals of both primary and secondary sides of both transformers are recorded using PSCAD Comtrade recorder, which can be read into Transformer Explorer application. As steady state signals are needed, initial transient part of each PSCAD simulation was avoided and only 2s in the latter part of the simulation period was recorded. As many Comtrade waveform files have to be recorded with varying load for each case studied, multiple run feature in PSCAD was used to perform parametric sweep [6]. For example, for each scenario mentioned in Table IV, 120 simulations (Runs) were performed.

B. *Unbalanced Scenarios and Transformer Configurations*

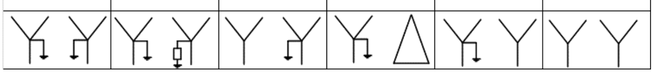
The zero-sequence equivalent circuit of a three-phase transformer varies depending on the type of winding configurations, earthed neutral points and the core construction. In some configurations, zero-sequence current cannot flow in the winding [7].

In order to see how zero-sequence removal could affect the accuracy of turn ratio and impedance estimations, several realistic scenarios of system imbalances and different transformer configurations are investigated. Transformer configurations and imbalance scenarios are listed in Table III and IV. The last two scenarios are associated with a simulated fault of 4% increase in one phase resembling a mechanical fault in the form of a buckling.

A constant imbalance on 150 kV load was simulated by setting a different load on phase A than the other two and a different load on phase B on the 20 kV side. On the other hand for variable imbalance, load on each phase was set to vary randomly.

Table III. Transformer Configurations.

TRANSFORMER CONFIGURATIONS					
CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6



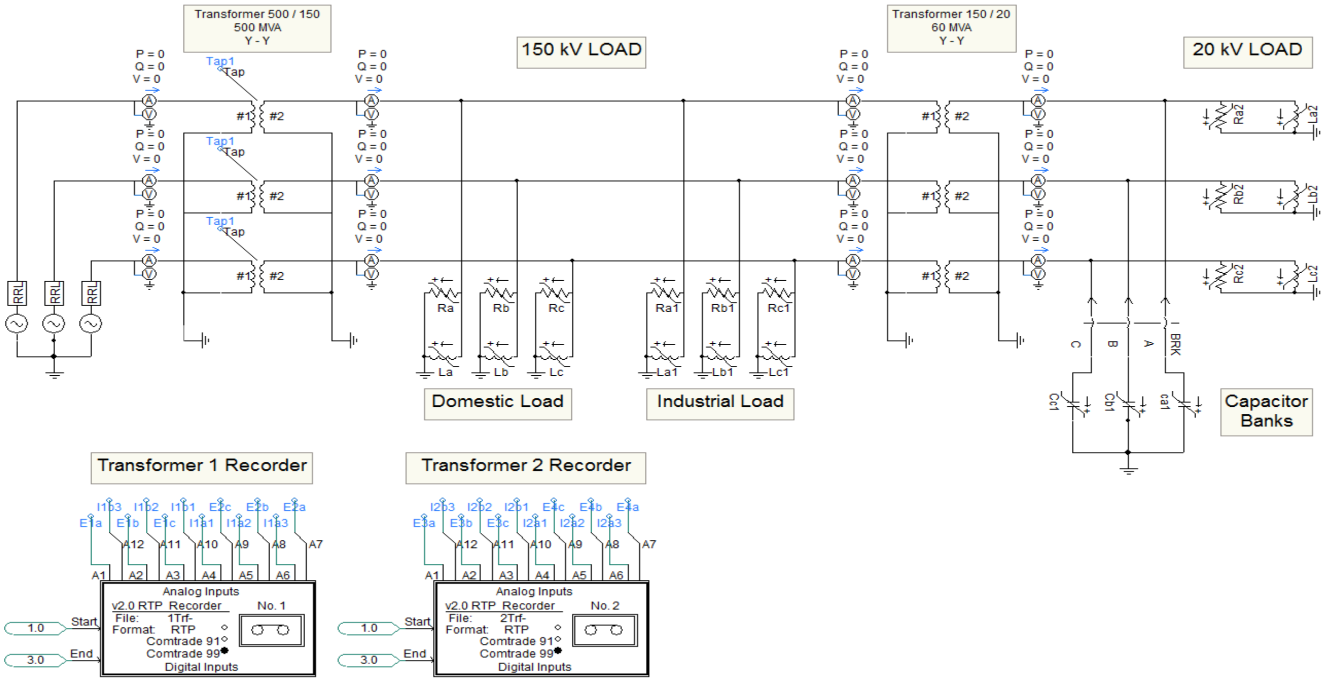


Fig. 4. System Simulation with Y-Y Transformers with Solidly Grounded Neutral.

Table IV. Imbalance Scenarios.

Scenario	State
1	No Imbalance
2	Constant Imbalance on 150 kV load and no imbalance on 20 kV load
3	Constant Imbalance on 20 kV load and no imbalance on 150 kV load
4	Variable Imbalance on 150 kV load and no imbalance on 20 kV load
5	Variable Imbalance on 20 kV load and no imbalance on 150 kV load
6	Combination variable imbalance on 150 and 20 kV load
7	Variable Imbalance on 150 kV load and no imbalance on 20 kV load with 4% impedance increase (fault) in phase A of the monitored transformer
8	No Imbalance with 4% impedance increase (fault) in phase A of the monitored transformer

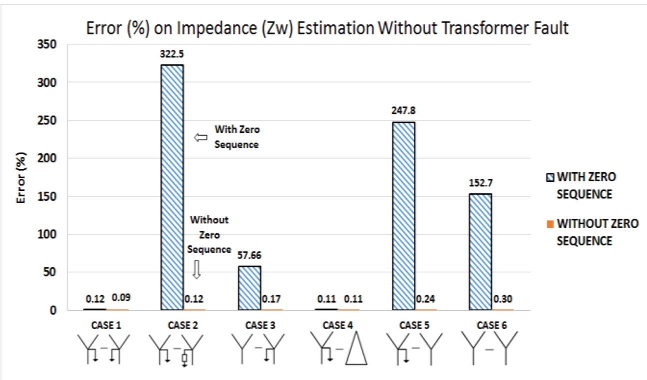


Fig. 5. Accuracy of Impedance estimation without fault on 150/20 kV Transformer.

IV. SIMULATION RESULTS ANALYSIS

The voltage and current signals that we obtained from Comtrade recorder in PSCAD simulation are analyzed by Transformer Explorer. In order to enable or disable the zero sequence voltage and current reduction, parameter k1 in equations (8) and (9) are set by the user. With this function we can analyzed and compare the estimated turn ratio and impedance with or without zero-sequence.

Signals from both transformers were analyzed to see the influence of zero-sequence on the primary side and/or secondary side. Fig. 5 shows accuracy for impedance estimation for 150/20 kV transformer without fault. In case 1 and 4, the impedance estimation with and without zero-sequence exhibits not much difference, meanwhile another transformer configuration (e.g. case 2) results in a large error as large as three times the nominal value. However the estimated values become quite close to the nominal values upon zero sequence removal.

Impedance estimations for another with a transformer fault (4 % impedance increase in phase A) on 150/20 kV transformer are shown in Fig. 6.

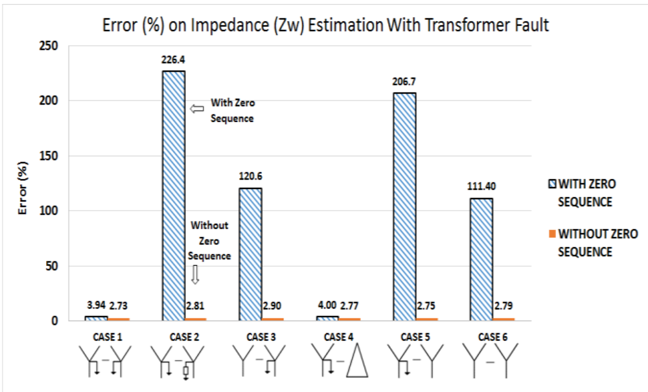


Fig. 6. Accuracy of Impedance estimation with 4% fault on 150/20 kV Transformer.

In case 1 and 4, estimation with zero-sequence approaches the real fault value (~3.9 % compared to expected 4 %) and estimation without zero-sequence also shows a good sensitivity to the fault (~2.7 % vs expected 4 %), however lost one third of the sensitivity to the fault along with the zero sequence removal. Even if a very good sensitivity to faults can be reached with zero sequence in Case 1, all the other

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transformer configurations can lead to very high errors in impedance and turn ratio estimations by Transformers Explorer, which eventually result in false alarms when exposed to system imbalances producing significant zero sequence in around the monitored transformer. Therefore zero sequence removal is recommended irrespective of the winding and earthling configuration.

Detailed result for each case on both transformers are shown in Table V and VI. The values shown in the tables are the largest percentage error, out of all simulated scenarios (see Table IV), compared to the corresponding nominal values. Actually in case of the simulated fault (4 % impedance increase), the percentage error is not really an error, instead Transformer Explorer is supposed to detect 4 % change in the impedance of the faulty phase.

Observing the results in Table V and VI, one can conclude the followings for each case:

Case 1: zero-sequence current or voltage don't influence the estimated turn ratio and impedance for this winding configuration (Y-Y) with solidly grounded neutral points. Even with 0.42 % zero sequence the estimated turn ratio shows good accuracy (less than 0.1 %) compared to the nominal value. In case of the impedance, the estimated values also show good accuracy (< 0.25 %), increased impedance by 4 % is also detected as a 3.8 % increase with zero sequence and 2.5 % without zero sequence. Decrease in fault detection accuracy by about one third without the zero sequence is understandable as one third of the imbalance created by the asymmetrical single phase fault (4 % impedance increase in phase A) is removed from each phase as the zero sequence.

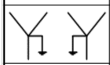
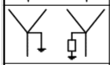
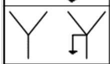
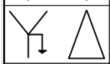
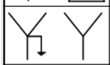
No influence on the accuracy of estimated impedance and turn ratio with zero sequence is actually due to the fact that in case of a solidly grounded transformer the zero-sequence can flow on both sides of the transformer providing a continuous path.

Case 2: in contrast to the previous case, the estimated impedance with zero sequence exceeds the nominal value by three times (>300 %), which is due to the elevated zero sequence impedance by three times the neutral to ground impedance on the secondary side compared to the zero sequence impedance on the primary side. Upon zero-sequence removal, the accuracy of estimated quantities returns to expected values (< 0.05 % for turn ratio and < 0.25 % for impedance). This is primarily because of not accounting the uneven zero sequence current and voltages between the primary and secondary sides.

Case 4: this case with a delta winding in the secondary leads the turn ratio to a wrong estimation. The estimated turn ratio with zero-sequence deviates from the nominal value by 32.84 %, especially on the 150/20 kV transformer when scenario 4 occurs resulting in high zero sequence in the primary side signals and not on the secondary side terminal signals as the zero sequence only flows inside the closed delta winding. However, when the zero sequence current and voltage are removed, estimations show a good accuracy (< 0.06 %) for turn ratio and (< 0.25 %) for impedance.

Table V. Accuracy of estimated turn ratio and impedance of 500/150 kV transformer.

WITHOUT TRANSFORMER FAULT

CONNECTION	WITHOUT ZERO-SEQUENCE		SCENARIO	WITH ZERO-SEQUENCE		SCENARIO
	TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR		TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR	
	0.0393 %	0.212 %	2	0.041 %	0.241 %	3
	0.0369 %	0.209 %	4	0.038 %	18.78 %	4
	0.0357 %	0.213 %	2	0.05 %	26.25 %	2
	0.0031 %	0.218 %	3	0.035 %	0.23 %	3
	0.0414 %	0.194 %	4	0.047 %	32.84 %	4
	0.0357 %	0.194 %	1	0.036 %	25.71 %	4

WITH TRANFORMER FAULT 4 % IN PHASE A ON 500/150 kV TRANSFORMER

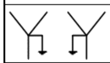
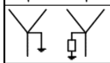
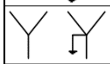
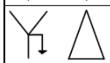
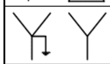
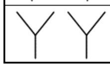
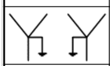
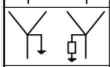
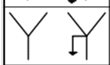
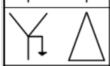
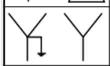
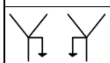
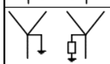
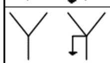
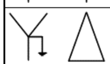
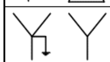
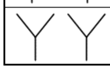
CONNECTION	WITHOUT ZERO-SEQUENCE		SCENARIO	WITH ZERO-SEQUENCE		SCENARIO
	TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR		TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR	
	0.036 %	2.481 %	8	0.036 %	3.851 %	7
	0.037 %	2.491 %	8	0.036 %	13.94 %	7
	0.039 %	2.484 %	7	0.053 %	43.915 %	7
	0.037 %	2.468 %	7	1.369 %	3.837 %	7
	0.039 %	2.476 %	7	0.039 %	45.12 %	7
	0.039 %	2.481 %	7	0.039 %	29.264 %	7

Table VI. Accuracy of estimated turn ratio and impedance of 150/20 kV transformer.

WITHOUT TRANSFORMER FAULT

CONNECTION	WITHOUT ZERO-SEQUENCE		SCENARIO	WITH ZERO-SEQUENCE		SCENARIO
	TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR		TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR	
	0.0492 %	0.093 %	1	0.095 %	0.116 %	1
	0.014 %	0.118 %	1	0.037 %	322.5 %	4
	0.0169 %	0.168 %	4	0.049 %	57.66 %	3
	0.052 %	0.105 %	2	32.84 %	0.113 %	4
	0.019 %	0.242 %	3	0.12 %	247.8 %	4
	0.022 %	0.303 %	3	0.035 %	152.7 %	4

WITH TRANFORMER FAULT 4 % IN PHASE A ON 150/20 kV TRANSFORMER

CONNECTION	WITHOUT ZERO-SEQUENCE		SCENARIO	WITH ZERO-SEQUENCE		SCENARIO
	TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR		TURN RATIO (n) ERROR	SC-IMPEDANCE (Zw) ERROR	
	0.049 %	2.727 %	7	0.08 %	3.939 %	7
	0.013 %	2.814 %	8	0.16 %	226.4 %	7
	0.013 %	2.9 %	8	0.005 %	120.56 %	7
	0.043 %	2.771 %	7	52.65 %	4.004 %	7
	0.013 %	2.749 %	8	0.13 %	206.7 %	7
	0.027 %	2.792 %	8	0.053 %	111.4 %	7

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Case 3, 5, 6: these cases are of Y-Y configurations with different neutral grounding practices, which also leads to high inaccuracy in impedance estimations when zero-sequence is included, can be due to the fact that the zero-sequence current cannot flow in either winding (as the absence of a path through one winding prevents the zero sequence current). With zero-sequence removal, the estimations reached the same accuracy as in the other cases without zero sequence.

V. CONCLUSION

Influence of zero sequence current and voltage on transformer fundamental quantity (turn ratio and impedance) estimation was investigated and found that the estimated quantities can contain significantly high error if the zero sequence is not removed. With Zero-sequence removal, transformer fundamental quantities estimation can reach the required accuracy to detect changes (as per the IEEE standard [8]) in the turn ratio and impedance without producing false alarms, even with the presence of system imbalances on one or both side of a transformer. Although the parameter estimations for solidly grounded Y-Y connected transformer, which is not common, is not prone to zero sequence issue, it is advisable to remove the zero sequence in case if the grounding system is not good.

It has been shown that the fault detection ability is not affected by the zero sequence removal as a 4 % impedance increase can be detected convincingly. If such an impedance change is detected, recommendation would be to plan for an outage and perform advanced measurements like FRA to confirm the on-line diagnosis by Transformer Explorer.

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