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## Estimation of the Zero Sequence Voltage on the D-side of a Dy Transformer by Using One Voltage Transformer on the D-side



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## Table of Contents

<b>1 INTRODUCTION.....</b>	<b>3</b>
<b>2 THEORY .....</b>	<b>3</b>
<b>3 VERIFICATION OF THE METHOD THROUGH SIMULATIONS IN MATLAB SIMPOWER.....</b>	<b>5</b>
<b>4 LABORATORY TESTS AND RESULTS.....</b>	<b>6</b>

# 1 Introduction

This report deals with the estimation of the zero sequence voltage on the D-side of a Dy transformer by the use of only one voltage transformer (VT) connected between one phase and ground on the D-side.

Zero sequence voltage can be used for phase to ground fault detection in non-directly earthed systems. Normally, on the D-side of a transformer the zero sequence voltage is measured by the use of three VTs, each of them connected between each phase and ground on the primary side and open delta connected on the secondary side.

The method described in this report allows D-side zero sequence voltage estimation by the use of one VT on the D-side and three VTs on the y-side. If the y-side is at a lower nominal voltage, the described method could be attractive on an economic point of view.

Though the described method is general and works for every Dy transformer (and with some adjustments for any transformer connection), the cases where it is economically advantageous are few. An example is the case where a distributed generator is connected to a medium voltage non-directly earthed network through a Dy step-up transformer and zero sequence voltage on the D-side is necessary for protection purposes.

## 2 Theory

The main idea behind the method described in this section for estimating the zero sequence voltage on the D-side is to use only one VT on the D-side and to use the information from three VTs connected on the y-side of the transformer.

The estimation of the zero sequence voltage is performed as described below. Two premises are necessary (Zoran Gačić's PhD thesis):

- a Dy transformer transforms sequence quantities independently
- positive and negative sequence are transformed accordingly to:

$$V_{\Delta 1} = \frac{N_{\Delta}}{N_y} V_{y1} e^{j\vartheta} = \tau V_{y1} e^{j\vartheta} \quad (1)$$

$$V_{\Delta 2} = \frac{N_{\Delta}}{N_y} V_{y2} e^{-j\vartheta} = \tau V_{y2} e^{-j\vartheta}$$

where

- $\vartheta$  is the angle by which the primary-secondary quantities are shifted in the transformation and it is determined by the transformer group number
- $\tau$  is the transformer ratio
- $N_{\Delta}$  and  $N_y$  are the number of windings on the D- and y-side respectively

Zero sequence quantities are not transformed in case of a Dyn transformer. **Equation (1)** does not take into account the voltage drop inside the transformer. This can be easily accounted for by modifying **Equation (1)** as follows:

$$V_{\Delta 1} = \tau V_{y1} e^{j\theta} - \tau Z_{tr} I_{y1} e^{j\theta} = \tau e^{j\theta} (V_{y1} - Z_{tr} I_{y1}) \quad (2)$$

$$V_{\Delta 2} = \tau V_{y2} e^{-j\theta} - \tau Z_{tr} I_{y2} e^{-j\theta} = \tau e^{-j\theta} (V_{y2} - Z_{tr} I_{y2})$$

where

-  $Z_{tr}$  is the transformer impedance as seen from the low voltage y-side

If we express the phase voltages on the D-side in terms of their sequence components, we get:

$$\begin{bmatrix} V_{\Delta a} \\ V_{\Delta b} \\ V_{\Delta c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} V_{\Delta 1} \\ V_{\Delta 2} \\ V_{\Delta 0} \end{bmatrix} \quad (3)$$

In this equation the unknown is the zero sequence voltage  $V_{\Delta 0}$ .  $V_{\Delta 1}$  and  $V_{\Delta 2}$  are obtained from **Equation (2)** through the information collected on the y-side. By inserting **Equation (2)** into **Equation (3)** we get:

$$\begin{bmatrix} V_{\Delta a} \\ V_{\Delta b} \\ V_{\Delta c} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} V_{\Delta 1} \\ V_{\Delta 2} \\ V_{\Delta 0} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \tau e^{j\theta} (V_{y1} - Z_{tr} I_{y1}) \\ \tau e^{-j\theta} (V_{y2} - Z_{tr} I_{y2}) \\ V_{\Delta 0} \end{bmatrix} \quad (4)$$

The previous is a system of three equations. Solving the first of these equations for  $V_{\Delta 0}$  we find:

$$V_{\Delta 0} = V_{\Delta a} - \tau e^{j\theta} (V_{y1} - Z_{tr} I_{y1}) - \tau e^{-j\theta} (V_{y2} - Z_{tr} I_{y2}) \quad (5)$$

This is an estimation of the zero sequence voltage on the D-side and voltage  $V_{\Delta a}$  is measured. Any of the three equations in **(4)** can be used for the estimation, each requiring a different phase voltage to ground to be measured on the D-side. The zero sequence voltage on the D-side can be accurately estimated if:

- positive and negative sequence currents and voltages on the low voltage y-side are known
- step-up transformer impedance, ratio and angle group are known
- one phase to ground voltage on high voltage D-side is known

The advantage of this method is the use of only one VT on the high voltage D-side to estimate the zero sequence voltage arising after a ground fault in a non-directly earthed system. The majority of the distributed generators are already provided with current and voltage transformers on the low voltage y-side, i.e. there are no additional costs to get the positive and negative sequence quantities used in **(5)**.

However, to date, distributed generators are not commonly operated in island and therefore, sensing the zero sequence voltage on the D-side of the step-up transform is not always needed. Instead, if island operation is desired, sensing the zero sequence

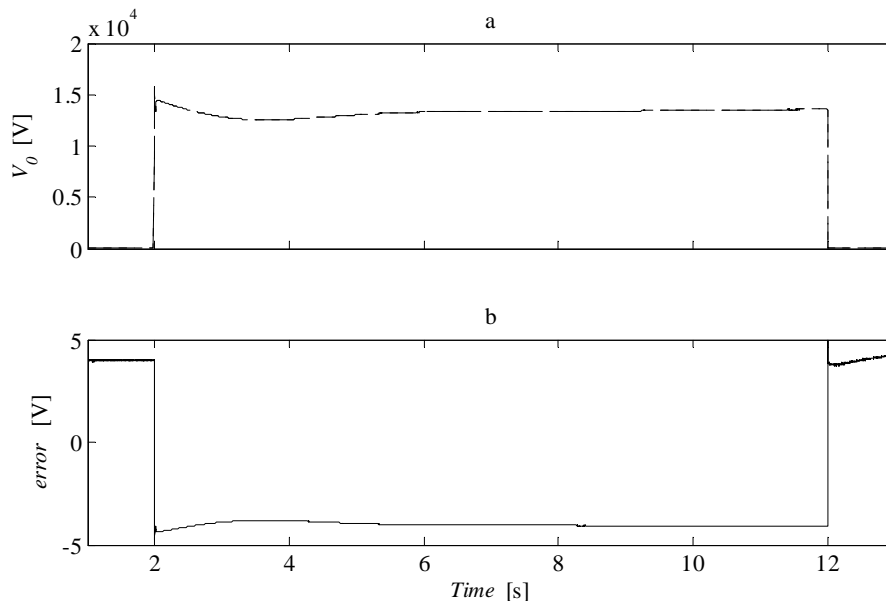
voltage on the D-side can be the most practical way to detect ground faults on that side.

The word “estimation” has been used through all the report instead of “calculation”. The zero sequence voltage can only be estimated because of the uncertainties in transformer parameters and measurement errors from CTs and VTs involved in **Equation (5)**. Another source of error in the estimation derives from neglecting the transformer magnetizing current in **Equation (5)**. However, as it is shown in the following, the estimation can be very accurate if the uncertainties are low. Also, the magnetizing current of a transformer is usually very small.

The physical meaning of the method is simple. On the y-side, any information is lost on the neutral point’s (which is not a physical point) shift on the D-side. By measuring one phase-to-ground voltage on the D-side we regain this information. All information about positive and negative sequence voltages is identical on both sides of the step-up transformer. Therefore the zero sequence voltage on the D-side can be estimated.

### 3 Verification of the method through simulations in MATLAB SimPower

The method has been implemented in MATLAB SimPower and it proved to be accurate. The estimated zero sequence voltage has been compared with the measured one on the D-side of the transformer, during a phase *a* to ground fault on that side at 20 kV voltage level. Results from simulations are shown below.



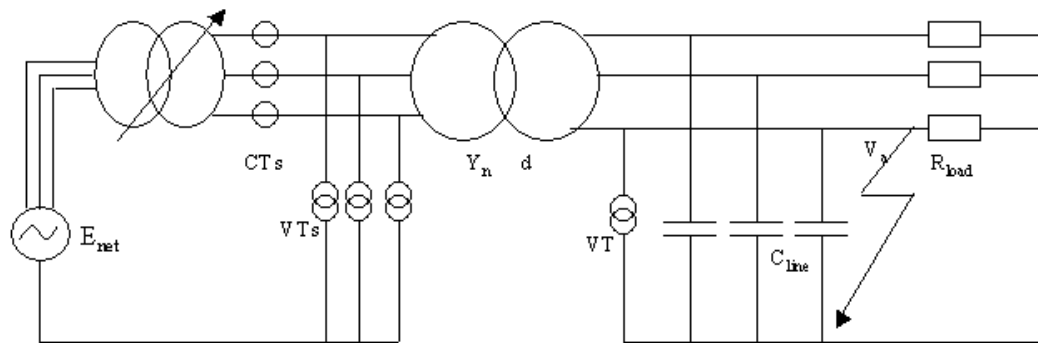
**Figure 3.1** Simulation of phase *a* to ground fault on the D-side. *a*) measured (dashed) and estimated (dotted) zero sequence voltage. *b*) error between the estimated and the measured zero sequence voltage

The measured and estimated zero sequence voltages are practically undistinguishable. The maximum error is around 5 V, i.e. around 0,035% of system nominal phase voltage and it can be totally neglected. The error depends on neglecting the magnetizing current in the transformer. In the simulations it has been assumed a magnetizing current equal to 0,01 pu, i.e. a magnetizing impedance of 100 p.u. Angle errors, not reported, are also very small.

## 4 Laboratory tests and results

Some tests have been performed in the lab to verify the method described above for estimating the zero-sequence voltage on the d-side of a Ynd transformer. The facts that the d-side is the low voltage side and that the Y-side is grounded do not affect the conclusions.

The laboratory experiment is described in the figure below.



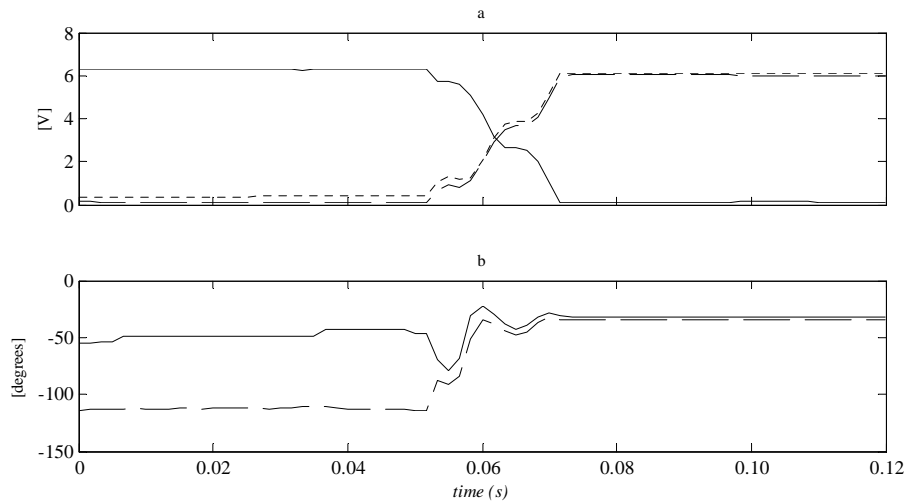
*Figure 4.1 Set-up of the laboratory experiment*

An Ynd transformer is fed through a tap-changer transformer from the net. The voltage on the Yn side is regulated so to get 11 V phase-to-phase voltage on the d-side. On the d-side a resistive load is fed and capacitances are connected so to simulate a long line. On the Yn side all phase currents and voltages are measured. On the d-side phase *a* to ground voltage is measured. Also the zero-sequence voltage is measured on the d-side through three open delta connected voltage transformers, not shown in the figure for sake of clarity. All measurements are fed in *DSPACE* and phasors calculations are performed in *DSPACE* through a one-cycle Fourier algorithm. Finally, the new algorithm for zero sequence estimation is also implemented in *DSPACE*.

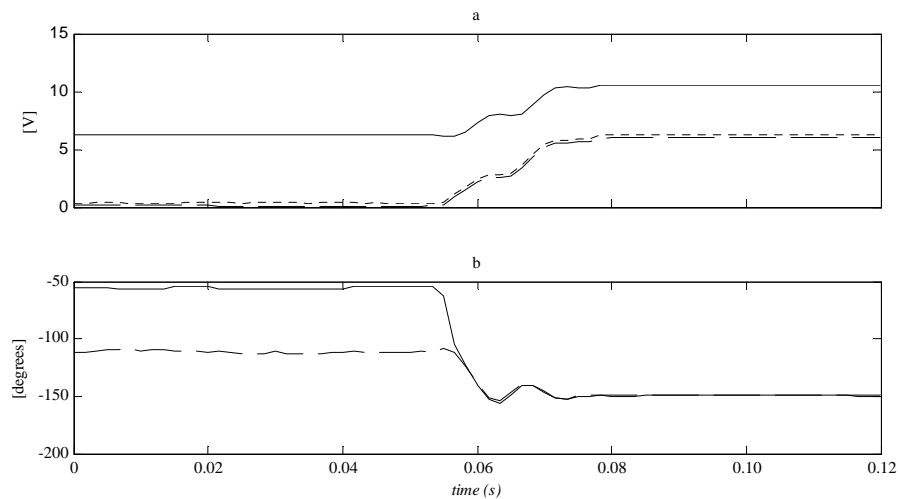
A phase to ground fault is simulated on the d-side by connecting one phase directly to the capacitances neutral point. Results below show the measured zero-sequence voltage, the zero sequence voltage estimated through the new algorithm and the faulted phase voltage.

It is noted that before fault occurrence, the angles of the estimated and measured zero sequence voltage have actually no meaning, being the voltage ideally equal to zero.

It is seen that the zero sequence voltage estimated through the algorithm reproduces fairly the measured zero sequence voltage, already after less than a cycle. After the transient, the two voltages are practically equal. The small differences are mainly due to uncertainties in the converting factors for *DSPACE* input signals.



**Figure 4.2** Phase a to ground fault on the d-side. a) Phase a voltage (solid), measured (dashed) and estimated (dotted) zero sequence voltage. b) measured (solid) and estimated (dashed) zero sequence voltage angle



**Figure 4.3.** Phase b to ground fault on the d-side. a) Phase a voltage (solid), measured (dashed) and estimated (dotted) zero sequence voltage. b) measured (solid) and estimated (dashed) zero sequence voltage angle