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*Publication date:*  
2005

*Document Version*  
Early version, also known as pre-print

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*  
Søgaard, K., Wiechowski, W. T., & Bak, C. L. (2005). *Measurements of the Distorted No-Load Current of a 20/60kV, 6MVA Power Transformer*. Paper presented at Australasian Universities Power Engineering Conference (AUPEC'2005), Hobart, Australia.

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# Measurements of the distorted no-load current of a 20/60kV 6MVA Yy0 power transformer

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## ABSTRACT

*This paper presents the results from measurements of the distorted no-load current of a 6MVA 20/60kV transformer. In the execution of the measurement, the supply setup during the measurements has been changed. The changes imply different connections of the 0.4/20kV supplying transformer. The secondary winding of the supplying transformer are connected in D, wye and YN, and for each connection, the measurements are repeated. The measurement is performed with constructed current and voltage transducers with an amplitude accuracy better than  $\pm 1\%$ . It has been shown that the harmonic contents in the no-load current the 6MVA 20/60kV transformer Thrige is as predicted by [6].*

## 1. INTRODUCTION

Due to the lack of measurements of the distorted no-load current of large power transformers published in the literature, this paper is prepared. The main reason for the measurements is to validate a new power transformer model based on a procedure presented by [3]. The Ph.D. student Wojciech Wiechowski implements the Transformer model in DIGSILENT Powerfactory. The origin of the Ph.D. project is that the Danish transmission company ELTRA has experienced operational malfunctions of some of the measuring and protection equipment. The conclusion after a preliminary investigation was that the reason for that were harmonic voltages and currents that propagate in the transmission grid. To investigate and map the harmonic propagation, ELTRA has offered this Ph.D. project. The Contribution of this Ph.D. project is to build a computer model of the entire transmission system in the area supplied by the Danish transmission company ELTRA so it will reflect the real system behaviour at harmonic frequencies, up to 1-2 kHz. Special focus shall be paid on the nonlinearities present on the transmission level, which means HVDC links and transformer core nonlinearities.

In the collaboration between Aalborg University and the Danish distribution company HEF Net, a 6 MVA 20/60 kV transformer 20/60 kV Thrige are at disposal for the author. The original setup for the transformer 20/60 kV Thrige includes voltage and current transformers intended to measure the fundamental frequency component of voltages and currents. These original voltage and current transformers do not measure with an acceptable accuracy in the frequency range dc up to 2 kHz. To measure more accurately a measuring setup has

been designed and constructed. The measuring setup consists of three current and voltage transducers and a data acquisition device. The current transducer is a LEM current clamp. The voltage transducer is made of two capacitors that form a capacitive voltage divider.

Originally, the 20/60 kV Thrige transformer is supplied from the 60 kV bus at the 60/20 kV station Aggersund in northern Jutland. However, to ensure that malfunction of the measuring setup does not interfere with the rest of the 60/20 kV station, this 20/60 kV transformer Thrige is supplied through the local 0.4 kV network in Aggersund. 0.4 kV supplying voltage is transformed to 20 kV through a 100 kVA transformer connected on the high voltage side in Y or YN or a 160 kVA transformer connected on the high voltage side in D. A schematic diagram of the supply setup for Thrige is shown on Figure 1, with the three different connection on the high voltage side of the 0.4/20kV transformer.

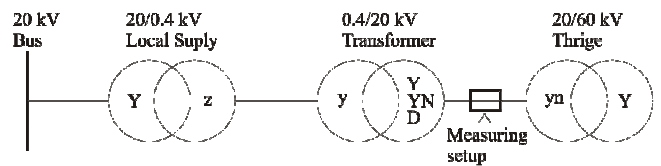


Figure 1. Schematic diagram of the supply setup for 20/60kV transformer Thrige in Aggersund.

## 2. MEASUREMENT SETUP

### 2.1. CURRENT TRANSDUCER

The current transducer is a LEM PR30 current probe. The current transducer transforms the measured current to a voltage with a precision that is presented in Table 1 next to the demands from IEC 61000-4-7[5].

Table 1. Precision for the current transducers and demands from IEC 61000-4-7.

Accuracy	Current transducer	IEC 61000-4-7
Amplitude	$\pm 1\%$	$\pm 5\%$
Phase	$< 2^\circ$	-
Frequency range	DC to 100 kHz	DC to 2.5 kHz

The precision for the current transducer is obtained from the relevant datasheet [4]. The LEM current transducer

is placed on adapted cardboard that guarantee centre position around the conductor.

## 2.2. VOLTAGE TRANSDUCER

The voltage transducer is constructed of two capacitors connected in series, as illustrated on Figure 2.

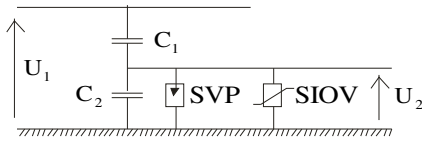


Figure 2. Equivalent diagram of voltage transducer.

The capacitor  $C_1$  is a high voltage capacitor from MessWandler Bau with a nominal voltage of 140 kV. The capacitance of  $C_1$  is 1200nF.  $C_2$  is constructed of one 100 nF, one 47 nF and three 10 nF capacitors from RIFA connected in parallel. For overvoltage protecting the data acquisition system, there is a spark gap SVP EPCOS type EC 230 and a varistor SIOV EPCOS type S20K275 installed in parallel with  $C_2$ . The voltage transducer is validated according to IEC 61000-4-7. The voltage transducer is tested for its frequency dependency. The frequency dependence test is performed by applying a sinusoidal voltage to the primary side with an amplitude of 120V, generated with California instruments sinus generator with a frequency that has been varied in the range 0-2500 Hz. The primary and secondary voltage  $U_1$  and  $U_2$  have been measured. The result of the frequency test is shown on Figure 3.

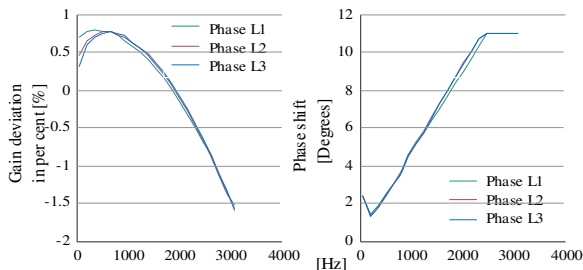


Figure 3. Result of frequency dependency test for the voltage transducer.

An additional test to validate the voltage dependency of the voltage transducer ratio is performed. The frequency test is performed with amplitude of 120V according IEC 61000-4-7, but the real measurement is performed with amplitude around 20 kV. The voltage transducer is designed so the voltage on the capacitor  $C_2$  (secondary voltage) is less than 95 V while the primary voltage applied to the voltage divider is 20 kV. The capacitance of  $C_2$  was measured with an accuracy of  $\pm 0.15\%$  in the range 10 to 100 V, and the capacitance changes less than  $\pm 0.1\%$ , so it is assumed voltage independent. Measurement of the high voltage capacitor  $C_1$  shows that it is also voltage independent. Therefore, it is sufficient to determine the frequency dependence with an applied voltage of 120V from IEC 6100-4-7 and not the voltage applied at measurement 20 kV. The voltage transducers transfer ratio changes less than  $\pm 1\%$  in the frequency ranges DC to 2500 Hz. The voltage transducers phase shift is less than  $10.88^\circ$ . The

determined phase shift error of the voltage transducer can be used to compensate the measurements. In Table 2 the result for the frequency dependency test is listed and compared with the demands of the IEC 61000-4-7.

Table 2. Precision for the voltage transducers and demands from IEC 61000-4-7.

Accuracy	Voltage transducer	IEC 61000-4-7
Amplitude	$\pm 1\%$	$\pm 5\%$
Phase	$< 10,88^\circ$	-
Frequency range	DC to 2.5 kHz	DC to 2.5 kHz

Both the current and voltage transducers comply with the IEC61000-4-7 standard. Voltage and current transducers are mounted on a wooden stand as it is shown on

Figure 4.

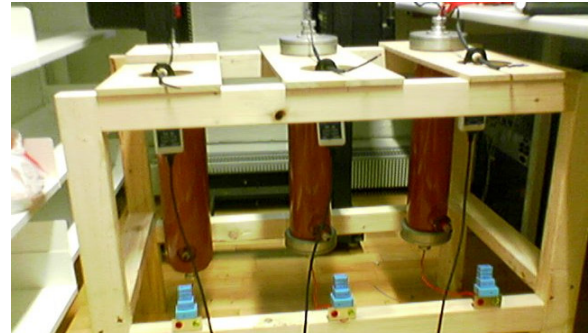


Figure 4. Voltage and current transducer mounted on a wooden stand.

## 2.3. DATA ACQUISITION

In order to gather and process the data, an Omicron test set with Enerlyzer version 2.0 software is used. The voltage amplitude measuring precision of Omicron is typically  $+0.1\%/ -0.8\%$  and guaranteed  $\pm 0.12\%$  of full-scale. The measured current is converted to a voltage with the current transducer with a full-scale range on 1V, for voltage, measurement is the full-scale range is 100V. The sampling rate is 9.48 kHz. The voltage measuring input is band limited with a low pass filter with a -3dB frequency at 4.74 kHz so aliasing is avoided. The Enerlyzer software performs the Fast Fourier transformation of the measured currents and voltages with the above-mentioned precision.

## 2.4. MEASUREMENT SETUP

During the measurements, three cases are investigated. In each case, the secondary winding of the 0,4/20 kV supplying transformer is connected differently. The measurements are performed for three different connections are Delta, Wye and Wye with the neutral grounded. The different winding configurations are used in order to observe the impact on the no-load current harmonic. On Figure 5 is the measurement setup when

20/60 kV Thrige is supplied from a Delta connected transformer.

The no-load current of power transformers is harmonically distorted, because is related to the (sinusoidal) supplying voltage with a nonlinear characteristic of the transformer iron core. In case of 1-ph transformers, this current will contain odd harmonic, including the triplens (3,5,7,9, etc.)

In the case of 3-ph transformers, this natural harmonic content of the magnetising current may be altered, depending on the connection arrangement of the primary winding. If it is a grounded star (yn), then all triplens harmonics (3<sup>rd</sup>, 9<sup>th</sup>, etc.) will be still present in the current, since they will have a return path provided. In the case if we connect this primary winding of investigated transformer in not-grounded star, all the triplens (which in balanced systems are of zero-sequence) will be blocked- they will not flow.

However, it is important to realise that not only the Y or D connection of the primary winding of this investigated transformer will block triplens, but also the connection of the source matters. If the source is connected in not-grounded star (Y) then, again, the triplens will not have the return path provided. In our case, the secondary winding of the supplying transformer is our source, therefore the way it is connected (Y, YN or D) will have an impact on the triplen harmonics that flow out of our investigated transformer.

The only return path for the zero sequence current components is through the voltage transducer. The impedance of the voltage transducer for the third harmonic is 890kΩ. The zero sequence component of the current is for that reason expected to be roughly zero. Since in balanced conditions, the 3<sup>rd</sup> harmonic component is of zero sequence, it should not be present in the noload current of the Thrige transformer, since it does not have any return path.

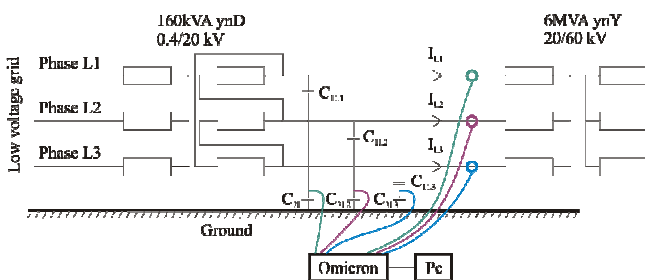


Figure 5. Measurement setup with the 6MVA transformer supplied from a delta connected 160kVA transformer.

$C_{1L1}$ ,  $C_{2L1}$  is the voltage transducer for phase L1. Omicron is measuring the voltage across  $C_{2L1}$ . This is carried out for all three phases. The currents  $I_{L1}$ ,  $I_{L2}$  and  $I_{L3}$  are converted to a voltage which the LEM current probes. The voltage generated by LEM current transducer is measured with Omicron. Next, the supply setup is changed, so the 20/60 kV transformer Thrige is supplied from the rebuild Wye connected transformer with grounded neutral. This establishes a return path through the ground for the zero sequence components. The setup is illustrated on Figure 6.

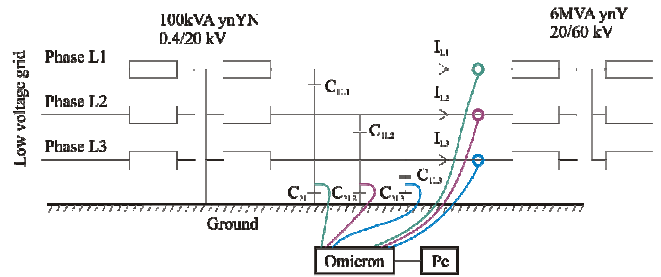


Figure 6. Measurement setup with the 6MVA transformer supplied from a Wye connected 100kVA transformer with grounded neutral.

The return path for the third harmonic is through the ground and the zero sequence impedance of the wye-connected transformer. This transformer was originally a wye-connected transformer without the neutral point available; it was rebuilt to make it available for the measurements. The zero sequence impedance is unknown but since it is a three limb transformer it is significantly smaller than the open-circuit impedance and higher than the short-circuit impedance [1].

The open-circuit impedance and short-circuit impedance is calculated to 240.44kΩ and 72.11Ω from the data presented in

Table 3. This makes the flow of the third harmonic current possible. The measurement setup in Aggersund is shown on Figure 7.

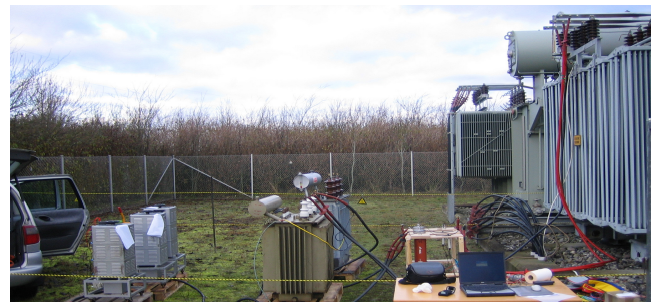


Figure 7. The measurement setup in Aggersund, northern Jutland.

## 2.5. TRANSFORMER DESCRIPTION

A Danish company Thomas B. Thrige produced the 6MVA 60/20 kV transformer. On August 1 1955, the transformer was delivered. The available data are listed in

Table 3.

The delta connected 160kVA 20/0.4 kV transformer essential data are in the lack of test report estimated [2]. The estimated results are listed in

Table 3. On the 0.4 kV side there is a tap changer so the output voltage on the 20kV side is adjustable in the discrete values [19.2, 20, 20,8]kV.

The star connected 100kVA transformer 20/0.4kV znYN is originally without available neutral tap. The transformer was rebuilt so the 20kV neutral tap becomes

available. The transformer essential data are in the lack of test report estimated; the results are listed in

Table 3[2]. On the 0.4 kV side there is a tap changer so the output voltage on the 20kV side is adjustable in the discrete values [19.2, 20, 20,8] kV.

Table 3 Rated transformer data

Transformer	6MVA	160kVA	100kVA
Ratio	20/60 kV	0.4/20kV	0.4/20kV
No-load current	0.68 %	1,42 %	1.6 %
Short-circuit voltage	7.6 %	3.61%	3.27%
Copper loss	50 kW	2.4 kW	1.3 kW
No-load loss	9.3 kW	0.56 kW	0.3 kW
Excitation	40 kVAr	-	-

### 3. RESULTS OF MEASUREMENTS

#### 3.1. BACKGROUND VOLTAGE DISTORTION

The Omicron CMC 256 performs a Fast Fourier transform (FFT) of the measured background voltage distortion. The measurement without the 20/60 kV Thrige transformer connected is performed as shown on Figure 5. The results are shown on Figure 8.

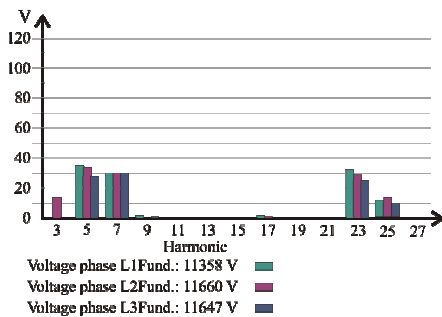


Figure 8. FFT of background distortion of supply voltage.

#### 3.2. RESULTS OF MEASUREMENTS WITH 20/60 kV TRANSFORMER THRIGE SUPPLIED FROM THE 160 kVA DELTA CONNECTED TRANSFORMER

Measurement of the no-load current for 20/60 kV Thrige when supplied from the 160kVA delta connected transformer is shown on Figure 5. The result is shown on Figure 9.

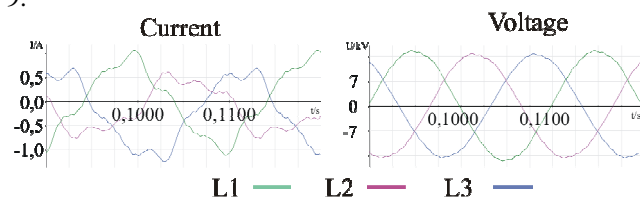


Figure 9. No-load current of 20/60 kV Thrige transformer when supplied from 160kVA delta connected transformer.

The 160kVA transformer is operated in the centre tap position, which gives a line voltage of 18.8kV. A FFT of the no-load current and voltage is performed by Omicron and the results are shown on Figure 10.

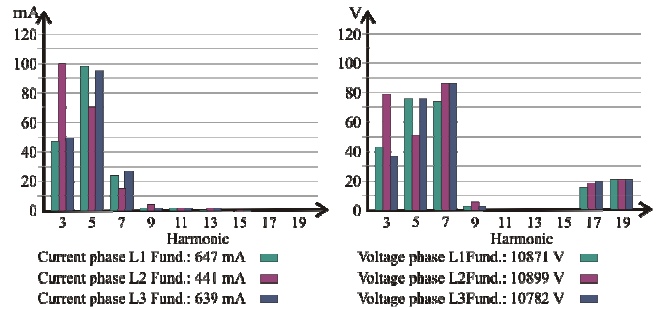


Figure 10. FFT of no-load current and voltage from 20/60 kV Thrige when supplied from a delta connected transformer with line voltage 18.8 kV.

There should not be any triplen harmonics when the 20/60 kV Thrige is supplied from a delta connected transformer. However, the triplen harmonics could still flow, through the outer two phases L1 and L3 and back through the centre phase L2 due to the core asymmetry. In [6] there is an estimate of the expected harmonic current compared to the total current for a single phase transformer constructed of cold sheet iron the expected and measured result are presented in Table 4.

Table 4. Expected ratio of harmonic current to total current [6], and the measured values.

	3'harmonic	5'harmonic	7'harmonic	9'harmonic
expected	0.46	0.17	0.06	0.03
Phase L1	0.07	0.15	0.04	0.00
Phase L2	0.23	0.16	0.04	0.01
Phase L3	0.08	0.15	0.04	0.00

The values of the 5'th and 7'th harmonic are as it was predicted by [6]. The zero-sequence, triplen harmonic shall be blocked by the delta winding of the supplying transformer. Their existence can be explained by the asymmetry of the magnetic core.

If the supplying voltage is increased to 19.5kV, by changing the tap position from 2 to 1 of the delta connected transformer, the harmonic components of the no-load current and voltage become as shown on Figure 11.

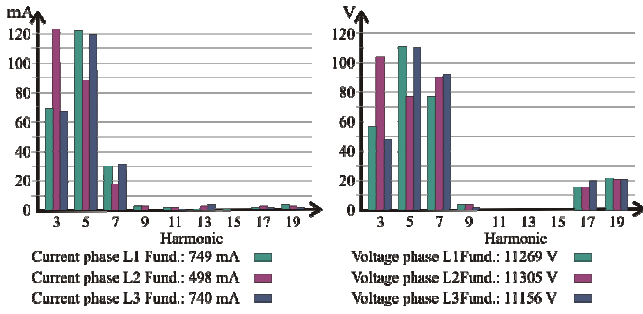


Figure 11. FFT of no-load current and voltage from 20/60 kV Thrige transformer when supplied from a delta-connected transformer with line voltage 19.5 kV.

It can be seen, that the values of all the current and voltage harmonics have increased, but their relative value, with respect to the fundamental component here remained unchanged.

If the tap position is changed to 3 so the line voltage is decreased to 18.1 kV the no-load current and voltage become as shown on Figure 12.

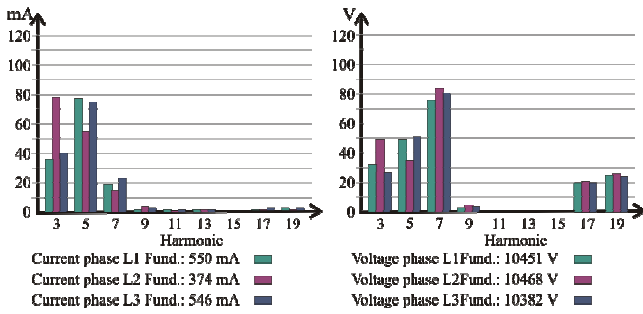


Figure 12. FFT of no-load current and voltage from 20/60 kV Thrige transformer when supplied from a delta connected transformer with line voltage 18.1 kV.

Again, there are no changes in the harmonic distribution only in the amplitude.

### 3.3. RESULT WHEN 20/60 kV THRIGE IS SUPPLIED FROM A TRANSFORMER CONNECTED IN WYE WITHOUT GROUNDED STAR POINT

The no-load current of the 20/60 kV Thrige transformer and the voltage when supplied from a wye-connected transformer where the neutral point is not connected to ground are shown on Figure 13.

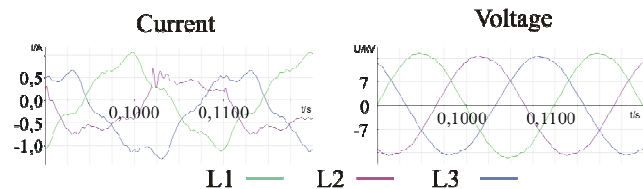


Figure 13. No-load current and voltage of 20/60 kV Thrige transformer when supplied from a transformer connected in wye without grounded neutral with line voltage 18.8 kV.

The FFT of the no-load current of 20/60 kV Thrige transformer is shown on Figure 14.

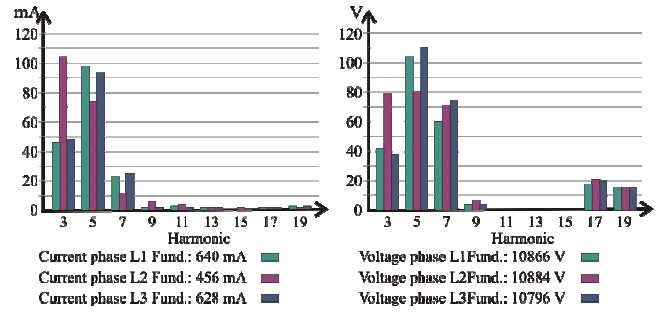


Figure 14. FFT of no-load current and voltage draw from 20/60 kV Thrige transformer when supplied from a transformer connected in wye without grounded neutral with line voltage 18.8 kV.

The triplen harmonics again are not expected in the no-load current, but it could flow through the outer two phases L1 and L3 and back through the centre phase L2. This partially confirms that the reason of their existence is the magnetic asymmetry of the Thrige transformer, which is under test

This time, again the measurements were made for three values of the supplying voltage. Since the ungrounded star, blocks triplen harmonics in the same way like D-winding the results of measurements are identical like in the case of secondary winding of supplying transformer connected in delta. Therefore only the results of the measurements for the center tap position are shown, see Figure 14.

### 3.4. RESULT WHEN 20/60 kV THRIGE IS SUPPLIED FROM WYE CONNECTED TRANSFORMER WHERE THE NEUTRAL POINT IS CONNECTED TO GROUND

The no-load current and voltage when 20/60 kV Thrige is supplied from a 100 kVA transformer connected in wye with grounded neutral is shown on Figure 15.

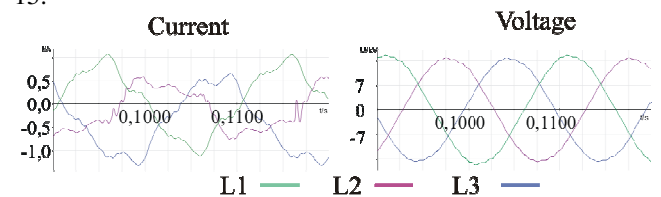


Figure 15. No-load current and voltage from 20/60 kV Thrige when supplied from a wye connected transformer with neutral grounded and line voltage 18.8 kV.

A FFT of the no-load current and voltage drawn from 20/60 kV Thrige is shown on Figure 16.

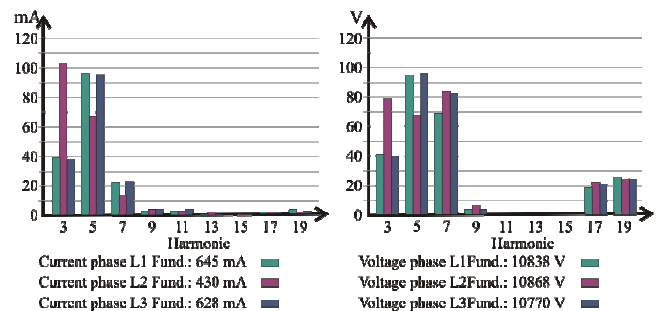


Figure 16. FFT of no-load current and voltage from 20/60 kV Thrige when supplied from a wye connected transformer with neutral grounded and line voltage 18.8 kV.

[6] Bödefeld, Theodor, Elektrische Maschinen, Springer-Verlag, 1965

When changing the tap position the result is the same as when 20/60 kV Thrige is supplied from a transformer connected in delta, therefore only the result from the centre tap position is present.

There are no considerable changes in the no-load current of the 6 MVA transformer when it is supplied from a delta or a wye connected transformer because the zero sequence impedance is too high in the 20/60 kV Thrige and the modified transformer.

#### 4. CONCLUSION

It was expected that the harmonic contents of the no-load current is changed when the supply setup changes. When the 20/60 kV Thrige transformer is supplied from a delta connected transformer, it was expected that the flow of the triplen harmonics (3<sup>rd</sup>, 9<sup>th</sup>, etc.) will be blocked. When the 20/60 kV Thrige transformer is supplied from a Wye connected transformer with or without grounded neutral the result is the same as when supplied from the delta connected transformer this is due to the large zero sequence impedance in the rebuilt wye connected transformer and the 20/60 kV transformer.

#### 5. FUTURE WORK

To repeat the measurement when 20/60 kV Thrige transformer is supplied with a transformer with a well defined and low zero sequence impedance and adjust the supply voltage to above the rated voltage of 20/60 kV Thrige transformer. With the purpose to validate the transformer model in that area.

#### 6. ACKNOWLEDGMENT

The authors would like to thank Himmerlands elforsyning net for help during experiments and ABB Aalborg for help with rebuilding the supplying transformer.

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