EE 563

Generalized Electrical Machine Theory

Fall 2016

Term Project

Final Report

Erencan Duymaz
1814029

26/01/2017

Submitted to: Prof.Dr. Muammer ERMİŞ

Contents

Abstract

This report explains the details of harmonic content decomposition from a current waveform by using Synchronously Rotating Reference Frame Analysis, Analytical Analysis and finally Discrete Fourier Transformation.

Part A -Synchronously Rotating Reference Frame Analysis

In this part of the project, the given data will be analysed by using Synchronously Rotating Reference Frame Analysis. The mean of the given current waveform will be subtracted from itself and then, it will be converted to dq frame. Meanwhile this transition occurs, the synchronously rotating frame will be used in order to make fundamental component of the current which is also rotating in the synchronous speed will be seen as stationary. Before the inverse transformation (dq-to-abc), the waveforms will be passed from a low-pass filter in order to get rid of the other waveforms whose speed is different than the synchronous speed. The low-pass filter will enable us to exclude higher harmonic content in the dq axis waveforms. Therefore, inverse transformation(dq-to-abc) will give us the positive sequence component of the initial current waveform since the reference frame also rotates in the same speed. In fact, if synchronously rotating speed is applied in reverse direction, then the negative sequence component of the fundamental current waveform will be stationary resulting in negative sequence fundamental component of the current will be obtained in the resultant transformation. If the summation of these sequence currents which is in fact the fundamental component (50 Hz component in the current waveform) is subtracted from the initial data (without DC component), the remaining current waveform will be composed of harmonics. The same procedure will be applied to that remaining waveform to obtained other frequency harmonics by rotating the reference speed in the corresponding harmonic angular frequency (i.e. 190π for 95 Hz harmonics).[1]

This SRRF analysis is basically making use of the reference frame analysis. The main logic is to make the desired components of the waveform as stationary and then filter it out. For example, in the fundamental component extraction, if you use synchronously rotating frame which is rotating at 100π rad/sec, 50 Hz component will be stationary. If one considers the phasor diagram logic, the stationary phasor means just as the Direct Current(DC) component. This is why after dq transformation; a low pass filter is used so that the resultant waveform constitutes only the 50 Hz component. Note that, when one rotates in positive direction, positive sequence of the corresponding waveform will be stationary and one rotates in negative direction, negative sequence of the corresponding waveform will be stationary.

Low pass filter should be carefully design especially for the close frequency harmonic extraction. For example, 95 Hz, 100 Hz and 105 Hz components are desired frequencies apart from fundamental, 50 Hz frequency. If the selected reference frame is 200π rad/sec or 100 Hz, the corresponding component frequencies will be 5 Hz (negative direction), 0 Hz and 5 Hz (positive direction). Therefore, the low-pass filter cut-off frequency is highly important. If a cut-off frequency 5 or 10 Hz is selected, then the resultant waveform from the filter would contain a 5 Hz component with the 0 Hz component. This is why 2.5 Hz corner frequency is selected in the paper: in order not to contain close frequency harmonics. The damping ratio is also important since it affects the time to reach steady state conditions. The bode diagram of the low pass filter used throughout the project is given in Fig.2.

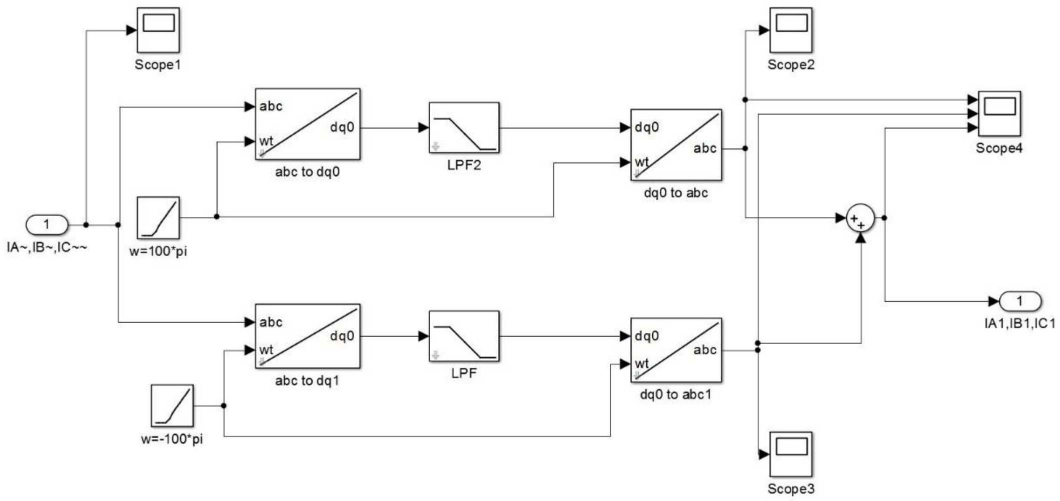

Figure 1: Blog Diagram of the Synchronously Rotating Reference Frame Analysis for 50 Hz

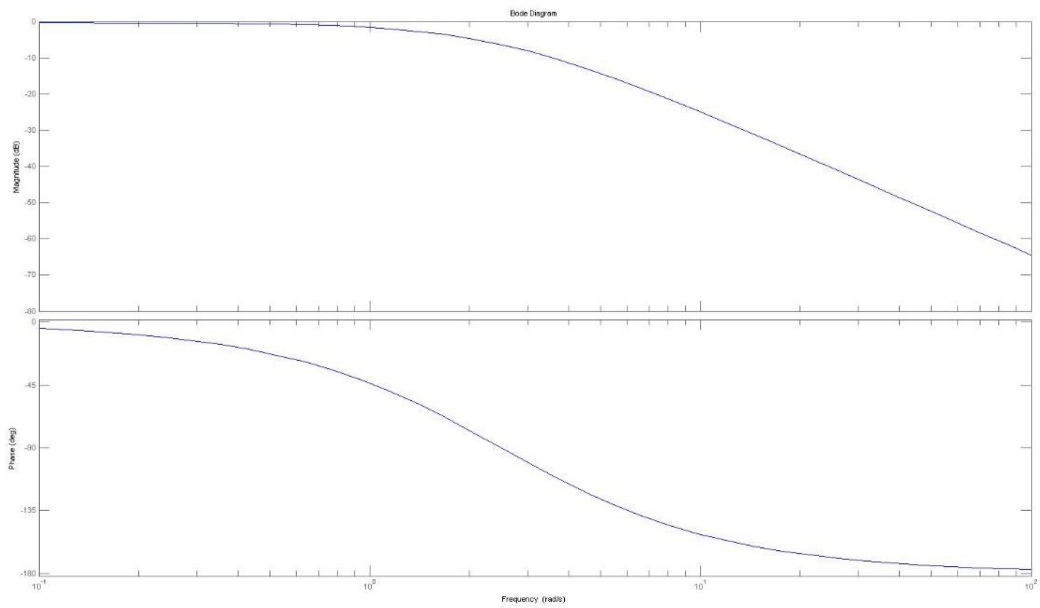

Figure 2:Second Order low-pass filter bode plots for magnitude and phase

Before any transformation, initial current waveforms are given in the Fig.3. This data is digitized with 25.6 kS/s/channel. Their means are subtracted by themselves and the transformation explained above is applied. Actually, since they are composed of pure AC waveforms, their mean will be zero which means there is no need to apply mean operation in this project. However, in the field applications, current waveforms may have a DC offset.

These applications definitely require mean subtraction The resulting positive, negative sequence currents and their summation are displayed in Fig.4 for the fundamental frequency 50 Hz.

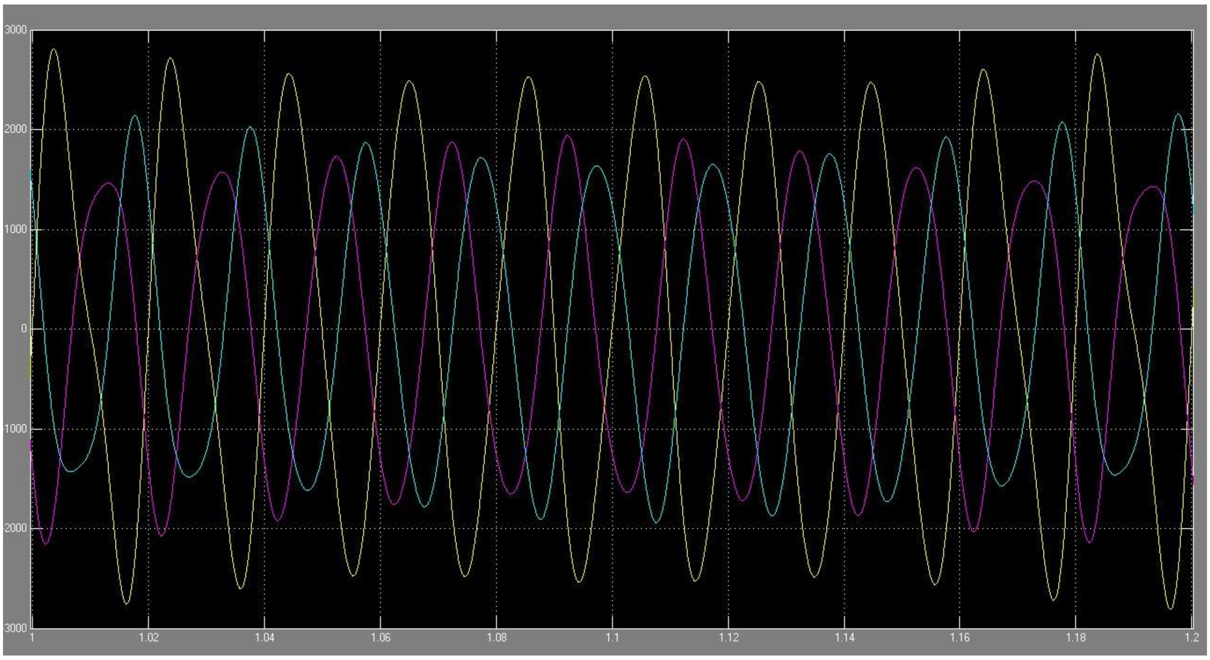

Figure 3: Initial Current Waveforms (Phase A,B and C are displayed with yellow, purple and blue respectively)

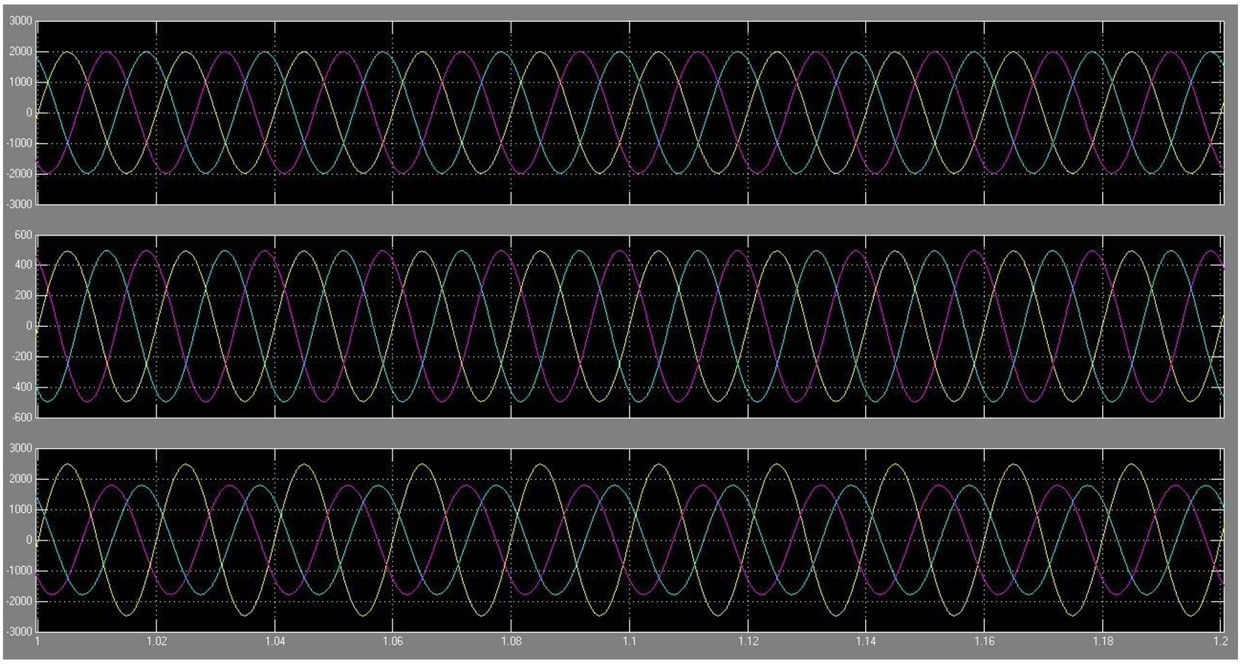

Figure 4: Fundamental, 50 Hz component of the phase currents A, B and C

Note that positive and negative sequence currents are displayed 120 degrees apart from each other and they are equal in magnitudes. However, their summation, 50 Hz component of the currents are neither equally apart from each other nor equal in magnitudes. This is because the waveforms are unbalanced.[2]When these currents are subtracted from the initial currents with no DC components, resulting waveform will have only the harmonics. The harmonic content of the currents is given in Fig.5.

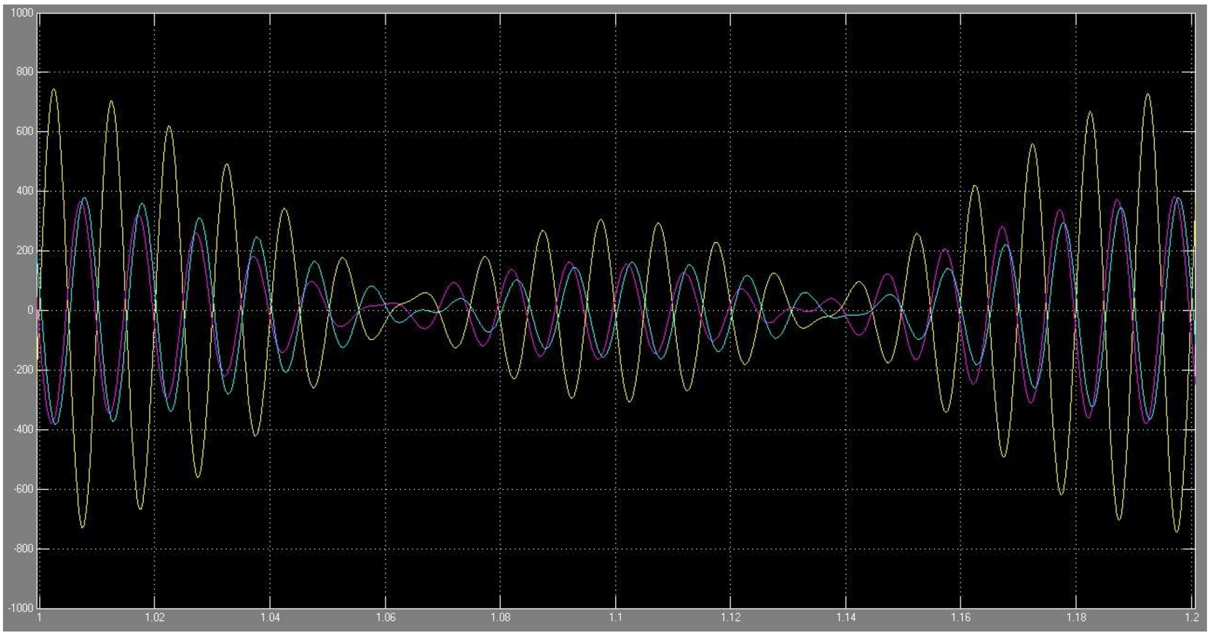

Figure 5: Harmonic Content of the Current Waveform

Now this harmonic composed waveform will be decomposed to its harmonics. This above used procedure will be applied to this current waveform. However, dq transformation will be in the reference frame which rotates at the harmonic waveform angular frequency i.e. 190π for 95 Hz. After inverse transformation (dq-to-abc), positive, negative sequence currents and their summation are achieved and resulting waveforms are given in Fig.6, 7, and 8.

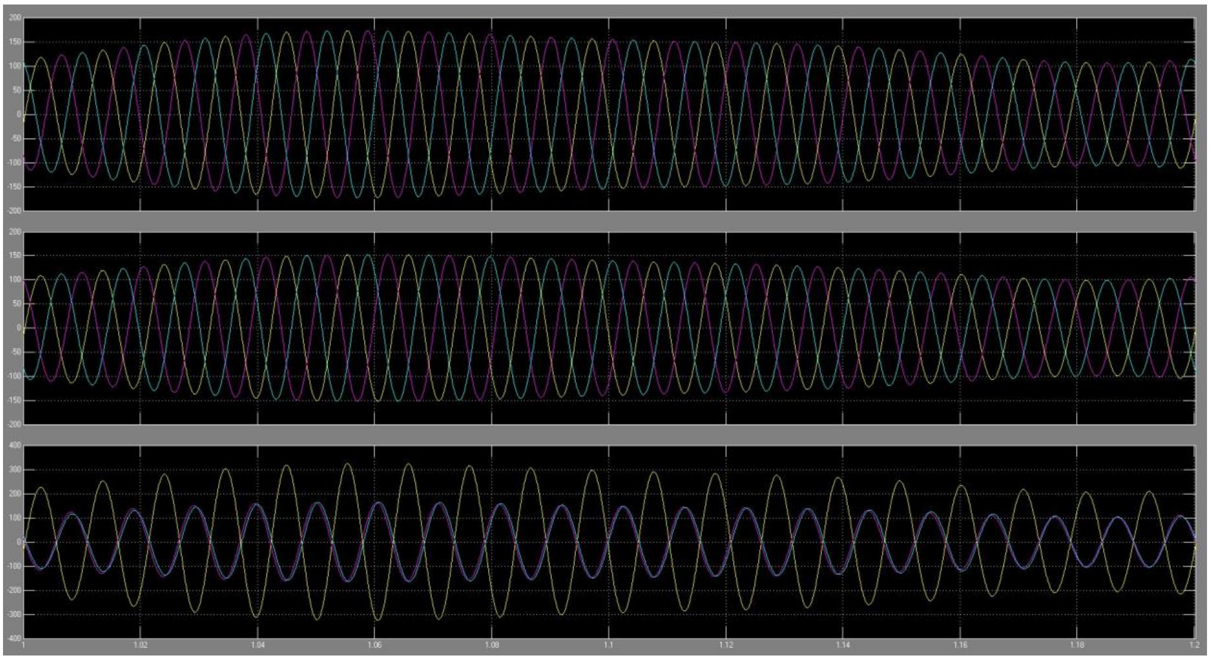

Figure 6: 95 Hz harmonic of the current waveforms (positive sequence currents on the top, negative sequence in the middle and phase currents are on the below)

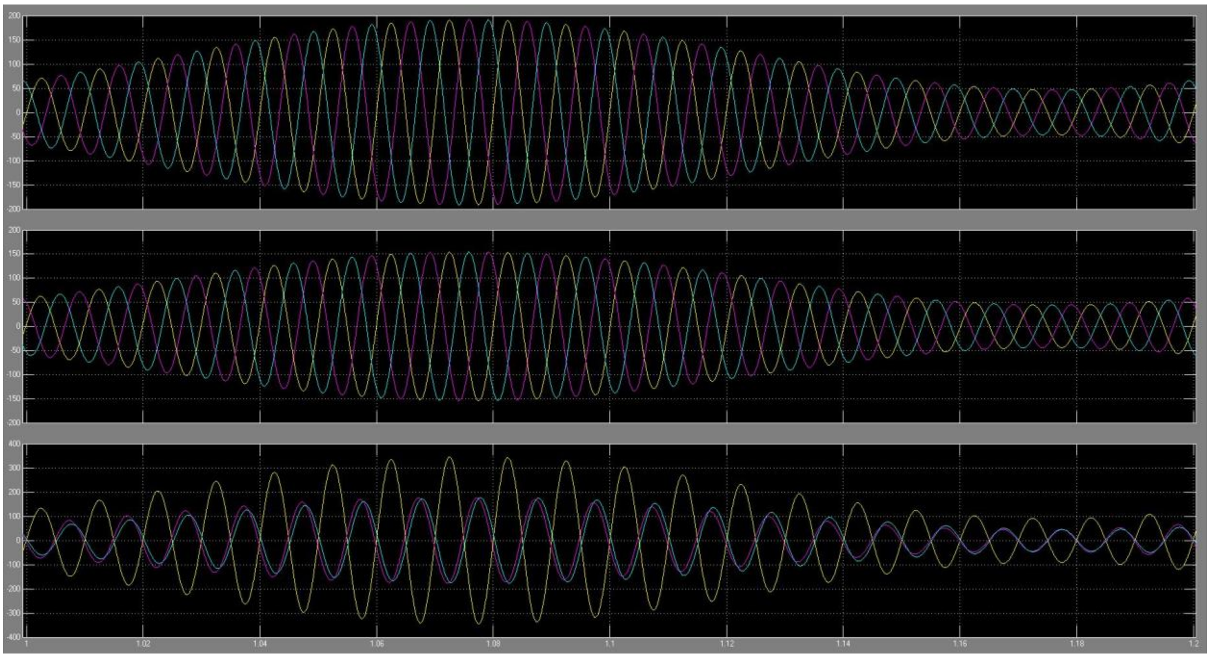

Figure 7: 100 Hz harmonic of the current waveform(positive sequence currents on the top, negative sequence in the middle and phase currents are on the below)

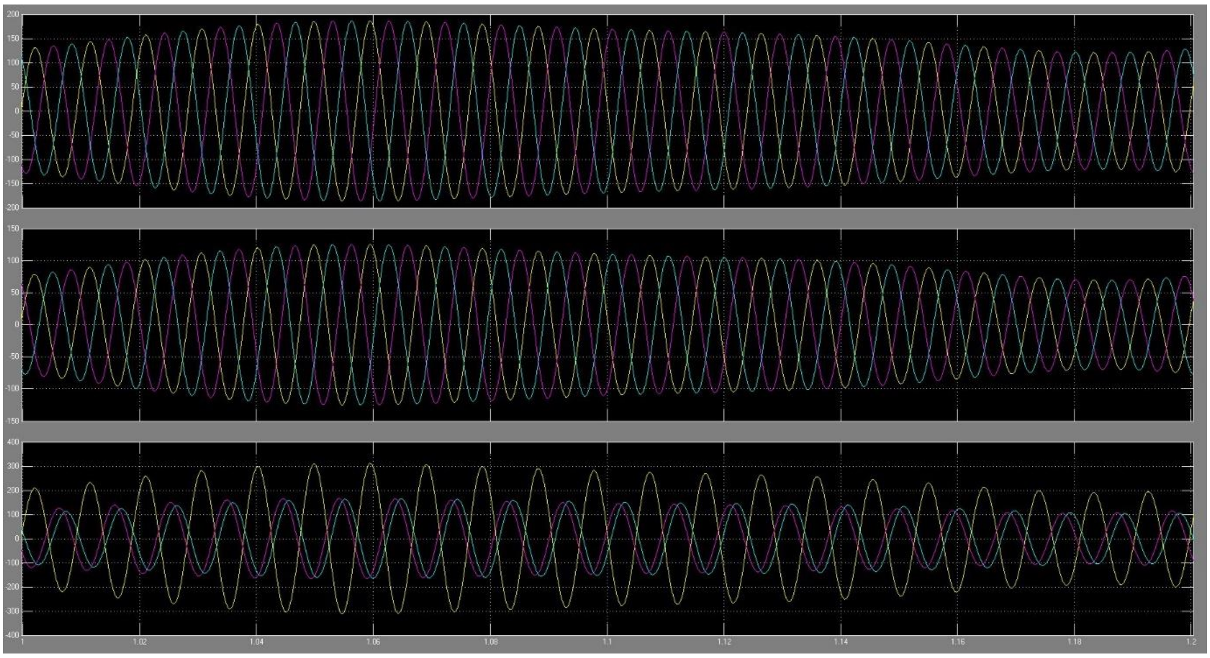

Figure 8:105 Hz harmonic of the current waveform(positive sequence currents on the top, negative sequence in the middle and phase currents are on the below)

Part B- Analytical Solution Technique

For each harmonic content, we can calculate the symmetrical current components.

- For 50 Hz current components, following procedure can be followed:

$$I_0 = \frac{1}{3}(I_A + I_B + I_C)$$

$I_A = \sqrt{2}\,1750 sin100\pi t$

$I_B = \sqrt{2}\,1261.9\sin(100\pi t - 0.7439\pi)$

$I_C = \sqrt{2}\,1261.9\sin(100\pi t + 0.7439\pi)$

$$I_0 = \frac{1}{3}[\sqrt{2}\,1750 sin100\pi t + \sqrt{2}\,1261.9\sin(100\pi t - 0.7439\pi) + \sqrt{2}\,1261.9\sin(100\pi t + 0.7439\pi)]$$

$$I_0 = \frac{1}{3}[\sqrt{2}\,1750\sin(100\pi t) + 2\sqrt{2}\,1261.9\sin(100\pi t) * \cos(0.7439\pi)\,]$$

$$I_0 = \frac{1}{3}\sin(100\pi t)[\sqrt{2}\,1750 + 2\sqrt{2}\,1261.9 * \cos(0.7439\pi)]$$

$$I_0 = \frac{1}{3} * (-0.1)\sin(100\pi t) = -0.033\sin(100\pi t) \text{ A} \approx 0$$

$$I_+ = \frac{1}{3}(I_A + I_B a + I_C a^2)$$

$$I_+ = \frac{1}{3}[\sqrt{2}\,1750\,\sin(100\pi t) + \sqrt{2}\,1261.9\sin(100\pi t - 0.7439\pi + 0.667\pi) + \sqrt{2}\,1261.9\sin(100\pi t + 0.7439\pi - 0.667\pi)]$$

$$I_+ = \frac{1}{3}[\sqrt{2}\,1750\,\sin(100\pi t) + 2\sqrt{2}\,1261.9\sin(100\pi t) * \cos(0.0772\pi)\,]$$

$$I_+ = \frac{1}{3}\sin(100\pi t)[\sqrt{2}\,1750 + 2\sqrt{2}\,1261.9 * \cos(0.0772\pi)]$$

I_+=1979.87 $\sin(100\pi t)$A

$$I_- = \frac{1}{3}(I_A + I_B a^2 + I_C a)$$

$$I_- = \frac{1}{3}[\sqrt{2}\,1750 sin 100\pi t + \sqrt{2}\,1261.9\sin(100\pi t - 0.7439\pi - 0.667\pi) + \sqrt{2}\,1261.9\sin(100\pi t + 0.7439\pi + 0.667\pi)]$$

$$I_- = \frac{1}{3}[\sqrt{2}\,1750\sin(100\pi t) + 2\sqrt{2}\,1261.9\sin(100\pi t) * \cos(1.4106\pi)\,]$$

$I_- = \frac{1}{3}\sin(100\pi t)[\sqrt{2}\,1750 + 2\sqrt{2}\,1261.9 * \cos(1.4106\pi)]$=495.187 $\sin(100\pi t)$ A

- For 95 Hz current components, same procedure can be followed:

$$I_0 = \frac{1}{3}(I_A + I_B + I_C)$$

$I_A = \sqrt{2}\,190\ sin 190\pi t$

$I_B = \sqrt{2}\,95.4\sin(190\pi t - 0.9711\pi)$

$I_C = \sqrt{2}\,95.4\sin(190\pi t + 0.9711\pi)$

$$I_0 = \frac{1}{3}[\sqrt{2}\,190 sin 190\pi t + \sqrt{2}\,95.4\sin(190\pi t - 0.9711\pi) + \sqrt{2}\,95.4\sin(190\pi + 0.9711\pi)]$$

$$I_0 = \frac{1}{3}[\sqrt{2}\,190\sin(190\pi t) + 2\sqrt{2}\,95.4\sin(190\pi t) * \cos(0.9711\pi)\,]$$

$$I_0 = \frac{1}{3}\sin(190\pi t)[\sqrt{2}\,190 + 2\sqrt{2}\,95.4 * \cos(0.9711\pi)]$$

$I_0 = \frac{1}{3} * (-0.02) = \ -0.0066$ A ≈ 0

$$I_+ = \frac{1}{3}(I_A + I_B a + I_C a^2)$$

$$I_+ = \tfrac{1}{3}[\sqrt{2}\,190 sin190\pi t + \sqrt{2}\,95.4 \sin(190\pi t - 0.9711\pi + 0.667\pi) + \sqrt{2}\,95.4 \sin(190\pi + 0.9711\pi - 0.667\pi)]$$

$$I_+ = \tfrac{1}{3}[\sqrt{2}\,190\sin(190\pi t) + 2\sqrt{2}\,95.4 \sin(190\pi t) * \cos(0.3044\pi)\,]$$

$$I_+ = \tfrac{1}{3}\sin(190\pi t)[\sqrt{2}\,190 + 2\sqrt{2}\,95.4 * \cos(0.3044\pi)]$$

$$I_+ = \frac{1}{3} * (424.27)\sin(190\pi t) = \ 141.42 \sin(190\pi t) A$$

$$I_- = \frac{1}{3}(I_A + I_B a^2 + I_C a)$$

$$I_- = \tfrac{1}{3}[\sqrt{2}\,190 sin190\pi t + \sqrt{2}\,95.4 \sin(190\pi t - 0.9711\pi - 0.667\pi) + \sqrt{2}\,95.4 \sin(190\pi + 0.9711\pi + 0.667\pi)]$$

$$I_- = \tfrac{1}{3}[\sqrt{2}\,190\sin(190\pi t) + 2\sqrt{2}\,95.4 \sin(190\pi t) * \cos(1.6378\pi)\,]$$

$$I_- = \tfrac{1}{3}\sin(190\pi t)[\sqrt{2}\,190 + 2\sqrt{2}\,95.4 * \cos(1.6378\pi)]$$

$$I_- = \frac{1}{3} * (381.9) = \ 127.3A$$

- For 100 Hz current components, same procedure can be followed:

$$I_0 = \frac{1}{3}(I_A + I_B + I_C)$$

$I_A = \sqrt{2}\,154\ sin200\pi t$

$I_B = \sqrt{2}\,77.95 \sin(200\pi t - 0.9503\pi)$

$I_C = \sqrt{2}\,77.95 \sin(200\pi t + 0.9503\pi)$

$$I_0 = \tfrac{1}{3}[\sqrt{2}\,154\ sin200\pi t + \sqrt{2}\,77.95 \sin(200\pi t - 0.9503\pi) + \sqrt{2}\,77.95 \sin(200\pi + 0.9503\pi)]$$

$$I_0 = \tfrac{1}{3}[\sqrt{2}\,154 \sin(200\pi t) + 2\sqrt{2}\,77.95 \sin(200\pi t) * \cos(0.9503\pi)\,]$$

$$I_0 = \tfrac{1}{3}\sin(200\pi t)[\sqrt{2}\,190 + 2\sqrt{2}\,95.4 * \cos(0.9503\pi)]$$

$$I_0 = \tfrac{1}{3} * (-0.005) = \ -0.00166 \text{ A} \approx 0$$

$$I_+ = \frac{1}{3}(I_A + I_B a + I_C a^2)$$

$$I_+ = \frac{1}{3}[\sqrt{2}\ 154\sin(200\pi t) + \sqrt{2}\ 77.95\sin(200\pi t - 0.9503\pi + 0.667\pi) + \sqrt{2}\ 77.95\sin(200\pi + 0.9503\pi - 0.667\pi)]$$

$$I_+ = \frac{1}{3}[\sqrt{2}\ 154\sin(200\pi t) + 2\sqrt{2}\ 77.95\sin(200\pi t) * \cos(0.2836\pi)\ ]$$

$$I_+ = \frac{1}{3}\sin(200\pi t)[\sqrt{2}\ 154 + 2\sqrt{2}\ 77.95 * \cos(0.2836\pi)]$$

$$I_+ = \frac{1}{3} * (356.4)\sin(200\pi t) = \ 118.8\sin(200\pi t)A$$

$$I_- = \frac{1}{3}(I_A + I_B a^2 + I_C a)$$

$$I_- = \frac{1}{3}[\sqrt{2}\ 154\sin(200\pi t) + \sqrt{2}\ 77.95\sin(200\pi t - 0.9503\pi - 0.667\pi) + \sqrt{2}\ 77.95\sin(200\pi + 0.9503\pi + 0.667\pi)]$$

$$I_- = \frac{1}{3}[\sqrt{2}\ 154\sin(200\pi t) + 2\sqrt{2}\ 77.95\sin(200\pi t) * \cos(1.6378\pi)\ ]$$

$$I_- = \frac{1}{3}\sin(200\pi t)[\sqrt{2}\ 154 + 2\sqrt{2}\ 77.95 * \cos(1.6378\pi)]$$

$$I_- = \frac{1}{3} * (297.015) = \ 99.005\sin(200\pi t)A$$

- Finally, for 105 Hz current components, again the same procedure can be followed:

$$I_0 = \frac{1}{3}(I_A + I_B + I_C)$$

$I_A = \sqrt{2}\ 180\ sin210\pi t$

$I_B = \sqrt{2}\ 96.4\sin(210\pi t - 0.883\pi)$

$I_C = \sqrt{2}\ 96.4\sin(210\pi t + 0.883\pi)$

$$I_0 = \frac{1}{3}[\sqrt{2}\ 180 sin210\pi t + \sqrt{2}\ 96.4\sin(210\pi t - 0.883\pi) + \sqrt{2}\ 96.4\sin(210\pi + 0.883\pi)]$$

$$I_0 = \frac{1}{3}[\sqrt{2}\ 180\sin(210\pi t) + 2\sqrt{2}\ 96.4\sin(210\pi t) * \cos(0.883\pi)\ ]$$

$$I_0 = \frac{1}{3}\sin(210\pi t)[\sqrt{2}\ 180 + 2\sqrt{2}\ 96.4 * \cos(0.883\pi)]$$

$$I_0 = \frac{1}{3} * (0.11) = \ 0.0368\ \text{A} \approx 0$$

$$I_+ = \frac{1}{3}(I_A + I_B a + I_C a^2)$$

$$I_+ = \frac{1}{3}[\sqrt{2}\ 180\sin(210\pi t) + \sqrt{2}\ 96.4\sin(210\pi t - 0.833\pi + 0.667\pi) + \sqrt{2}\ 96.4\sin(210\pi + 0.833\pi - 0.667\pi)]$$

$$I_+ = \frac{1}{3}[\sqrt{2}\ 180\sin(210\pi t) + 2\sqrt{2}\ 96.4\sin(210\pi t) * \cos(0.1663\pi)\ ]$$

$$I_+ = \frac{1}{3}\sin(210\pi t)[\sqrt{2}\ 180 + 2\sqrt{2}\ 96.4 * \cos(0.1663\pi)]$$

$$I_+ = \frac{1}{3} * (466.65)\sin(210\pi t) = \ 155.55\sin(210\pi t)A$$

$$I_- = \frac{1}{3}(I_A + I_B a^2 + I_C a)$$

$$I_- = \frac{1}{3}[\sqrt{2}\ 180\ \sin(210\pi t) + \sqrt{2}\ 96.4\sin(210\pi t - 0.883\pi - 0.667\pi) + \sqrt{2}\ 96.4\sin(210\pi + 0.883\pi + 0.667\pi)]$$

$$I_- = \frac{1}{3}[\sqrt{2}\ 180\sin(210\pi t) + 2\sqrt{2}\ 96.4\sin(210\pi t) * \cos(1.6378\pi)\ ]$$

$$I_- = \frac{1}{3}\sin(210\pi t)[\sqrt{2}\ 180 + 2\sqrt{2}\ 96.4 * \cos(1.6378\pi)]$$

$$I_- = \frac{1}{3} * (296.958) = \ 98.986\sin(210\pi t)A$$

Note that symmetrical component analysis helps us to decompose the unbalanced three phase system to positive, negative and zero sequence currents. Ones these currents are obtained; three phase currents can be calculated as follows. [3]

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

Figure 9: Symmetrical Component Relations with Three Phase Currents

Part C- Discrete Fourier Transformation Analysis

In this part, the sequence currents of the given data will be found by using Fourier Transformation. Discrete Fourier Transformation gives the phase and magnitude of the specified frequency included in the current waveform. In general, Fourier Analysis gives the magnitude of the harmonics existing in a signal. If one specifies the harmonic frequency, corresponding frequency and the phase of that frequency component can be obtained.

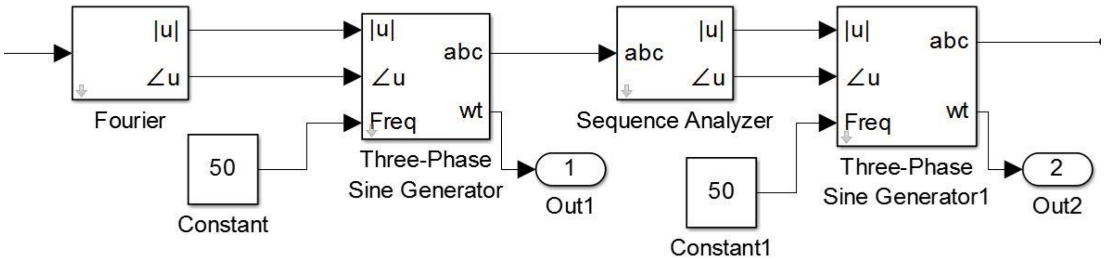

Figure 10: Blog Diagram of the Discrete Fourier Transformation Analysis

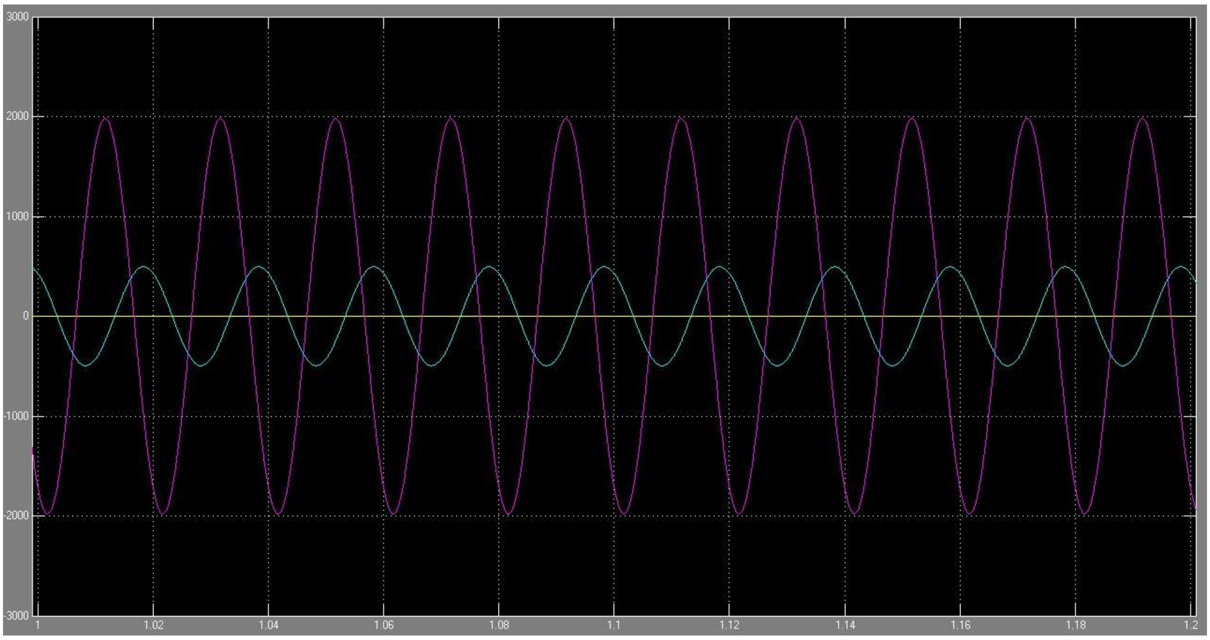

Figure 11: 50 Hz Sequence Currents(Purple:Positive Seq,Blue:Negative Seq.Yello: ZeroSeq)

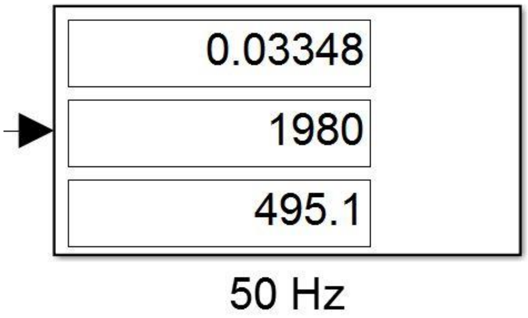

Figure 12: 50 Hz Sequence Current Magnitudes

For, 50 Hz; RMS values for sequence currents are 1400A for positive sequence current and 350.1A for negative sequence current. Zero sequence current is found as 0.02369A.

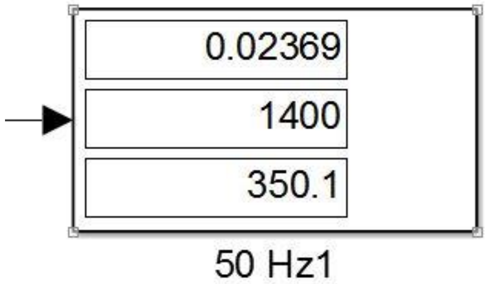

Figure 13: RMS values for sequence currents calculated for 50 Hz

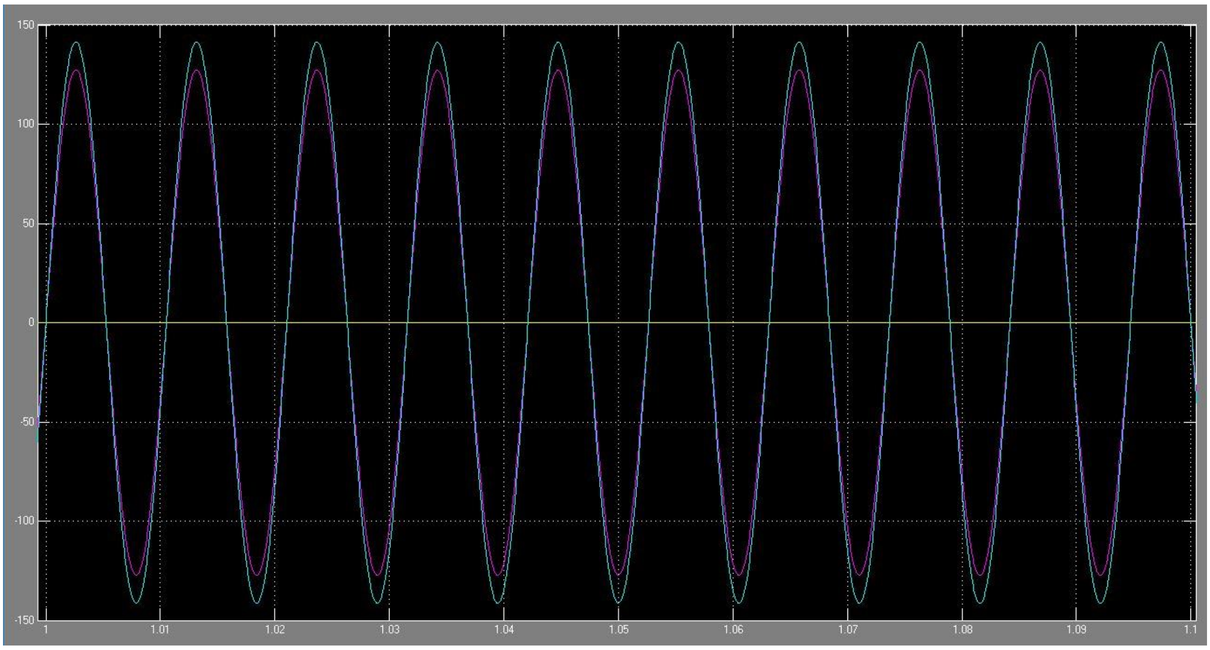

Figure 14: 95 Hz Sequence Currents

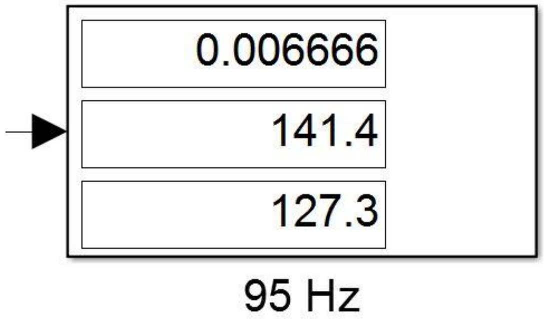

Figure 15: 95 Hz Sequence Current Magnitudes

For, 95 Hz; RMS values for sequence currents are 100A for positive sequence current and 90.01A for negative sequence current. Zero sequence current is found as 0.004717A.

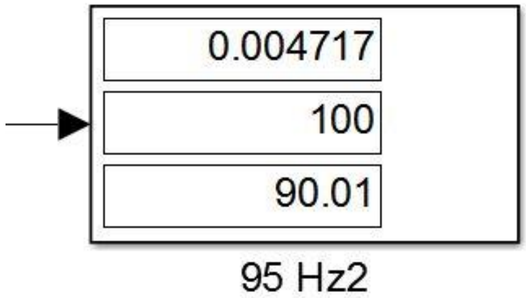

Figure 16: RMS values for sequence currents calculated for 95 Hz

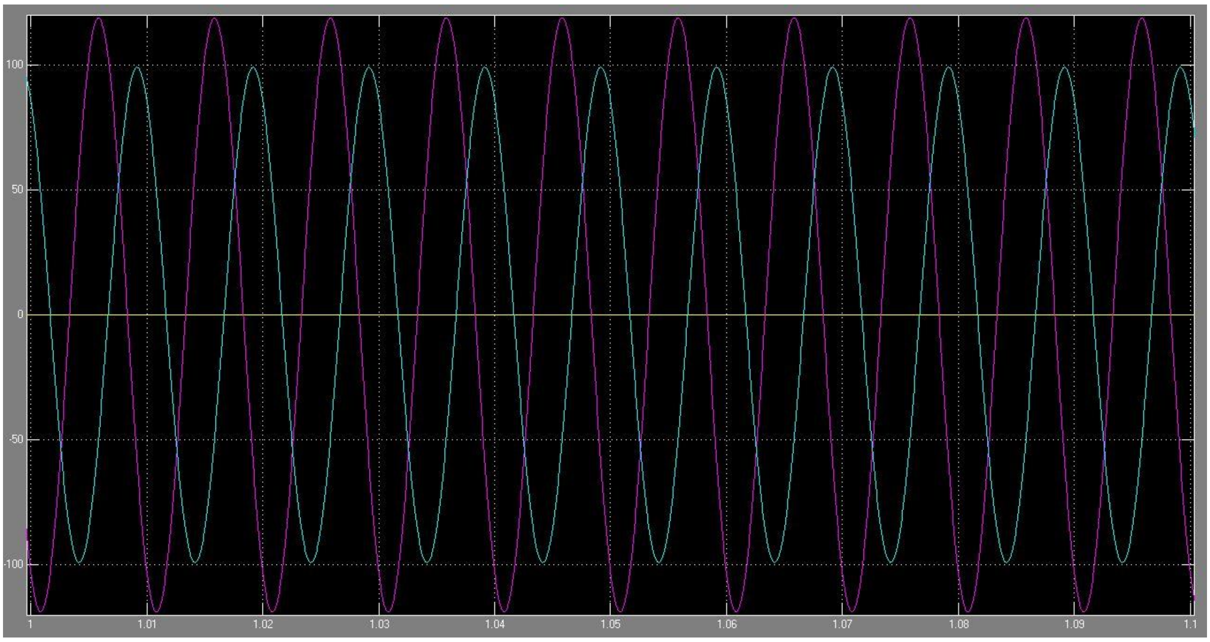

Figure 17: 100 Hz Sequence Currents

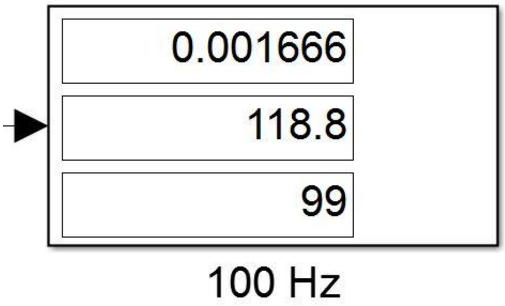

Figure 18: 100 Hz Sequence Current Magnitudes

For, 100 Hz; RMS values for sequence currents are 84A for positive sequence current and 70A for negative sequence current. Zero sequence current is found as 0.001187A.

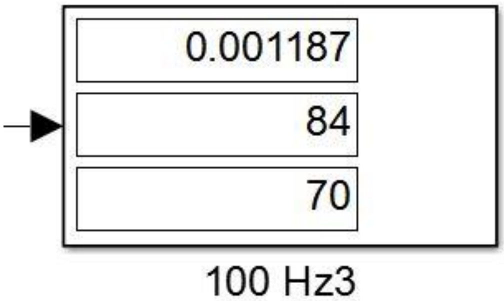

Figure 19: RMS values for sequence currents calculated for 100 Hz

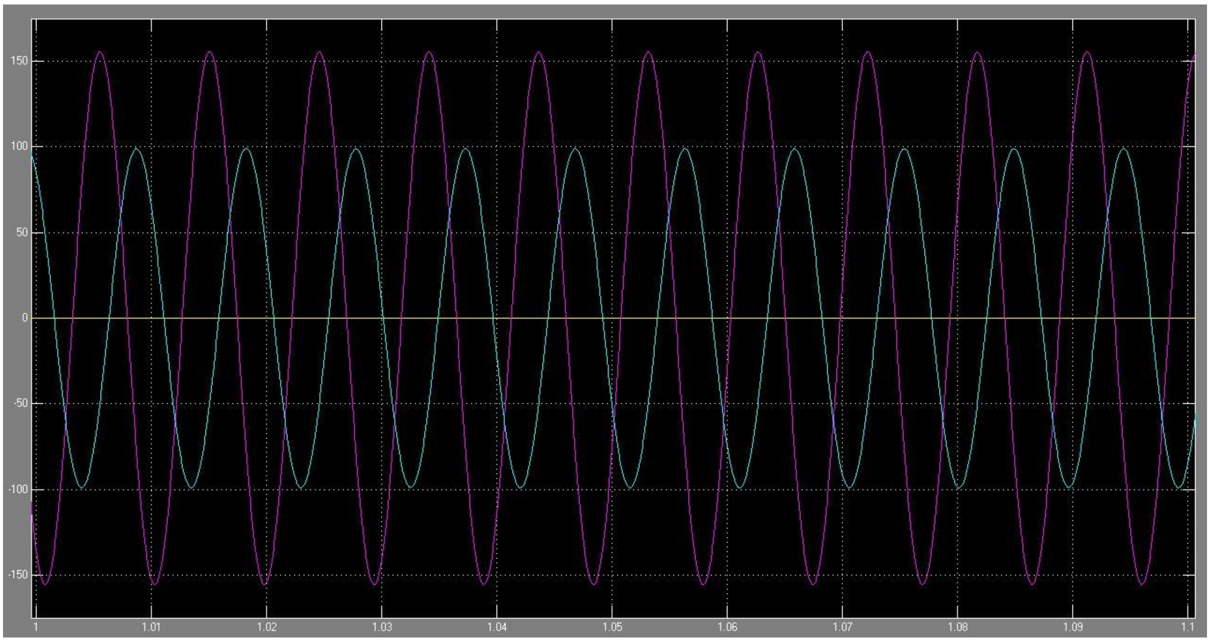

Figure 20: 105 Hz Sequence Currents

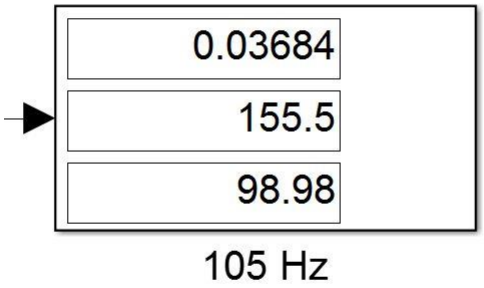

Figure 21: 105 Hz Sequence Current Magnitudes

For, 105 Hz; RMS values for sequence currents are 110A for positive sequence current and 69.99A for negative sequence current. Zero sequence current is found as 0.02605A.

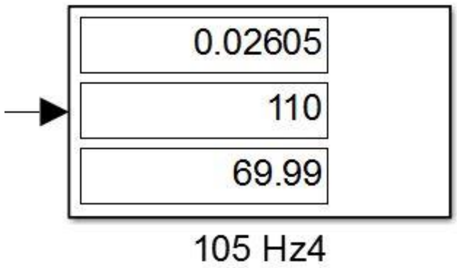

Figure 22: RMS values for sequence currents calculated for 105 Hz

Part D-Conclusion and Comments

In this project, a given current data is analysed in terms of harmonic content. In this first part, the harmonic content is obtained by using Synchronously Rotating Reference Frame Analysis. Since the abc-to-dq transformation is achieved by a reference frame, selection of the reference frame speed enables the decomposition of the required harmonic content. If one chooses the reference frame rotating speed same as the required harmonic rotational speed, then the corresponding dq components of the harmonic content will be stationary. Then, a low pass filter is used to filter out the harmonic content by choosing the corner frequency as low as possible. Since the harmonic content frequencies are close to each other, the filter design requires special attention. For example, choosing a corner frequency as 5 Hz would results an inclusion of the neighbouring harmonics. This is why in the filter 2.5 Hz corner frequency is selected. Moreover, the filter damping ratio is also important in terms of the time to reach steady state.

In the second part of the project, the analytical solution procedure is followed. By using symmetrical component properties, one can calculate the positive, negative and zero sequence current components for the three phase network. It is found that zero sequence components are almost zero. This part also verifies that why the zero sequence components are not considered in part a.

In the part c, the sequence currents are found by using Discrete Fourier Transformation Analysis. The found results are exactly equal to the results found in part b. Actually, this is because the used methods give the exact and true results. Note that results found by Synchronously Rotating Reference Frame Analysis very close to the results found by part-b and part c. These are actually expected results since the good correlation between results of part-a and part-c has already been verified in the literature. However, it is should be noted that even though the FFT analysis gives the most accurate result, SRRF analysis gives very accurate results for instantaneous magnitudes of harmonic and interharmonic components of some special applications since SRRF results uses 1-sec averaged rms values of cycle-by-cycle computed rms values where FFT results uses 1-sec averaged rms values of moving 10-cycle data windows.[1]

Bibliography

[1] E. Uz-Logoglu, O. Salor, and M. Ermis, “Online Characterization of Interharmonics and Harmonics of AC Electric Arc Furnaces by Multiple Synchronous Reference Frame Analysis,” *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2673–2683, 2016.

[2] G. Atkinson-Hope, “Relationship between harmonics and symmetrical components,” *Int. J. Electr. Eng. Educ.*, vol. 41, no. 2.

[3] A. Amberg, A. Rangel, and S. E. Laboratories, “Tutorial on Symmetrical Components,” *Selinc.Cachefly.Net*, no. 1, pp. 1–6.

The SIMULINK file created for this project and the digital form of this report can be achieved from:

https://github.com/ErencanDuymaz/Dersler/