Government of the Northwest Territories

Microgrid Stability with Intermittent Renewables

Renewable Energy Penetration Analysis



CIMA+ Project Number: S13291A
2021-06-10 – Revision 3

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3	JFV	2021-06-10	Revised following latest comments

Ownership and confidentiality

Executive Summary

CIMA+ has been mandated by the Government of the Northwest Territories (GNWT) to perform a renewable energy penetration analysis on the electrical distribution systems of Fort Liard, Fort Simpson, Tulita, Łutselk'e and Inuvik. The goal of this study is to determine the maximum penetration of renewable energies that would be suitable for the five communities and extend the conclusions of this analysis to all communities of the Northwest Territories (NWT). It should be noted that in the past, an original recommendation of 20% was provided. However, this recommendation was more of a starting point and was mainly based on the Inuvik gas generators capability. No in-depth studies were completed to validate the actual limit. This study uses a rigorous scientific approach to refine the original recommendation of 20% and determine the new maximum limit.

Throughout this analysis, the worst-case scenario was used as the base case. When results were considered to be too unrealistic, more reasonable assumptions were used to yield realistic but conservative results.

The first phase of this analysis consists in evaluating the steady state impacts when increasing the renewable energy penetration. A load flow study is completed to evaluate the reactive power requirements of the communities, and a harmonic analysis is carried out to evaluate the impact of adding renewable energy systems on the overall community power quality.

The second phase of the analysis aims at validating the dynamic responses of the existing systems when connecting and disconnecting renewable energy systems. The generators response and overall grid stability is evaluated in such situations. It should be noted that the analysis confirmed that a 75% renewable energy penetration would not be possible without an energy storage system, since the minimum annual load of the communities is between 46% and 60% of their average annual load, which is used as a reference for calculating the renewable energy penetration. It should also be noted that this limit is obtained by considering that any type of renewable could be used (such as PV, wind turbines or hydro), whereas the most probable case would be PV. By using PV, the grid stability limit can be pushed to 75% (as shown in section 8 of this report) since the minimum load happens during the night while the PV is not generating any power.

The results of this analysis showed that all evaluated criteria provided similar maximum renewable energy penetration limits. The analysis also showed that when it comes to power quality, the size of the existing power demand will have an impact on the renewable energy penetration limit. The following table provides a summary of the results. Based on the technical aspect of the results, an overall 45% renewable energy penetration limit is recommended. It should be noted that this does not take into account the financial aspect, which is evaluated further down in the analysis.

Communities	Renewable Energy Penetration Results			
	Reactive Power	Power Quality	Grid Stability	Recommended Overall Limit
Fort Liard	55 %	75 %	53%	50 %
Tulita	55 %	50 %	48%	45 %
Łutselk'e	55 %	75 %	46%	45 %
Fort Simpson	55 %	50 %	60%	50 %
Inuvik	55 %	50 %	59%	50 %

Table 1: Recommended Renewable Energy Penetration Limit

Finally, an evaluation of the production losses for the utility was performed. This showed that at the maximum recommended limit of 50% penetration (results are similar for 45% penetration), the annual revenue losses due to PV integration would be in the range of 3%. A visual representation of the percentage of annual revenue loss in function of the penetration level for each community is shown on the next figure.

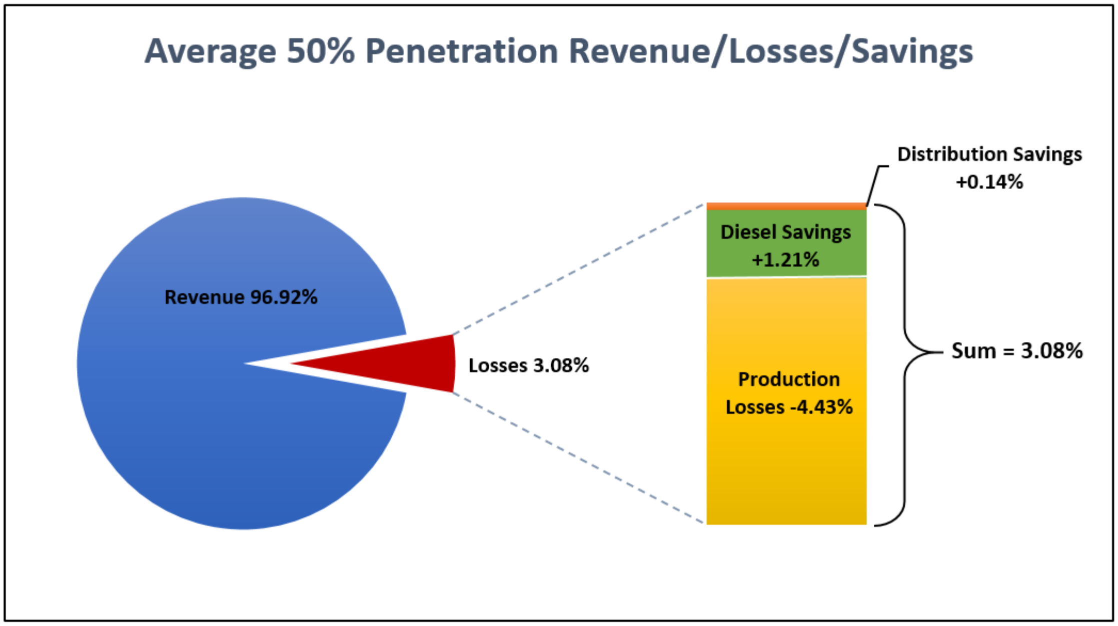

Figure 1: Expected Revenue Losses

Following the technical feasibility, a second analysis was performed to evaluate multiple options that could improve the limit to 75%. At this point, it is expected that these solutions will either require some control of each individual systems, or the addition of a battery energy storage system (BESS) to compensate for the added generation which could create technical problems with the generators in place during specific time periods throughout the year. Power quality issues could also be overcome with the addition of filters on the network. The detailed evaluation of required filters could be evaluated in a subsequent phase of the project.

The details of adding a BESS to allow for a higher RE penetration level were evaluated in this second analysis. It was also noted that when integrating a BESS, a microgrid controller is also necessary to insure proper interconnection with the existing grid, and efficient management of the battery's charge/discharge cycles. An analysis of the different types of microgrid controllers was completed to evaluate which options could be worth integrating in each community. The results showed that although this option would be technically viable, the financials do not allow for any return on investment if the renewable energy systems is owned by the customers. In that scenario, customers would benefit from the electricity production, therefore reducing their electricity bill, while the utility would be paying to store the excess energy produced by their clients. This problem could however be addressed by having the utility own and operate a centralized renewable energy system. This could then make the BESS addition financially viable.

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1. Introduction

CIMA+ has been mandated by the Government of the Northwest Territories (GNWT) to perform a renewable energy penetration analysis on the electrical distribution systems of Fort Liard, Fort Simpson, Tulita, Łutselk'e and Inuvik. The goal of this study is to determine the maximum penetration of renewable energies that would be suitable for the five communities and extend the conclusions of this analysis to all communities of the Northwest Territories (NWT).

The first phase of this analysis consisted in evaluating the steady state impacts of increasing the renewable energy penetration. In order to do so, each of the five (5) communities distribution systems were modeled in the Easypower software, version 10.2.0.108, to perform both a load flow analysis and a harmonic analysis. The load flow was completed to evaluate the reactive power requirements of the communities, while the harmonic analysis was carried out to evaluate the impact of adding renewable energy systems on the overall community power quality.

The second phase of the analysis aimed at validating the dynamic responses of the existing systems when connecting and disconnecting renewable energy systems. This was performed by creating a simplified dynamic model using Simulink (Matlab) to evaluate the dynamic response of the generators when coupled with intermittent renewable energy.

Finally, the production losses were evaluated in terms of distribution losses as well as revenue losses for the utility.

2. Inputs and Assumptions

This analysis is based on the five (5) communities listed above, but it aims at providing a guideline for all communities. With that in mind, the following assumptions were used.

- The generators and transformers data were based on the single line diagrams of the communities which can be found in Appendix A. When information was missing from the SLDs, a worst-case scenario approach was used instead.
- The distributions lines length were approximated using the CAD drawings received from GNWT and Google Earth images. As for the lines sizing, it was provided by GNWT.
- The renewable energy systems were simulated using photovoltaic (PV) inverter systems. It is important to note that this assumption is also valid for other renewable energy systems such as wind turbines, hydrokinetic devices or any other system that would use DC/AC converters, since their impact on the grid is similar.
- The distribution of the load along the grid was based on the 2019 community load files and the information available on the CAD drawings.
- Since only the active power (kW) were available for the generation and load, a power factor (PF) of 0.95 was used for each load. This is a typical worst-case scenario approach for residential and commercial systems.
- The auxiliary services of each power plants were calculated with the difference between the total generated power and the total consumed power from all feeders.
- The renewable energy penetration calculation was done using the average annual load.

+ Using a worst-case scenario approach, the renewable energy sources harmonics were considered to be equal to the maximum allowable values accepted by standard IEEE 1547-2018.
+ The renewable energy systems were modeled right next to the load as shown in the Easypower model which can be found in Appendix B. Six % of penetration were simulated in this study.
  - 0 %
  - 20 %
  - 25 %
  - 30 %
  - 50 %
  - 75 %.
+ Using a worst-case scenario approach, the renewable energy sources power factor was considered to be fixed and non controllable and was set to 1.
+ Even though all generators were modeled for all communities, only the smallest generator that could provide energy for the average annual load was used in the model to have a better representation of the reality/worst case. However, in the case of Inuvik, 3 scenarios were performed using G11, G3 or G10. The worst-case scenario is presented in the results for Inuvik.
+ Inuvik's gas generators were not considered in this study. Similar results are expected except in the economical analysis where results could vary. However, such variations are expected to be close to negligeable. It is also considered that in a scenario where the load would be too low for the gas generator to perform properly, the energy production would be switched to the diesel generators.
+ The cost of electricity was determined from the rates provided by GNWT for each community. An average rate from the general service, residential, governmental and non governmental rates was created based on the historical sales of previous years.

3. Renewable Energy Modeling

3.1 System Modeling

When performing a steady state analysis, the elements of the electrical network provided as inputs by the client were modelized in the software Easypower 10.2. The elements modelized are for example the generators, the cables/lines, transformers, loads and renewable energy sources. When performing a steady state analysis, it allows the user to know the magnitude and the angle of the voltage and current at every location of the network. Therefore, the power factor, the harmonics magnitude and the losses in all the system can be extracted. Harmonics are a sinusoidal wave whose frequency is an integer multiple of the fundamental frequency (60 Hz). Having too much of these can cause damages or equipment malfunction throughout the network, which is why they are analysed in the section 5 of this report.

Concerning the dynamic study (section 6), the analysis is performed on Simulink (Matlab). The reason is that this software allows the user to see the voltages and currents at various timestamps. For example, the user can see in real time what happens on the network when a breaker opens, when load shedding occurs, when a new source is connected to the grid etc.

For the BESS sizing, the software PVSyst was used. This is a software that can be used for the study, sizing and data analysis of complete PV systems. It was possible to model a typical PV system and get the output power over the course of a year and compare it to the annual load file received as input to study the potential use of a BESS system.

In order to represent a realistic case of renewable energy integration by the community members, the modelling of the renewable energy was done considering that the renewable resources would be evenly distributed throughout the network. The distribution of the resources was based on each transformer on the distribution system whereas each transformer was coupled with a renewable energy resource with an equivalent ratio. As an example, a 50kVA transformer representing 1% of the total distribution transformer power, was coupled with 1% of the renewable energy resources. The same logic was used to model the loads so that they be distributed proportionally on the distribution system.

3.2 Study Limitations

This study was completed using multiple assumptions that are required to be used when planning for the integration of future systems. Assumptions being based off existing systems in each community, and existing equipment available on the market, results will slightly differ from what will be available once more integration of renewable energies is done, as the technology will have evolved, and the electrical network of each community will likely have changed.

Having a planned electrical distribution network configuration for the near/mid future could have provided more accurate results. However, the assumptions used in this study should be closed to the reality and having been provided with such input would likely not have changed the outcome of this study, unless major changes are expected in the evaluated communities.

As for future technology, it is expected that new technologies will provide better capacity and easier integration on the network. However, it is expected that not all customers would go with newer systems and that old technologies possibly being cheaper will still be used. Therefore, using the existing technology at this point in time should be close to what would likely be installed in the future.

4. Reactive Power Analysis

4.1 Methodology

The reactive power analysis is performed with a load flow study which aims at validating the capacity of the existing diesel generators to provide the required reactive power. Because the renewable energy sources are considered fixed at a power factor of 1, the diesel generators will be the only source of reactive power. Based on typical diesel generators characteristics, such as those presented in the Caterpillar Operation and Maintenance Manual [4], a 0.8 PF limit has to be respected in order to ensure the good operation of the generator.

4.2 Results

Since the results are similar for all communities and the different generators in the same community, the average results are presented below for conciseness. The table provides detailed results of the expected power factor required from the diesel generators for each scenario.

Communities	Renewable Energy Penetration					
	0 %	20 %	25 %	30 %	50 %	75 %
Fort Liard	0,94	0,92	0,91	0,90	0,83	0,61
Tulita	0,95	0,92	0,91	0,90	0,84	0,61
Łutselk'e	0,95	0,92	0,91	0,90	0,83	0,61
Fort Simpson	0,95	0,92	0,91	0,90	0,84	0,61
Inuvik	0,94	0,92	0,91	0,90	0,83	0,60

Table 2: Communities' Power Factors

Extrapolating from these results, the actual renewable energy penetration limit based on the power factor capacity of the diesel generators [4] is evaluated at 55%. This is where the 0.8 power factor limit is reached.

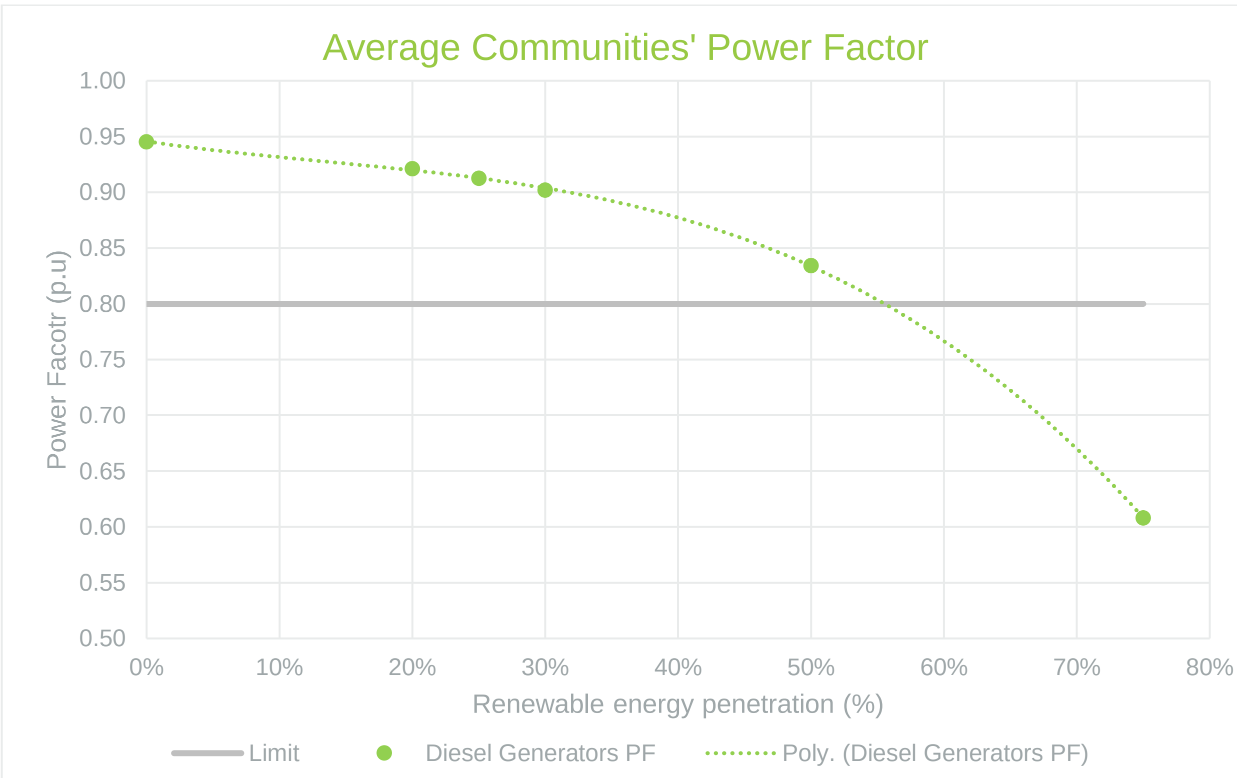


Figure 2: Communities' Power Factors

The detailed results for all communities are available in the sections below. The results include the following results for all renewable energy scenarios evaluated.

Renewable (kW): Total renewable capacity installed

Diesel (kW): Maximum real power provided by the diesel generators

Diesel (kVAR): Maximum reactive power provided by the diesel generators

Diesel (PF): Power factor of the diesel generators

Load (kW): Maximum real power of the distribution system load

Load (kVAR): Maximum reactive power of the distribution system load

4.2.1 Fort Liard

	Renewable Energy Penetration					
	0 %	20 %	25 %	30 %	50 %	75 %
Renewable (kW)	0	49	62	74	123	185
Diesel (kW)	249	199	186	174	124	62
Diesel (kVAR)	87	85	84	84	82	80
Diesel (PF)	**0.94**	**0.92**	**0.91**	**0.90**	**0.83**	**0.61**
Load (kW)	246					
Load (kVAR)	81					
Generator in use	Generator 2 (320 kW)					

Table 3: Fort Liard – Load Flow Results

4.2.2 Tulita

	Renewable Energy Penetration					
	0 %	20 %	25 %	30 %	50 %	75 %
Renewable (kW)	0	58	73	87	146	218
Diesel (kW)	294	235	220	205	146	73
Diesel (kVAR)	99	97	97	97	96	95
Diesel (PF)	**0.95**	**0.92**	**0.91**	**0.90**	**0.84**	**0.61**
Load (kW)	291					
Load (kVAR)	96					
Generator in use	Generator 2 (320 kW)					

Table 4: Tulita – Load Flow Results

4.2.3 Łutselk'e

	Renewable Energy Penetration					
	0 %	**20 %**	**25 %**	**30 %**	**50 %**	**75 %**
Renewable (kW)	0	35	44	53	88	131
Diesel (kW)	177	141	132	123	88	44
Diesel (kVAR)	61	60	59	59	58	58
Diesel (PF)	**0.95**	**0.92**	**0.91**	**0.90**	**0.83**	**0.61**
Load (kW)	175					
Load (kVAR)	58					
Generator in use	Generator 2 (320 kW)					

Table 5: Łutselk'e – Load Flow Results

4.2.4 Fort Simpson

	Renewable Energy Penetration					
	0 %	**20 %**	**25 %**	**30 %**	**50 %**	**75 %**
Renewable (kW)	0	172	215	258	431	646
Diesel (kW)	876	699	655	611	436	218
Diesel (kVAR)	297	292	291	289	286	283
Diesel (PF)	**0.95**	**0.92**	**0.91**	**0.90**	**0.84**	**0.61**
Load (kW)	861					
Load (kVAR)	283					
Generator in use	Generator 3 (1250 kW)					

Table 6: Fort Simpson – Load Flow Results

4.2.5 Inuvik

	Renewable Energy Penetration					
	0 %	**20 %**	**25 %**	**30 %**	**50 %**	**75 %**
Renewable (kW)	0	656	820	983	1639	2459
Diesel (kW)	3344	2665	2497	2328	1658	828
Diesel (kVAR)	1188	1150	1142	1134	1110	1093
Diesel (PF)	**0.94**	**0.92**	**0.91**	**0.90**	**0.83**	**0.60**
Load (kW)	3278					
Load (kVAR)	1077					
Generator in use	Multiple Gen	Generator 3 (2500 kW)		Generator 11 (2100 kW)		

Table 7: Inuvik – Load Flow Results

5. Power Quality Analysis

5.1 Methodology

The power quality analysis is performed with a harmonic which aims at evaluating the impact of adding renewable energy sources on the power quality of the overall community grid. Because no harmonics measurements of the communities were available to use as a base case scenario, the analysis provides the additional harmonics that could be introduced on the grid.

For this analysis a worst-case scenario approach was used. The rationale behind this approach is that RE resources would be owned by clients and would likely be price driven, which often results in equipment with lower power quality. To account for such scenario, the renewable energy sources harmonics were considered to be equal to the maximum allowable values accepted by standard IEEE 1547-2018, which provides power quality requirements for interconnecting distributed energy resources.

In order to evaluate the impact of this addition on the existing system, the results are compared to the limits provided by IEEE 519-2014. As per IEEE 519-2014, the voltage distortion limits are defined in the table below.

Bus Voltage at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Table 8: IEEE 519-2014 – Voltage Distorsion Limits

In order to determine the current distortion limits for each scenario of each communities, a short-circuit evaluation was performed. Based on the ratio between the available short-circuit and the load, the limits were defined from the table below. As stated in IEEE 519-2014, the even harmonics should be limited to 25% of the odd harmonic limits.

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (odd harmonics)						
ISC/IL	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h < 50	TDD
< 20	4	2	1.5	0.6	0.3	5
20 < 50	7	3.5	2.5	1	0.5	8
50 < 100	10	4.5	4	1.5	0.7	12
100 < 1000	12	5.5	5	2	1	15
> 1000	15	7	6	2.5	1.4	20

Table 9: IEEE 519-2014 – Current Distortion Limits for Systems Rated 120 V Through 69 kV

5.2 Results

The results of the analysis show that the four (4) smaller communities have similar results, while Inuvik results show that a higher renewable energy penetration will provide worst power quality results. However, the results for Inuvik showed that the worst-case scenario approach yielded some unrealistic results.

In order to get more realistic results, the summation law as described in the IEC 61000 standard was used to validate the case of 50% renewable energy penetration for Inuvik. This calculation methodology takes into account that not all harmonic sources will be perfectly combined and therefore, the following equation can be used to evaluate their combined contribution.

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}}$$

Where α is defined in the following table.

Harmonic Order	α
h < 5	1
5 ≤ h ≤ 10	1.4
h > 10	2

Table 10: Summation Exponents for Harmonics

The figures below provide a resume of the THD results for all communities and the results for the summation law approach for Inuvik.

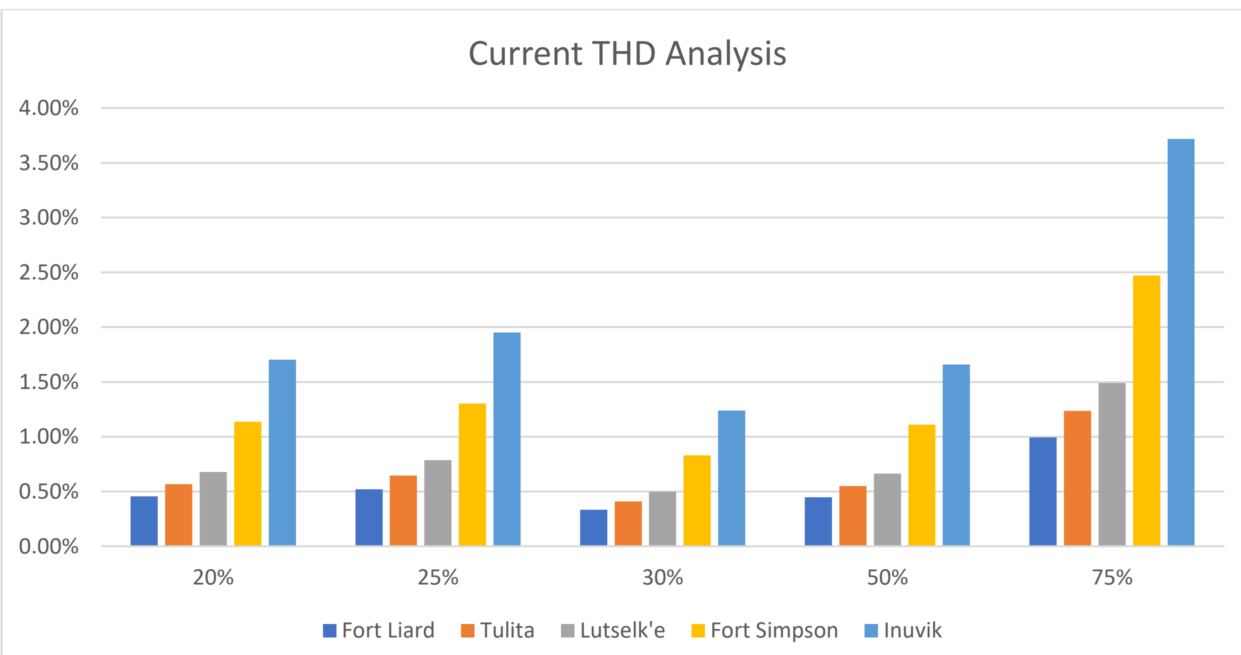


Figure 3: Current THD Results

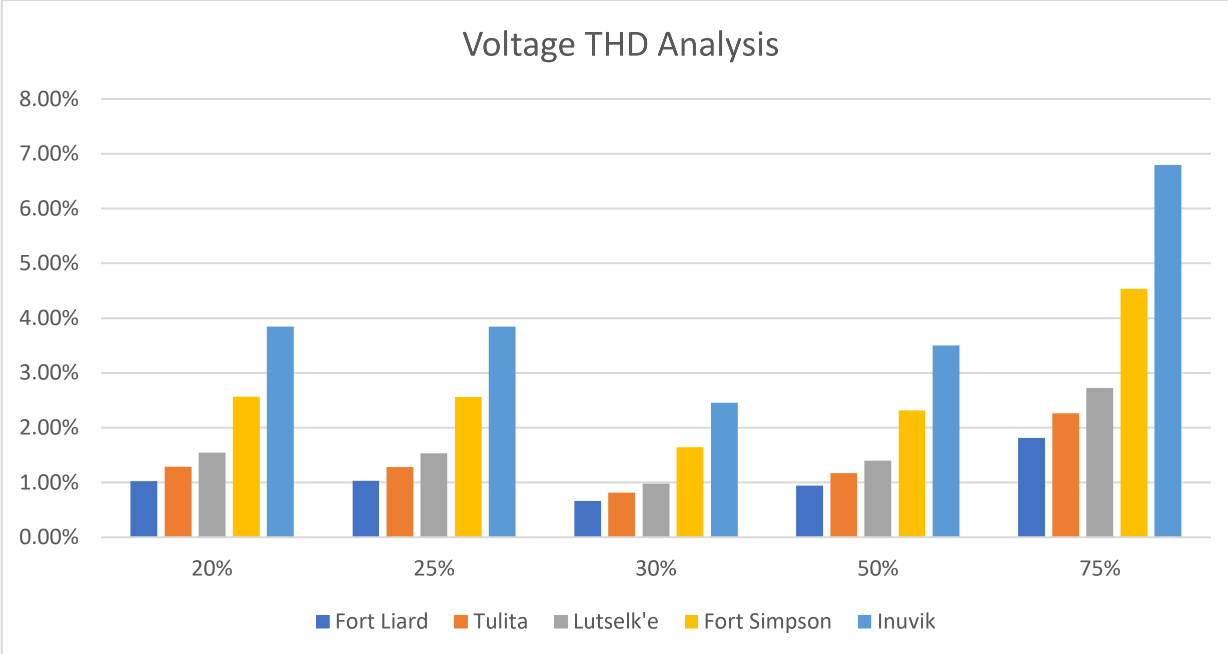


Figure 4: Voltage THD Results

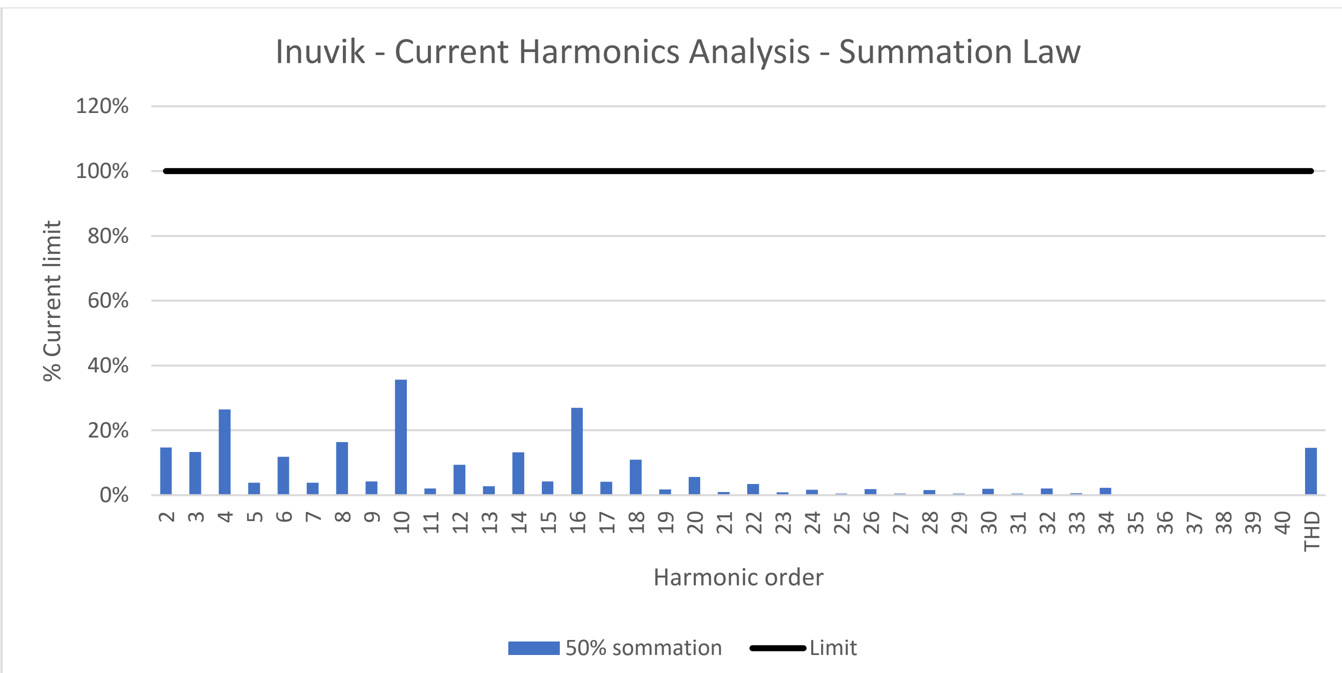


Figure 5: Current Harmonic Distortion Results – Summation Law – Inuvik with G11

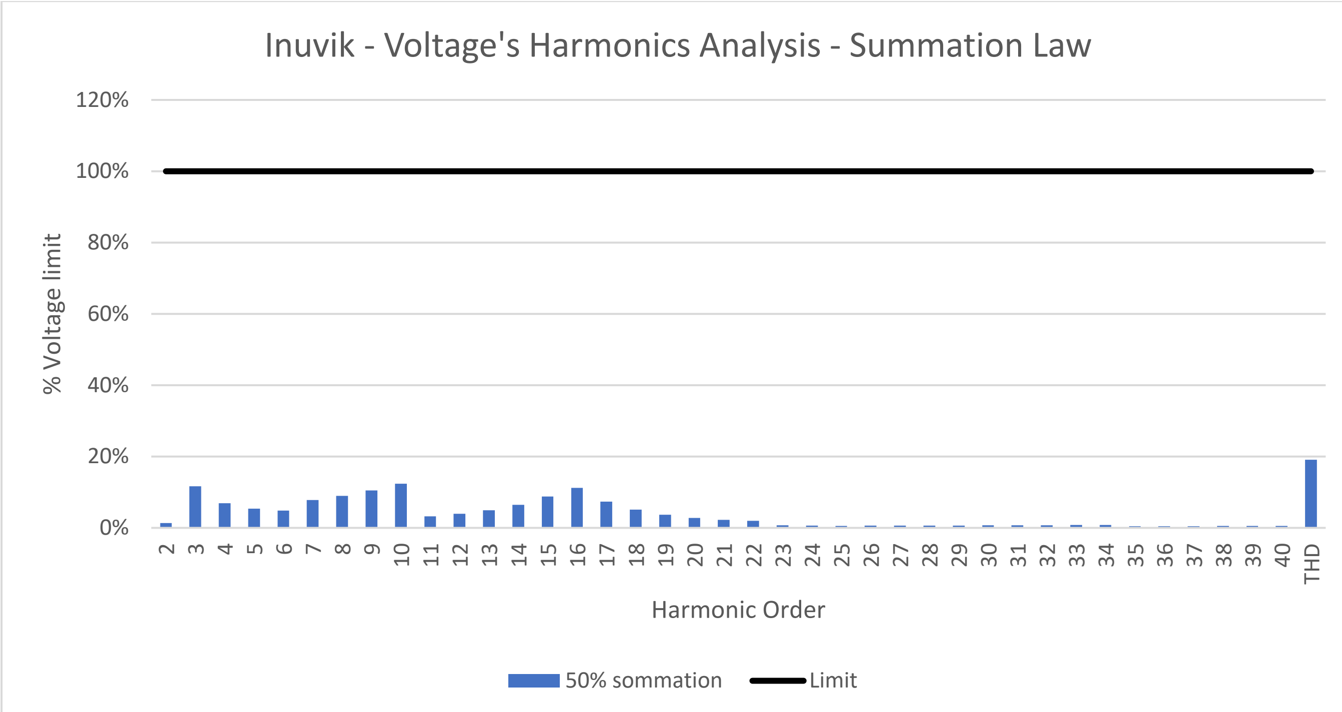


Figure 6: Voltage Harmonic Distortion Results – Summation Law – Inuvik with G11

For the purpose of this analysis, it is evaluated that a ratio of 50% of the IEEE 519-2014 limit would be an acceptable target for renewable energy. This would leave the remaining 50% for the existing systems. Considering a 50% ratio, the expected renewable energy penetration limit based on the harmonic analysis would be evaluated between 50% and 75%. Moreover, the summation law's more realistic approach confirmed that a 50% penetration should have limited impacts on the power quality of the existing systems.

The detailed results of the worst-case scenario approach are presented in Appendix D. The figures present the percentage (%) of added harmonics on the existing grid in relation to the IEEE 519-2014 limit. It should however be noted that the results are based on a worst-case scenario approach.

6. Grid Stability Analysis (Dynamic Study)

6.1 Methodology

The grid stability analysis is performed with a dynamic study which aims at validating the stability of the existing grid to ensure that any sudden variations in the existing loads, or in the future renewable energy sources will not affect the customers. In order to validate the dynamic response in realistic and worst case operational scenarios, the following cases were evaluated.

+ Load increase from minimum to maximum summer load with renewable energy connected
+ Load decrease from maximum to minimum summer load with renewable energy connected
+ Renewable energy sources instantaneous connection with the average annual load
+ Renewable energy sources instantaneous disconnection with the average annual load

6.2 Results

The detailed results of the grid stability analysis are presented in Appendix E. These results show that the existing grid could support up to 45% of renewable energy penetration without grid stability concerns for the customers. The dynamic responses of the grid in such situations, as seen by the customers, is well within the acceptable limits defined by the IEEE 1547-2018 standard, with voltage variations of 30% for less than 5 cycles.

It should be noted that this analysis confirmed that a 75% renewable energy penetration would not be possible without an energy storage system, since the minimum annual load of the communities is between 46% and 60% of their average annual load, which is used as a reference for calculating the renewable energy penetration.

Communities	Minimum Annual Load (kW)	Average Annual Load (kW)	Ratio (%)
Fort Liard	130	246	53%
Tulita	140	291	48%
Lutselk'e	80	175	46%
Fort Simpson	520	861	60%
Inuvik	1950	3278	59%

Table 11: Minimum Annual Loads

It should be noted that these limits are obtained by considering that any type of renewable could be used (such as PV, wind turbines or hydro), whereas the most probable case would be PV. By using PV, this limit is pushed to 75% (as explained in section 8) since the minimum load happens during the night and the PV are not generating during this time.

7. Losses Analysis

7.1 Methodology

The integration of DER (distributed energy resources) to a distribution network will have an impact on the overall losses of the grid. The goal of this analysis is to evaluate the losses reduction in the distribution system compared to losses without renewable energy sources.

In order to have a model that represents reality as accurately as possible, the DER are located closer to the loads in comparison to the substation. An example of this situation would be if each client had solar panels right on their roof. Due to the proximity between the generation and the load, the instantaneous losses will be reduced, because the generated electricity will not have to go through the distribution network to reach the loads. If the renewable generation was located in a single point of the distribution system, this effect would not be observed since the generated electricity would still need to go through the distribution network to reach the loads.

In addition to the instantaneous losses, a calculation was performed to evaluate the annual losses in revenue for the utility considering the energy produced locally by the DER. Following discussions with GNWT, the DER were all considered to be PV, as this is what is expected to be installed. With that in mind, a simulation of the energy generated by a solar system of 100 kW for each community was produced with a complex software named PV syst. The generated energy of each scenario was determined proportionally with the Renewable Energy Penetration installed. This annual production was then compared with the annual production data received. Calculations were performed to evaluate roughly the efficiency of the diesel generator to determine the diesel saved yearly. Finally, with inputs of diesel cost for the last 5 years and the NTPC cost of electricity, revenue losses were determined for each community based on the renewable energy penetration.

7.2 Results

The detailed results of the losses analysis are presented in Appendix F. The table below provides the expected total losses for a period of 1 year in MWh for each community at different renewable energy penetration levels. The total losses are calculated with the following:

$$\sum Total.Losses_{RE=x\%} = Prod.Losses_{RE=x\%} - Dist.Savings_{RE=x\%}$$

Where,

Prod. Losses = Revenue losses due to energy generated by the renewable energy systems

Dist. Savings = Losses reduction in the distribution system in comparison to the scenario where no renewable energy is used.

	Renewable Energy Penetration (%)					
	0 %	20 %	25 %	30 %	50 %	75 %
Fort Liard	0	34	43	51	85	128
Tulita	0	39	48	58	96	145
Lutselk'e	0	26	32	38	64	96
Fort Simpson	0	123	153	184	307	461
Inuvik	0	427	534	641	1069	1607

Table 12: Total Losses (MWh)

Based on the results in the above table, and the electricity rates provided by the GNWT, revenue losses were calculated. The table below provides detail results for each community.

$$\sum Revenue\ Losses_{RE=x\%} = \left(\sum Losses\ (kWh)_{RE=x\%} \times Electricity\ Rate\ (\frac{\$}{kWh})\right) - Diesel\ Savings_{RE=x\%}$$

Where, Diesel Savings = Estimated savings ($) in diesel usage due to lower energy production requirement. Diesel savings are evaluated from reduction in energy production defined in Table 12 and from typical generator consumption data.

	Renewable Energy Penetration (%)					
	0%	20 %	25 %	30 %	50 %	75 %
Fort Liard	0	19	23	28	47	71
Tulita	0	24	30	36	61	92
Lutselk'e	0	16	20	24	40	61
Fort Simpson	0	79	99	119	199	299
Inuvik	0	226	282	338	560	837

Table 13: Total Revenue Losses (k$)

Using the results presented in the table above, the expected revenue losses were compared to the evaluated yearly revenues for each community. Evaluated yearly revenues are based on the provided detailed rates and consumptions. The detailed results are presented in the table and figure below and calculated with the following.

$$Revenue\ Losses\ (\%) = \frac{\sum Revenue\ Losses_{RE=x\%}}{Expected\ Annual\ Revenues}$$

	Estimated Annual Revenues
Fort Liard	1 558 k$
Tulita	1 646 k$
Lutselk'e	1 032 k$
Fort Simpson	5 312 k$
Inuvik	18 275 k$

Table 14: Estimated Annual Revenues (k$)

	Renewable Energy Penetration (%)					
	0%	20 %	25 %	30 %	50 %	75 %
Fort Liard	0%	1.2%	1.5%	1.8%	3.0%	4.5%
Tulita	0%	1.2%	1.5%	1.7%	2.9%	4.4%
Lutselk'e	0%	1.2%	1.5%	1.8%	3.1%	4.6%
Fort Simpson	0%	1.3%	1.6%	2.0%	3.3%	5.0%
Inuvik	0%	1.2%	1.6%	1.9%	3.1%	4.6%

Table 15: Revenue Losses (%)

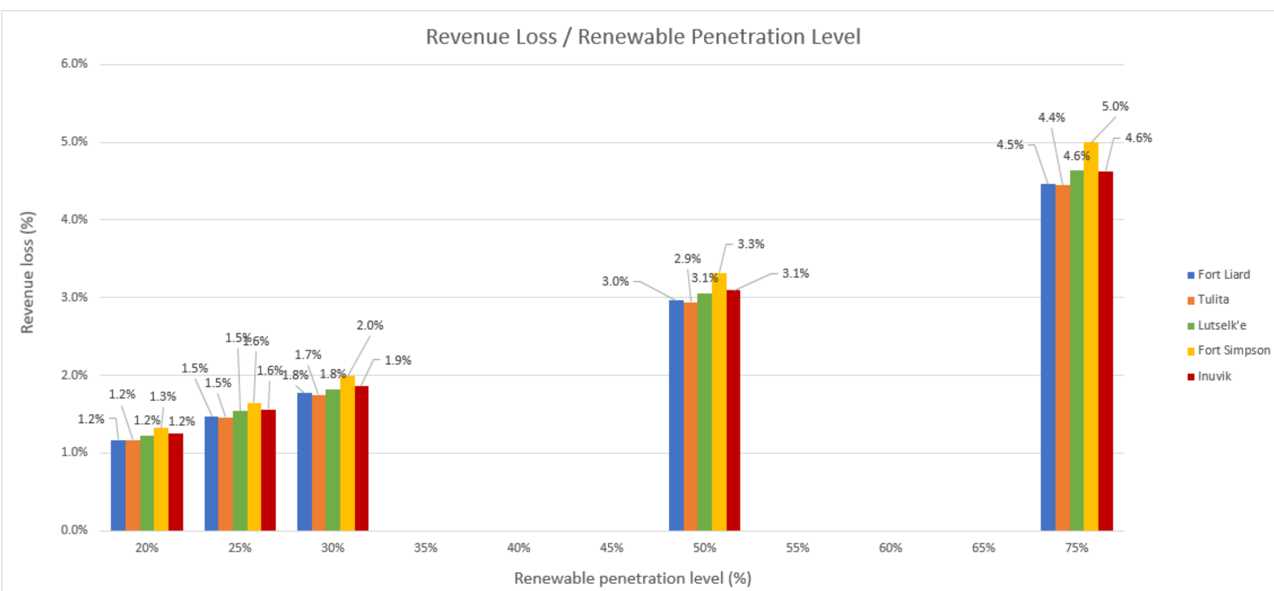


Figure 7: Revenue Losses/Renewable Penetration Level

This comparison showed an approximate reduction of 3.1% in revenues for a 50% renewable energy penetration. The figure below shows a graphical representation of the percentage of Revenue Losses/Savings in comparison to the expected revenues without renewable energy sources.

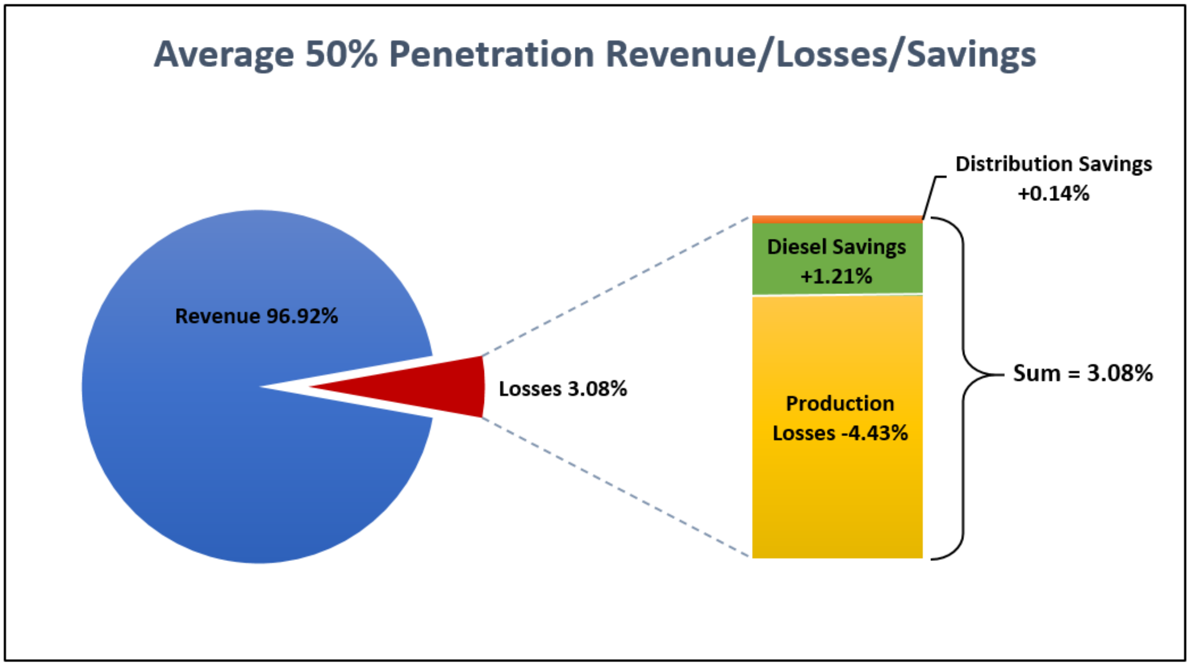


Figure 8: Average 50% Penetration - Revenue/Losses/Savings

8. Options to Increase Renewable Energy Integration

8.1 BESS System

In order to integrate more renewable energy in each community, a centralized BESS system could be implemented. This would remove the limiting factors related to reactive power and grid stability, as the battery would be able to provide the required reactive power when necessary, and absorb the extra power generated by the renewable energy sources in cases of low loads from the community. To evaluate the best BESS sizing for each community, an analysis was performed based on multiple technical factors to determine the minimum sizing.

8.1.1 Grid Stability Improvement

In order to ensure a grid stability where the renewable energy generation will never exceed the community's load, BESS could be used to store the extra energy produced. For this example, PV generation was used to determine at which penetration level a BESS becomes required, and an analysis of other penetration level was completed to determine minimal BESS sizing. It should be noted that using a centralized BESS at levels under the minimum RE penetration calculated would only improve the diesel generators efficiency as no extra energy generated by the RE would be used to charge the BESS. Therefore, BESS sizing was evaluated for RE penetration above the minimum calculated.

Because PV is used for this analysis, the results differ from the ones presented in the grid stability analysis. This is due to minimum loads occurring at night, while no PV generation is available.

Communities	Minimal RE Penetration	Minimal BESS Sizing (kWh)			
		75%	85%	100%	125%
Fort Liard	77%	0	75	350	650
Tulita	75%	25	125	500	750
Łutselk'e	78%	0	75	350	650
Fort Simpson	75%	25	300	1500	2000
Inuvik	97%	0	0	100	1250

Table 16: Minimal BESS Sizing

The results above show that all communities have similar result patterns except for Inuvik. A more in-depth analysis determined that this is related to the load profile of Inuvik which differs from the other communities.

8.1.2 BESS Cost Analysis

The addition of a BESS will require a substantial initial investment, and limited maintenance costs over the years. The table below provides estimated pricing for different BESS sizes, as bigger system will have lower $/kWh costs. It should be noted that the following are to be considered when looking at the prices below.

- Prices are based on pricing from manufacturers at the beginning of 2021 and are likely to decrease over time.
- Not all BESS sizing will be available, and it will vary from manufacturer to manufacturer.
- The pricing reflects a premium cost for systems install in Northern communities, which usually cost an estimated 300% more to ship and install, compared to southern cities installation.
- Pricing does not include the engineering to integrate the BESS system to the distribution network.

BESS Sizing	Cost ($/kWh)
< 500 kWh	3 500 $ - 4 500 $
Between 500 kWh and 1 MWh	3 000 $ - 3 500 $
Between 1MWh and 5 MWh	2 500 $ - 3 000 $

Table 17: BESS Estimated Pricing

Based on the pricing above and expected diesel savings from the utility with a centralized BESS, calculations were completed to validate the return on investment for different scenarios. It should be noted that this calculation does not take into account the diesel savings resulting from a more efficient use of the diesel generators with a BESS, which should be neglectable at this stage.

Following detailed calculations, it was determined that there are no valid economic business cases for integrating a centralized BESS for the utility if they do not own the renewable energy systems. The results showed that the return on investment would exceed by a fair margin the life expectancy of the system. To make the BESS addition economically viable, it would be required that the system be coupled with a centralized renewable energy system owned by the utility. This system would need to generate more power than the required loads at peak production so that the extra power production can be stored in the BESS. Therefore, the only benefit for a BESS for each community would be on the technical side to allow for more renewable energy penetration.

8.2 Microgrid Controller

In a scenario where the utility would move forward with the addition of a BESS, a microgrid controller system would be required to properly manage the diesel generators and the BESS. On the market, there are currently multiple options available, with a wide range of functionalities. However, microgrid controller can usually be categorized in three different categories.

1- Basic microgrid controller

a. Will allow automatic connection/disconnection of multiple power sources or loads based on preprogrammed sequences.

b. Will allow the operator to manually connect/disconnect multiple power sources or loads from the user interface.

c. Will provide information on the state of the system (power outputs, breaker status, alarms, …) on the user interface.

d. Might allow the operator to manually preprogram sequences.

e. Normally used for microgrids that only integrates a limited number of RE sources to be controlled with basic connect/disconnect functionalities.

2- Microgrid controller with automatic forecasting and optimisation

a. Will provide all basic microgrid functionalities.

b. Will analyse “live” weather data and/or statistical data to forecast power production and load usage to efficiently manage loads, BESS, diesel generators and RE production. This requires controllable loads, that can be managed in time for better efficiency such as building heating.

c. Will optimise RE, BESS and diesel generator usage to minimize the use of diesel and maximize the use of RE and BESS.

d. Normally used for microgrids that requires a higher level of efficiency.

3- Microgrid controller with complete Distributed Energy Resource Management System (DERMS) functionalities.

a. Will provide all basic microgrid functionalities, as well as forecasting and optimisation functionalities.

b. Will allow the complete integration of extensive amount of DER to be controlled and monitored by the controller.

c. Normally used for microgrids that will integrate more than fifty (50) RE sources (usually a few hundreds) that are required to be monitored and controlled. This is normally the case in larger systems where the utility owns multiple RE systems.

Depending on the type of microgrid controller that is required for each project, prices will vary greatly. In order to estimate costs for a microgrid controller, information from manufacturers and previous known projects were gathered. Because of the nature of a microgrid controller, the microgrid size (in kW or MW) does not play a significant role in pricing. However, the following criteria will impact the pricing, in addition to the difference in functionalities listed above.

- Number of individual systems to be connected.
- Complexity and connection requirements of each individual systems.
- Communication and cybersecurity requirements.

Using the above criteria, microgrid controller costs were estimated and are provided in the table below. It should be noted that the complete DERMS solution cost can widely vary depending on the utility size. However, for this report, the expected cost presented were limited to communities with size similar to NWT's.

Microgrid Controller Type	Cost
Basic	150k$ - 350k$
Forecasting and Optimisation	600k$ - 1M$
Complete DERMS	1.5M$ - 3M$

Table 18: Microgrid Controller Estimated Pricing

Should any of the listed communities move forward with the addition of a BESS, including a centralized renewable energy system or not, integrating the basic microgrid controller would be recommended for smaller communities. However, for bigger communities, the microgrid controller with forecasting and optimisation would likely be economically viable. The reasoning behind this is that having a microgrid controller with forecasting and optimisation will surely allow the utility to save on diesel consumption, most likely in the 2% to 5% range. This would likely be neglectable and yield a return on investment in the range of 15 years for small communities but would save a lot more money in bigger communities. However, the additional cost to implement such system would remain in the same range, which would drastically decrease the return on investment. The table below provides expected return on investment if selecting a microgrid controller with forecasting and optimisation for each community.

Community	Return on Investment Forecasting and Optimisation (years)
Fort Liard	15 – 25
Tulita	10 – 20
Łutselk'e	15 – 25
Fort Simpson	5 – 10
Inuvik	3 – 5

Table 19: Estimated RoI for a Microgrid Controller with Forecasting and Optimisation

It should be noted that integrating a microgrid controller with complete DERMS capabilities would not be worthwhile in a foreseeable future, as the plus-value of the type of controller resides in the control of a very large amount of loads and DER, which would only occur if the utility was to control all systems that are owned by the customers.

9. Conclusion

This analysis was conducted with the goal of evaluating the suitable limit of renewable energy penetration on the electrical distribution systems of the Northwest Territories communities currently powered with diesel generators. In order to do so, an evaluation of five (5) communities (Fort Liard, Fort Simpson, Tulita, Łutselk'e and Inuvik) was conducted.

The results of this study showed that the major concern related to the existing grid when integrating major amounts of renewable energy is related to the minimum annual load. This is especially true with the integration of PV which produces at its peak while the loads are at their lowest consumption period of the year. Therefore, the minimum community load should also be taken into account as a limiting factor when integrating large amount of renewable energy. The following table provides the summarized results of this analysis.

Communities	Renewable Energy Penetration Results			
	Reactive Power	Power Quality	Grid Stability	Recommended Overall Limit
Fort Liard	55 %	75 %	53%	50 %
Tulita	55 %	50 %	48%	45 %
Łutselk'e	55 %	75 %	46%	45 %
Fort Simpson	55 %	50 %	60%	50 %
Inuvik	55 %	50 %	59%	50 %

Table 20: Recommended Renewable Energy Penetration Limit – Without BESS

Even though some communities would theoretically be able to go above 45% of RE penetration level, the overall recommendation that can be applied to all communities is 45%. If PV is considered to be the only RE resource used, a 50% overall limit would be recommended for all communities.

Following these results, a second analysis was performed to evaluate if BESS could be installed to allow for a higher RE penetration level. The results showed that although this would be technically viable, the financials do not allow for a proper return on investment if the renewable energy systems are owned by the customers. However, having the utility own and operate a centralized renewable energy system could make the BESS financially viable.

When integrating a BESS, a microgrid controller is also necessary to insure proper interconnection with the existing grid, and efficient management of the battery's charge/discharge cycles. An analysis of the different types of microgrid controllers was completed to evaluate which options could be worth integrating in each community. However, as it was determined with adding a BESS, the addition of a microgrid controller would not be economically viable.

10. References

[1] IEEE 1547-2018, Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, 2018-02-15

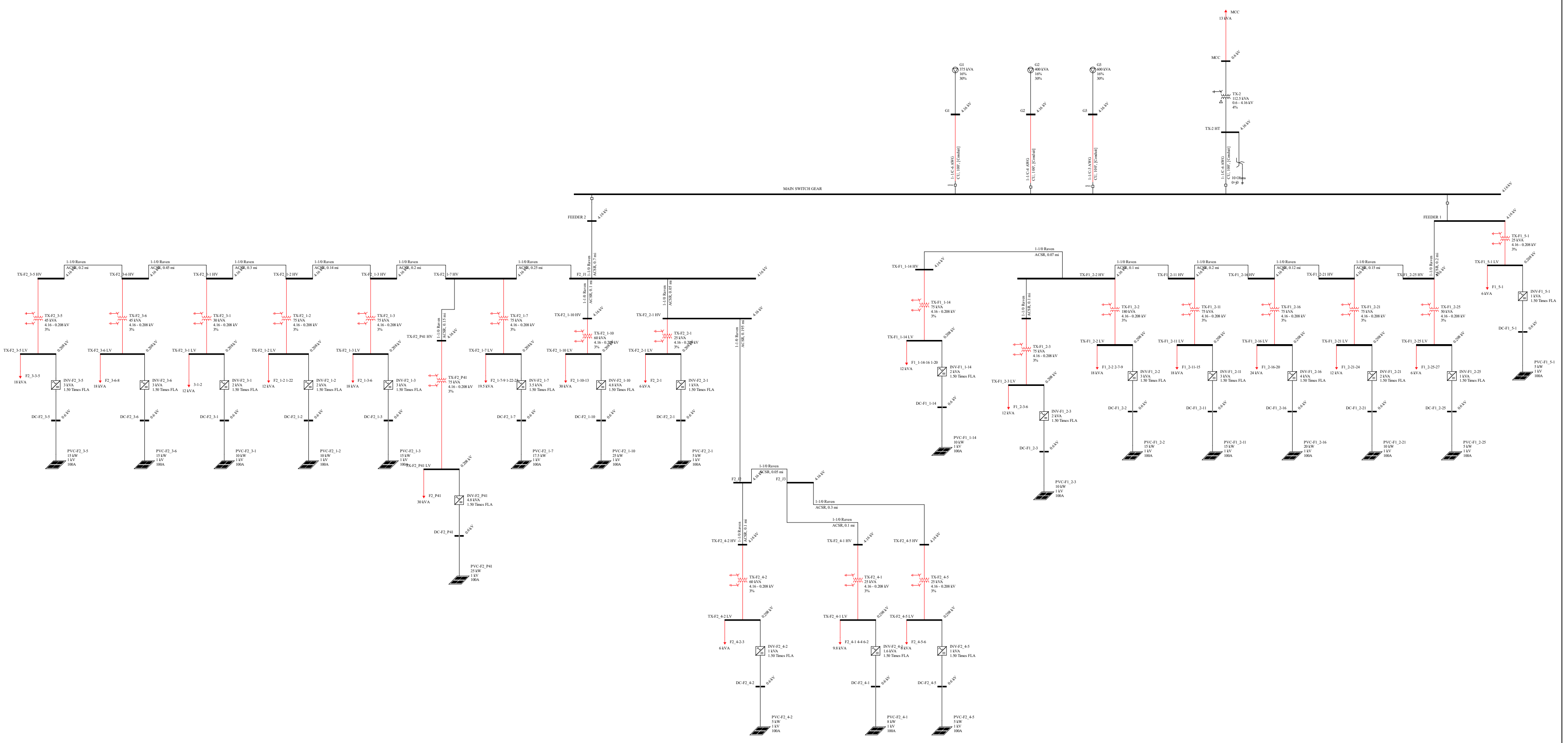
[2] IEEE 519-2014, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

[3] IEC/TR 61000-3-6 2012, Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.

[4] Caterpillar Operation and Maintenance Manual, C27 and C32 Generator Sets, January 2009

B

Appendix B
EasyPower Models



Government of Northwest Territories

Microgrid Stability with Intermittent Renewables

Tulita

Prepared by: Émile Forcier/Simon St-Onge

Verified by: Jean-François Veilleux, P.Eng

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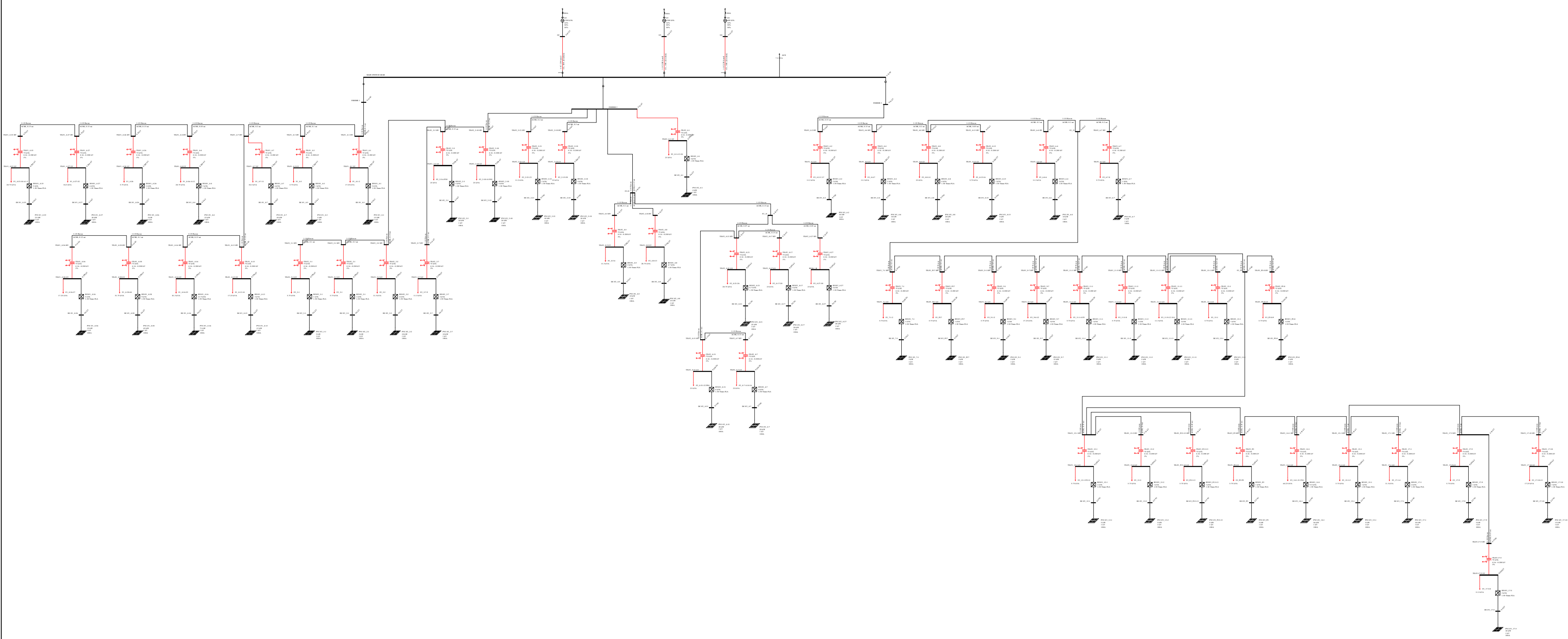
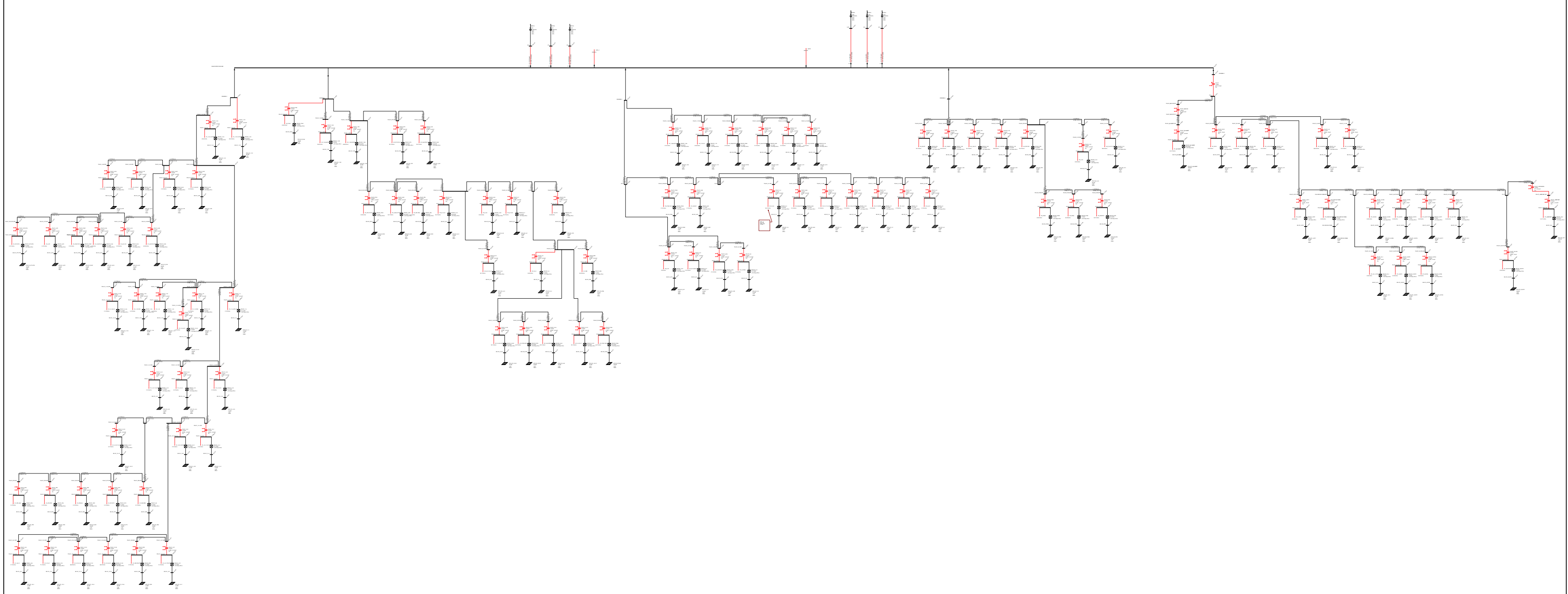


CIMA+

Government of Northwest Territories
Microgrid Stability with Intermittent Renewables
Fort Simpson

Prepared by: Émile Forcier/Simon St-Onge
Verified by: Jean-François Veilleux, P.Eng

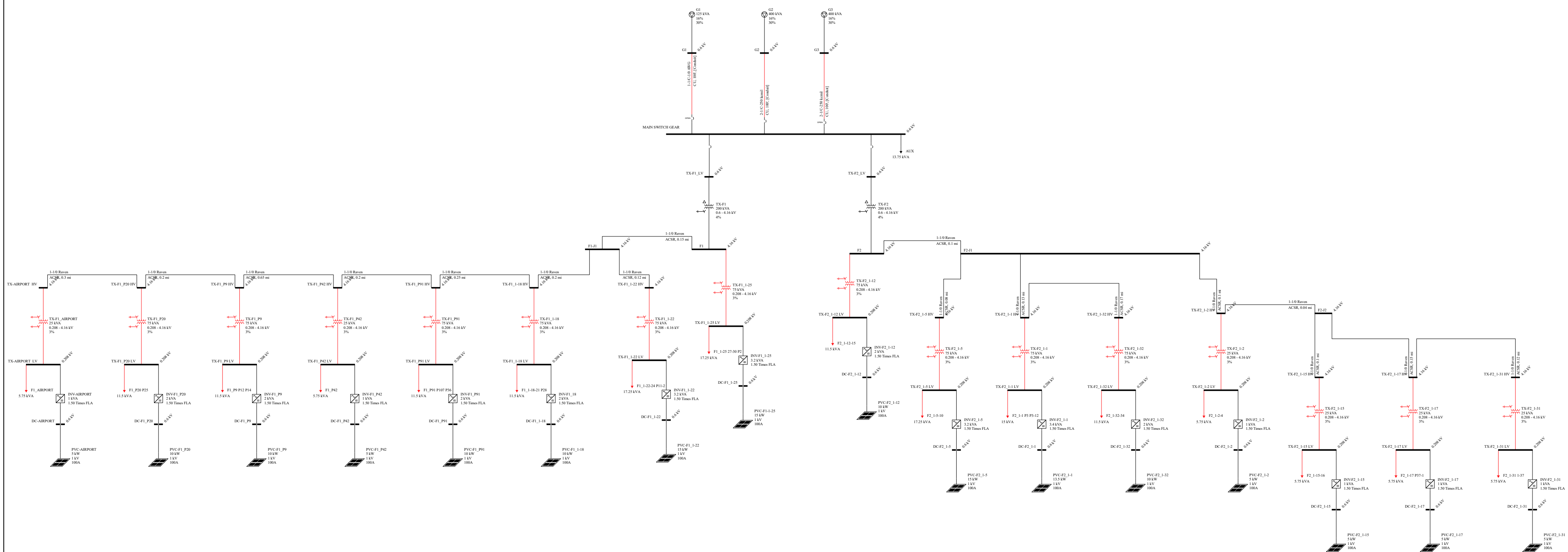
Printed by EasyPower



Government of Northwest Territories
Microgrid Stability with Intermittent Renewables
Inuvik

Prepared by: Émile Forcier/Simon St-Onge
Verified by: Jean-François Veilleux, P.Eng

Printed by EasyPower

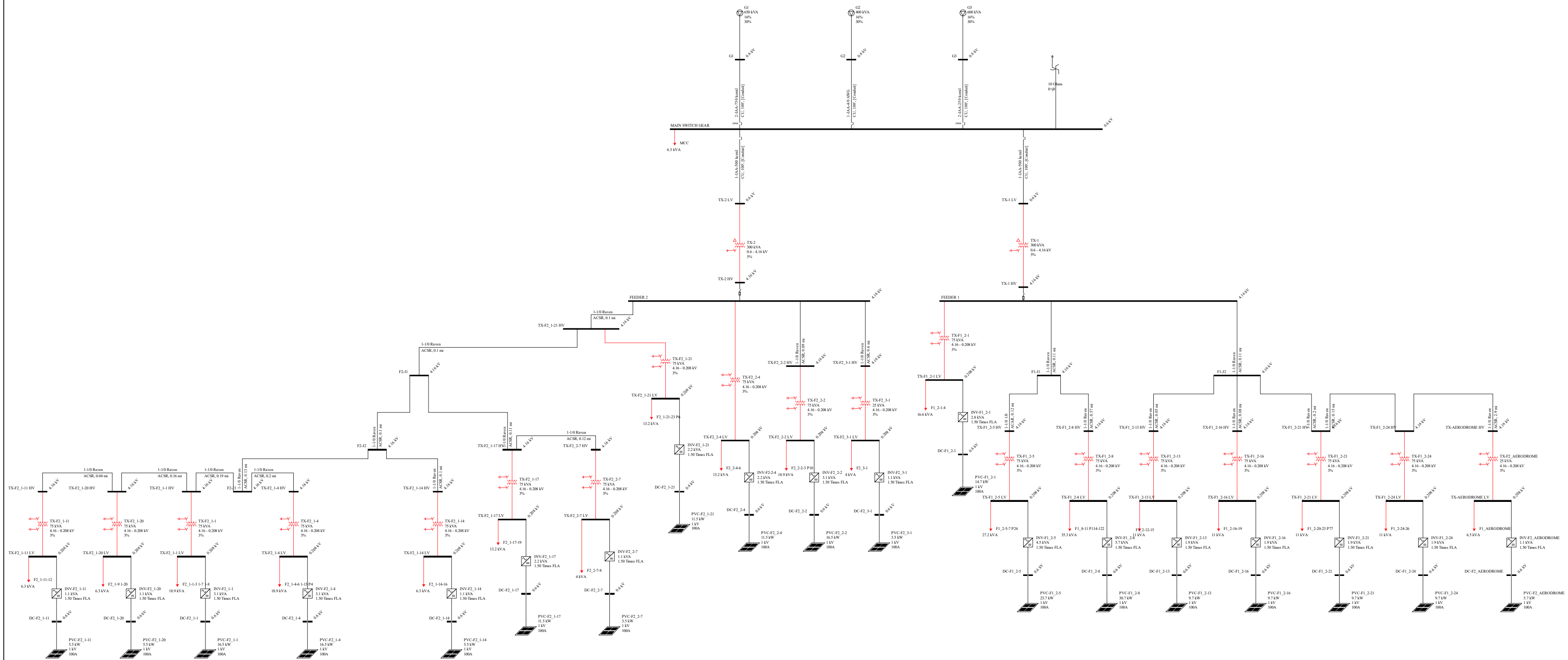


CIMA+

Government of Northwest Territories
Microgrid Stability with Intermittent Renewables
Łutselk'e

Prepared by: Émile Forcier/Simon St-Onge
Verified by: Jean-François Veilleux, P.Eng

Printed by EasyPower

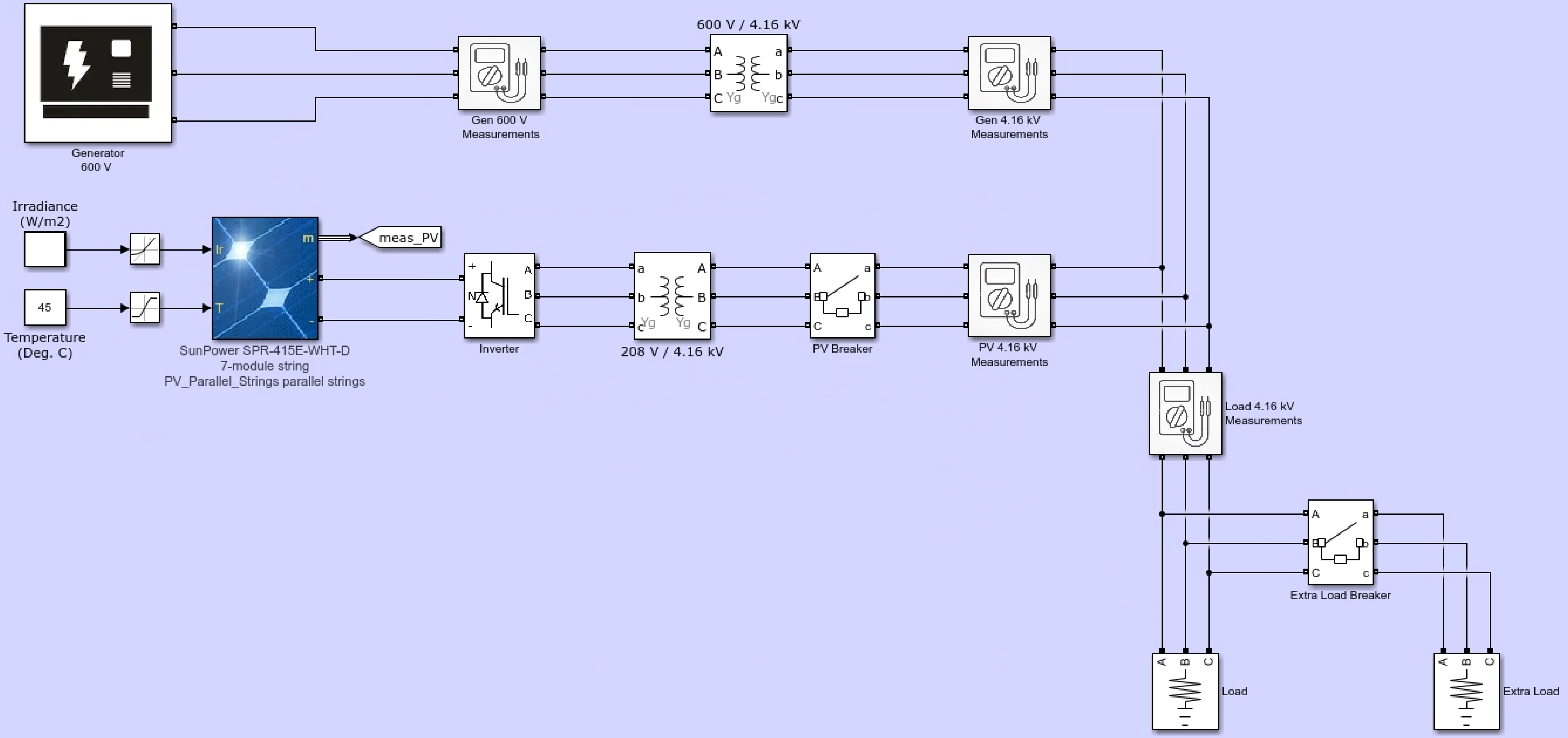


Government of Northwest Territories
Microgrid Stability with Intermittent Renewables
Fort Liard

Prepared by: Émile Forcier/Simon St-Onge
Verified by: Jean-François Veilleux, P.Eng

C

Appendix C
Matlab Simulink Model



Generator
600 V
Gen 600 V
Measurements
600 V / 4.16 kV
Gen 4.16 kV
Measurements
Irradiance
(W/m2)
45
Temperature
(Deg. C)
meas_PV
SunPower SPR-415E-WHT-D
7-module string
PV_Parallel_Strings parallel strings
Inverter
208 V / 4.16 kV
PV Breaker
PV 4.16 kV
Measurements
Load 4.16 kV
Measurements
Extra Load Breaker
Load
Extra Load

D

Appendix D
Detailed Harmonics Results

D.1. Fort Liard

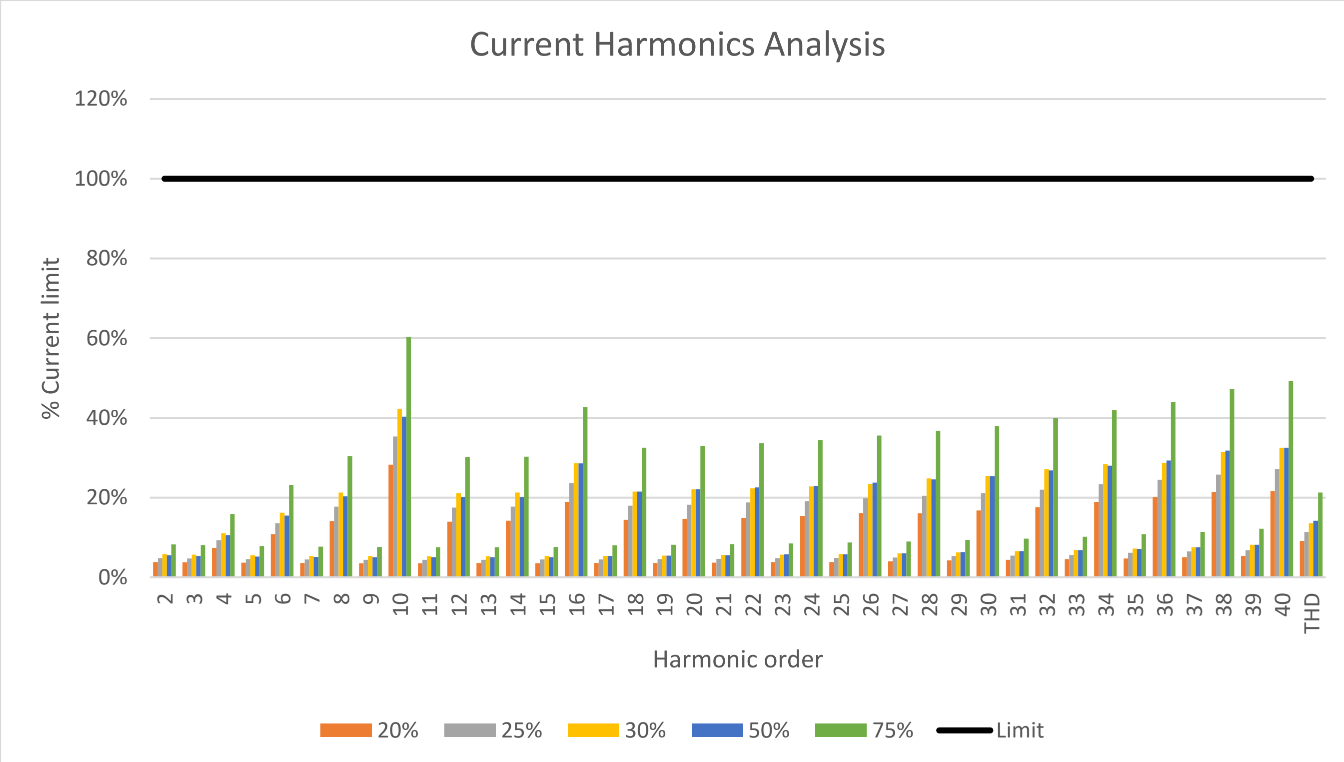


Figure 9: Current Harmonic Distortion Results – Fort Liard

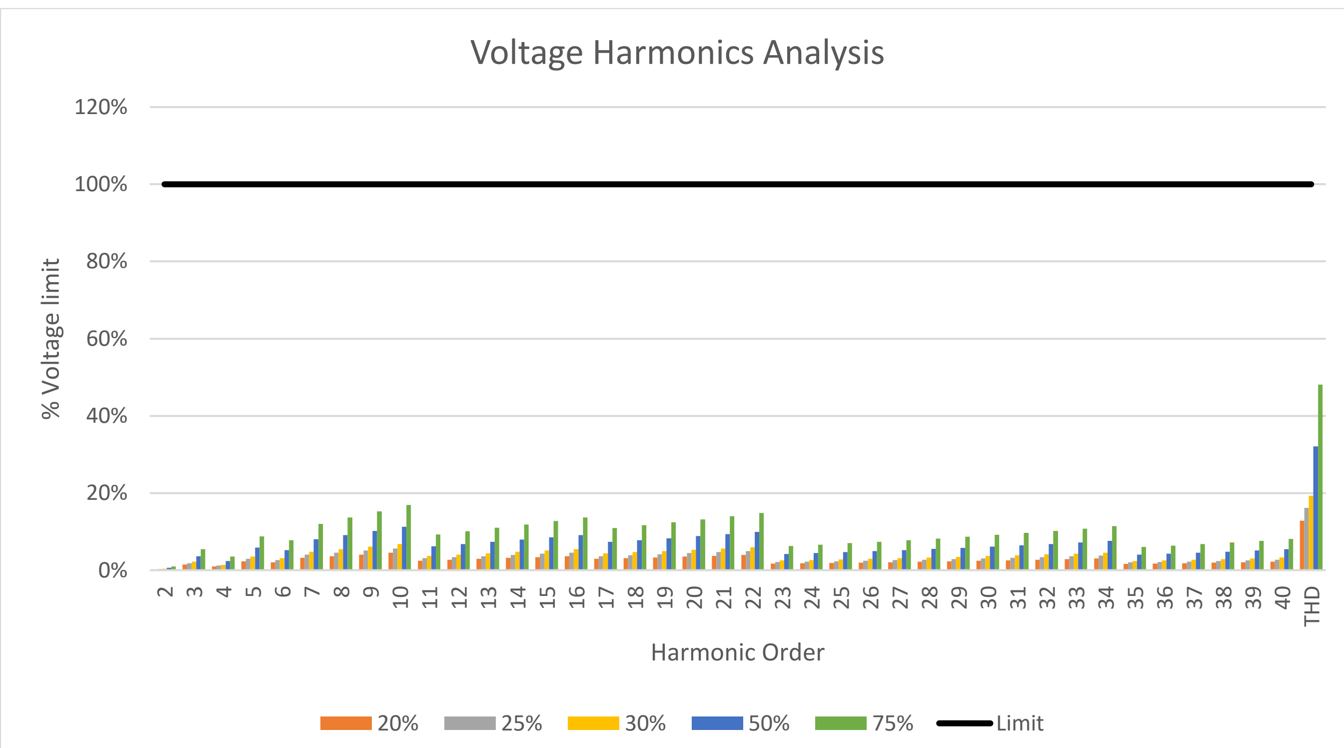


Figure 10: Voltage Harmonic Distortion Results – Fort Liard

D.2. Tulita

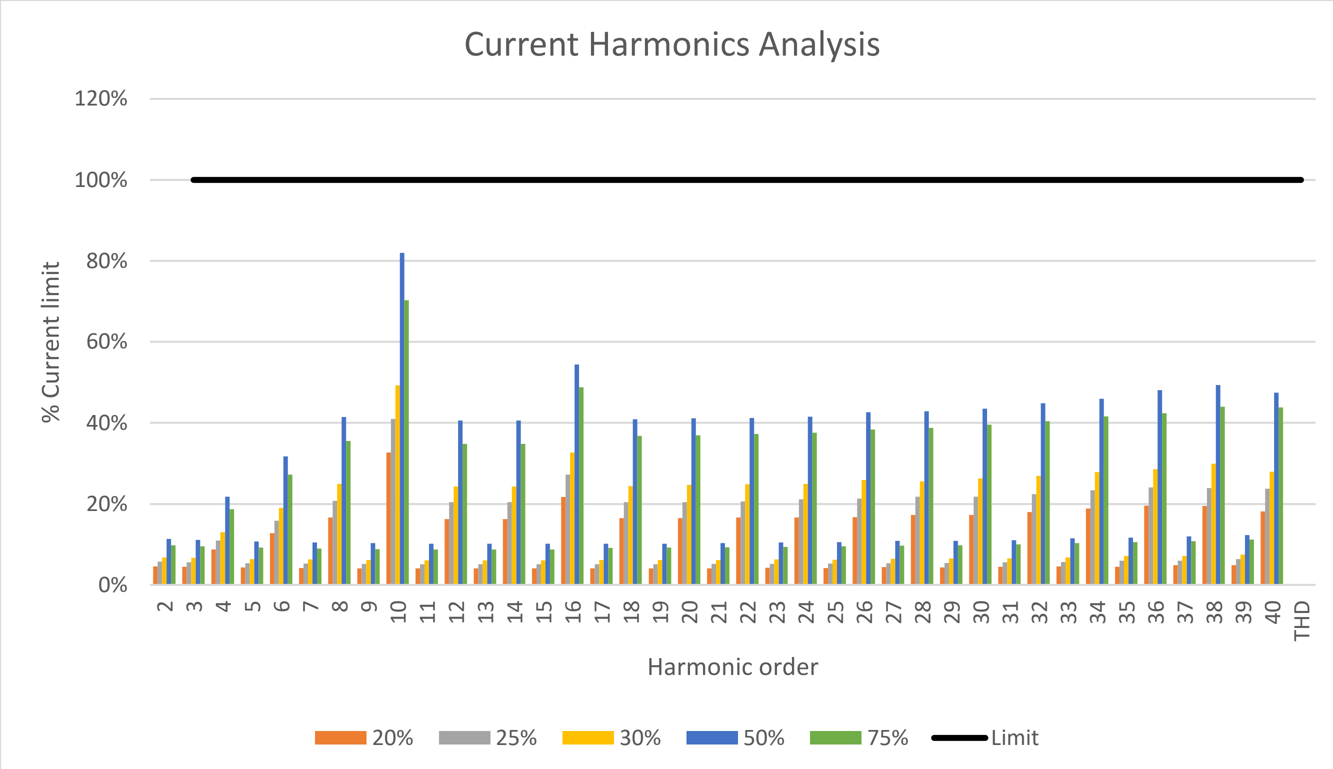


Figure 11: Current Harmonic Distortion Results – Tulita

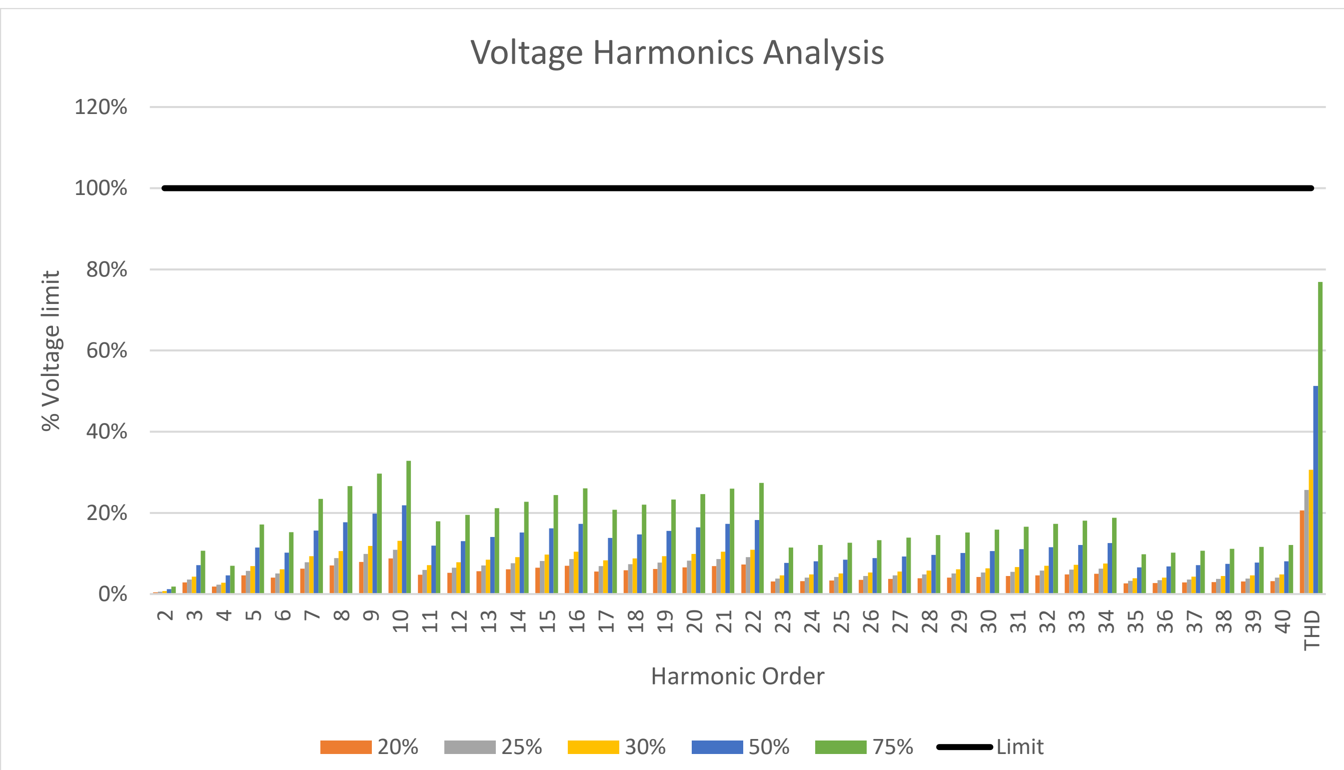


Figure 12: Voltage Harmonic Distortion Results – Tulita

D.3. Łutselk'e

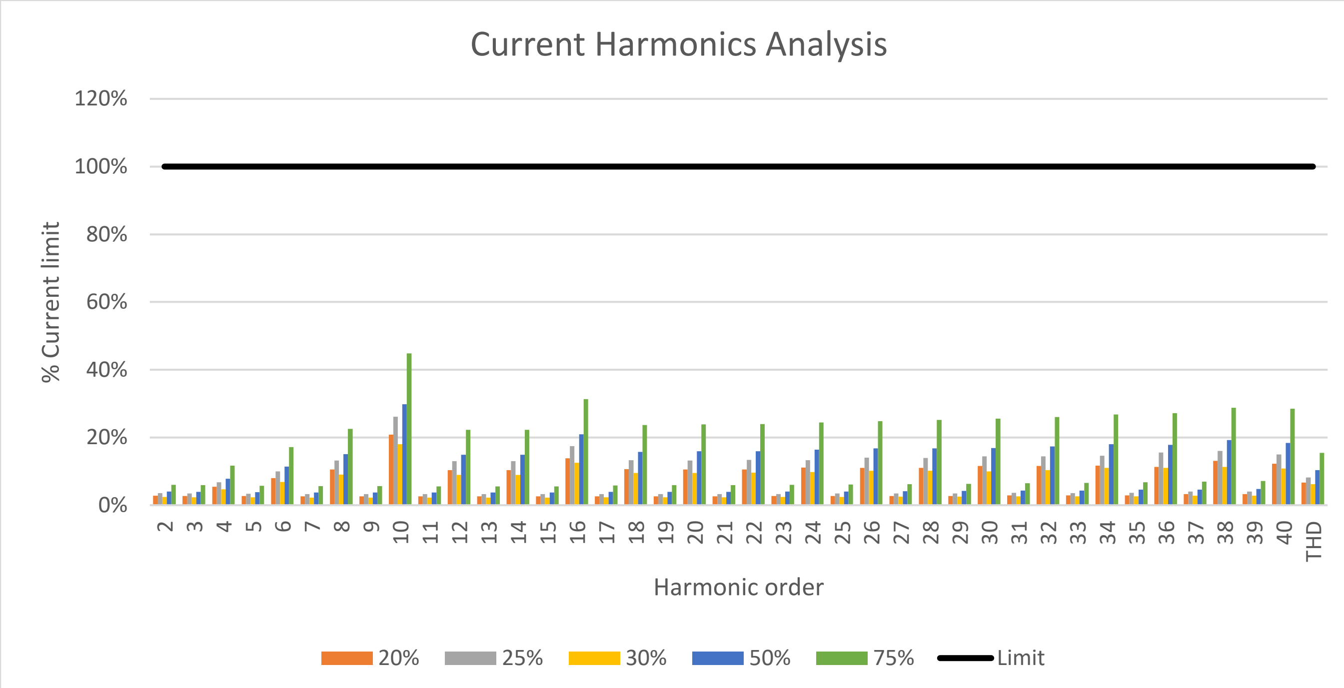


Figure 13: Current Harmonic Distortion Results – Łutselk'e

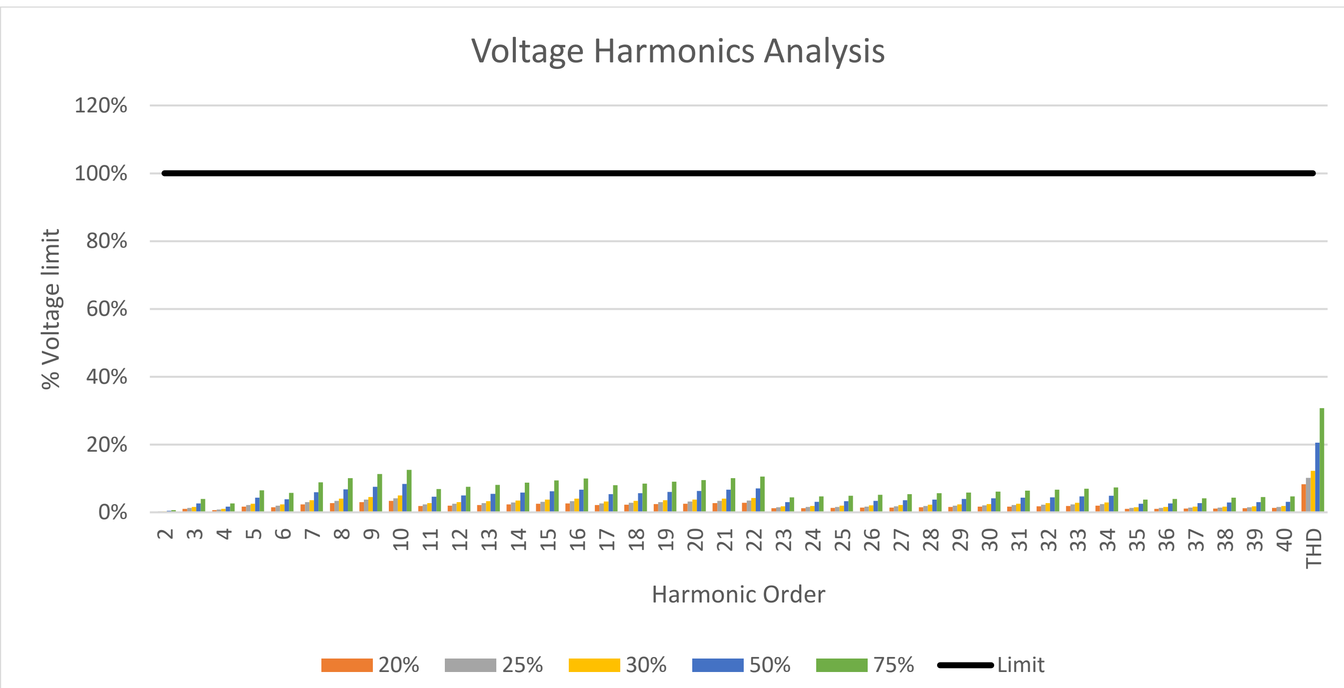


Figure 14: Voltage Harmonic Distortion Results – Łutselk'e

D.4. Fort Simpson

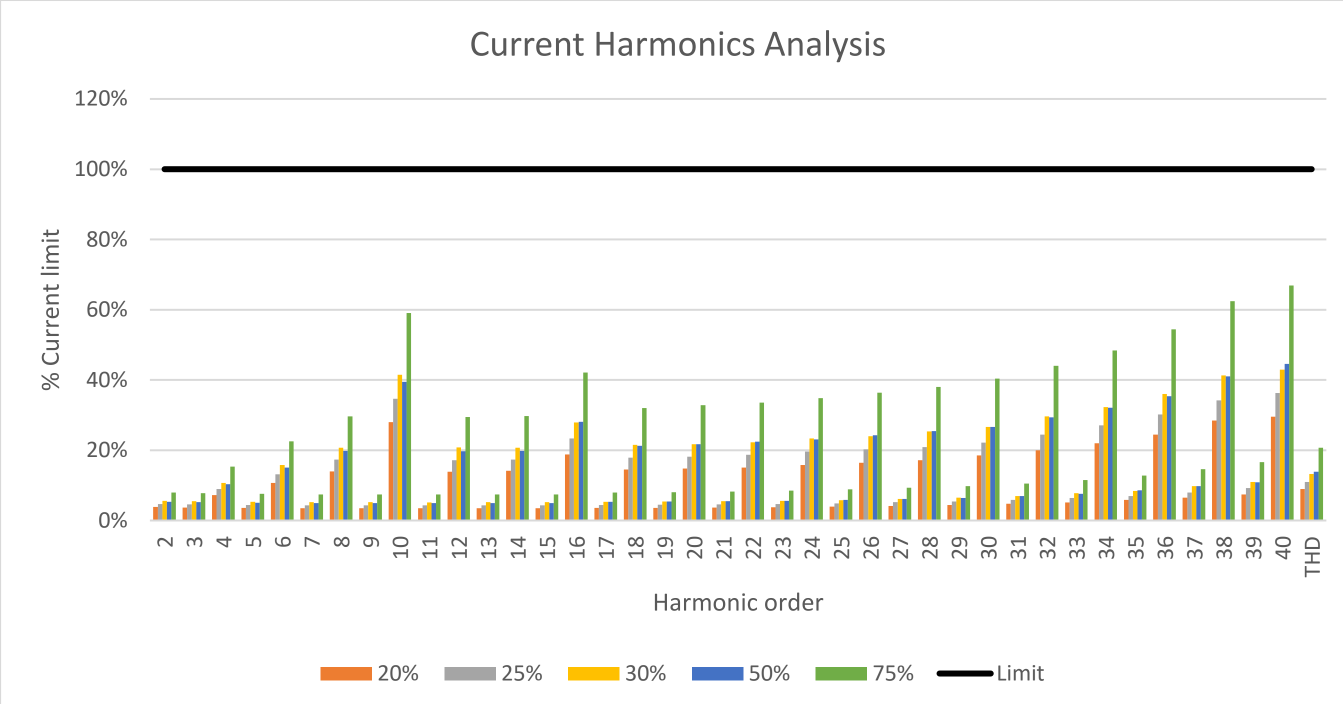


Figure 15: Current Harmonic Distortion Results – Fort Simpson

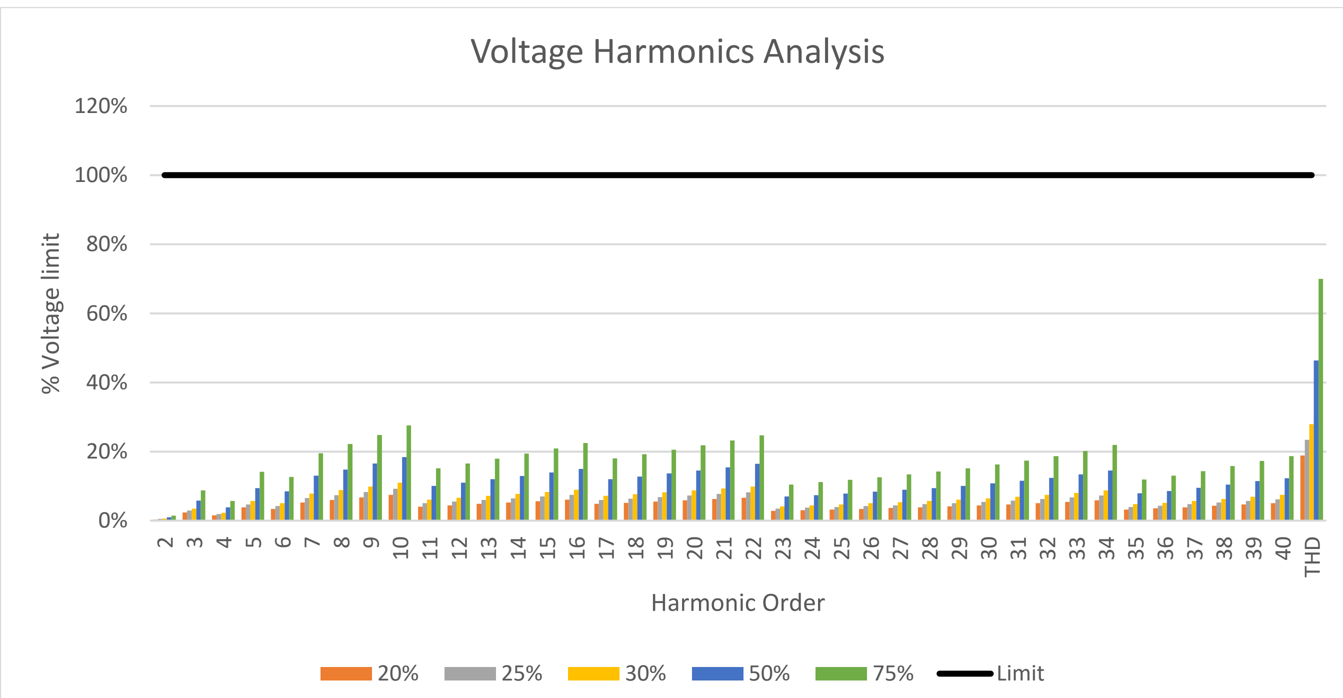


Figure 16: Voltage Harmonic Distortion Results – Fort Simpson

D.5. Inuvik

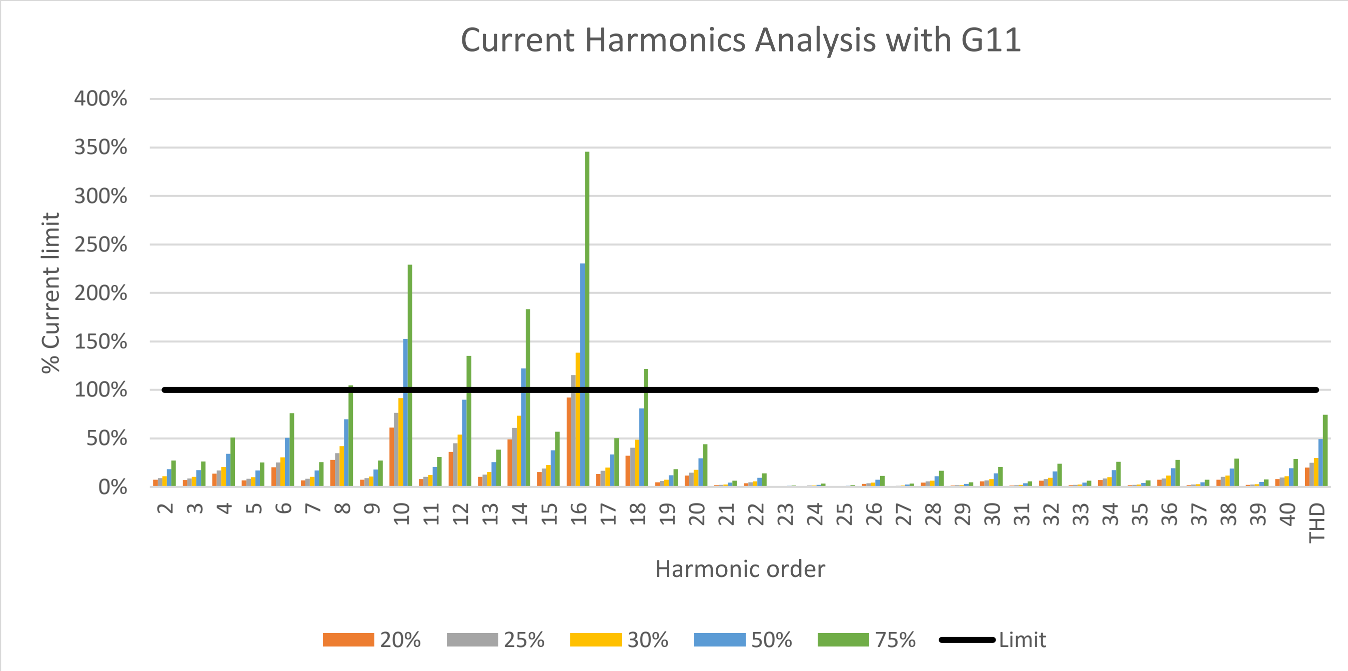


Figure 17: Current Harmonic Distortion Results – Inuvik with G11

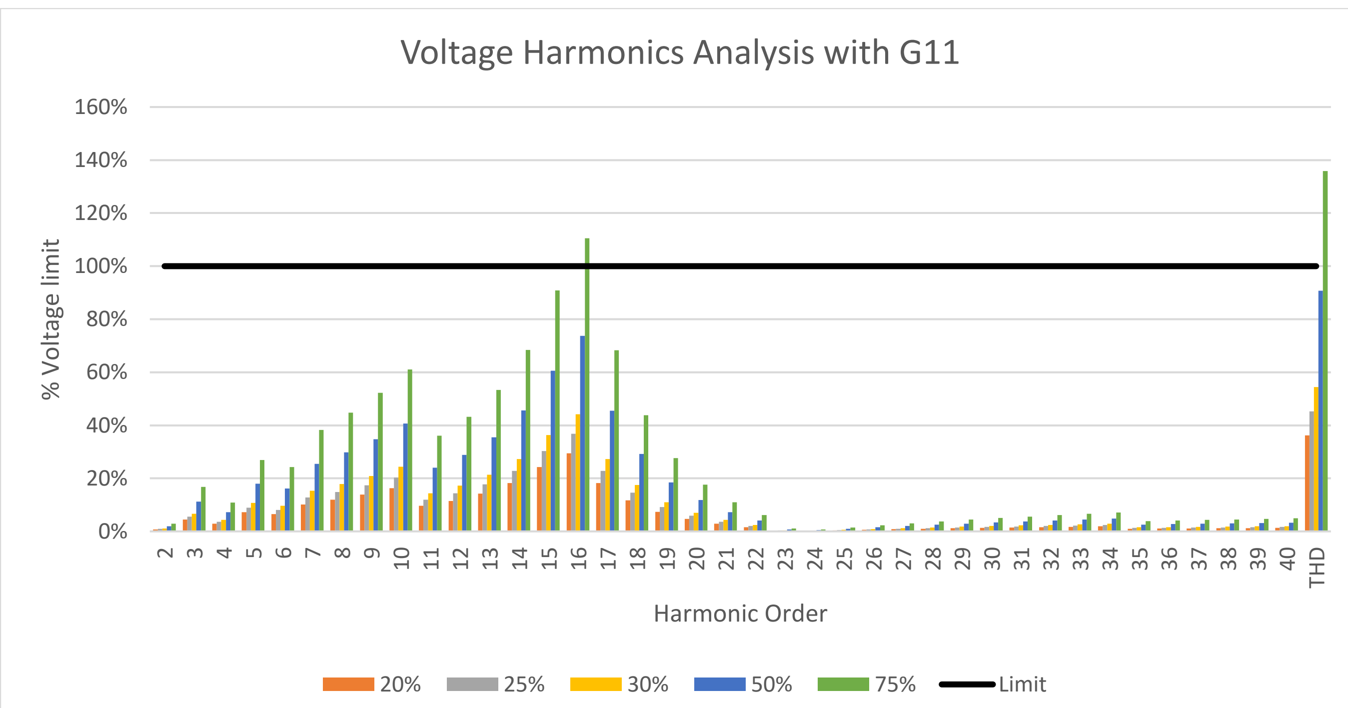


Figure 18: Voltage Harmonic Distortion Results – Inuvik with G11

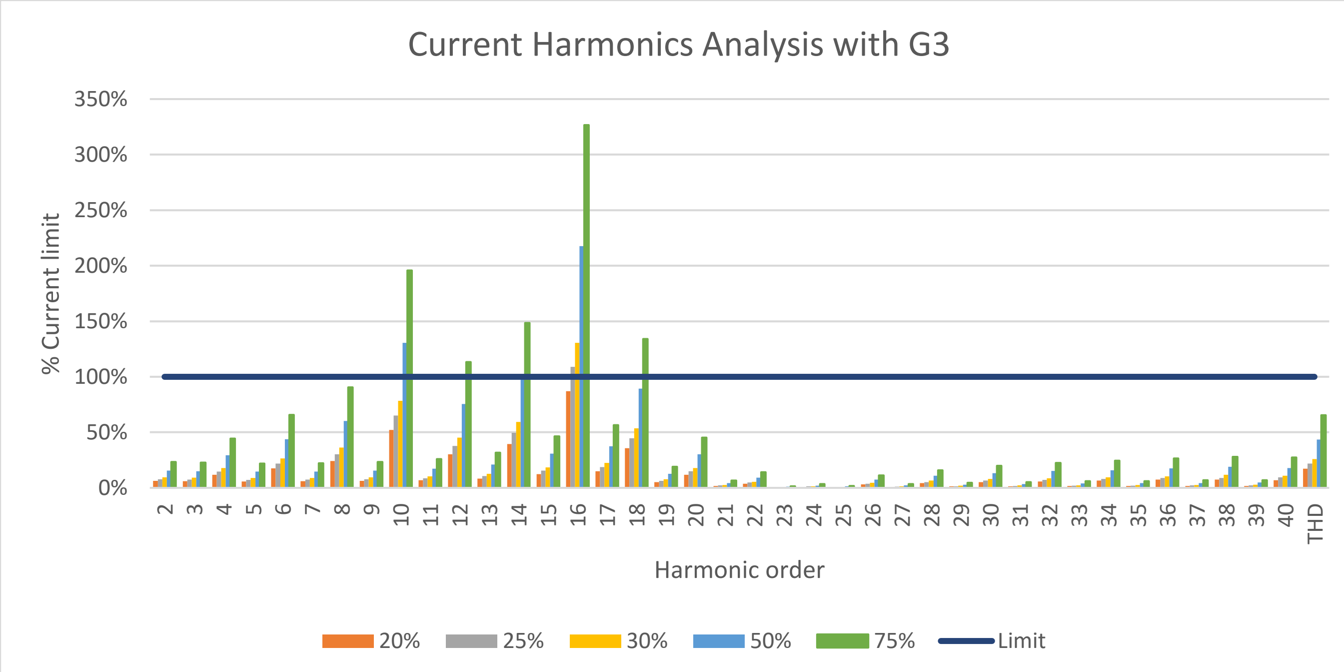


Figure 19: Current Harmonic Distortion Results – Inuvik with G3

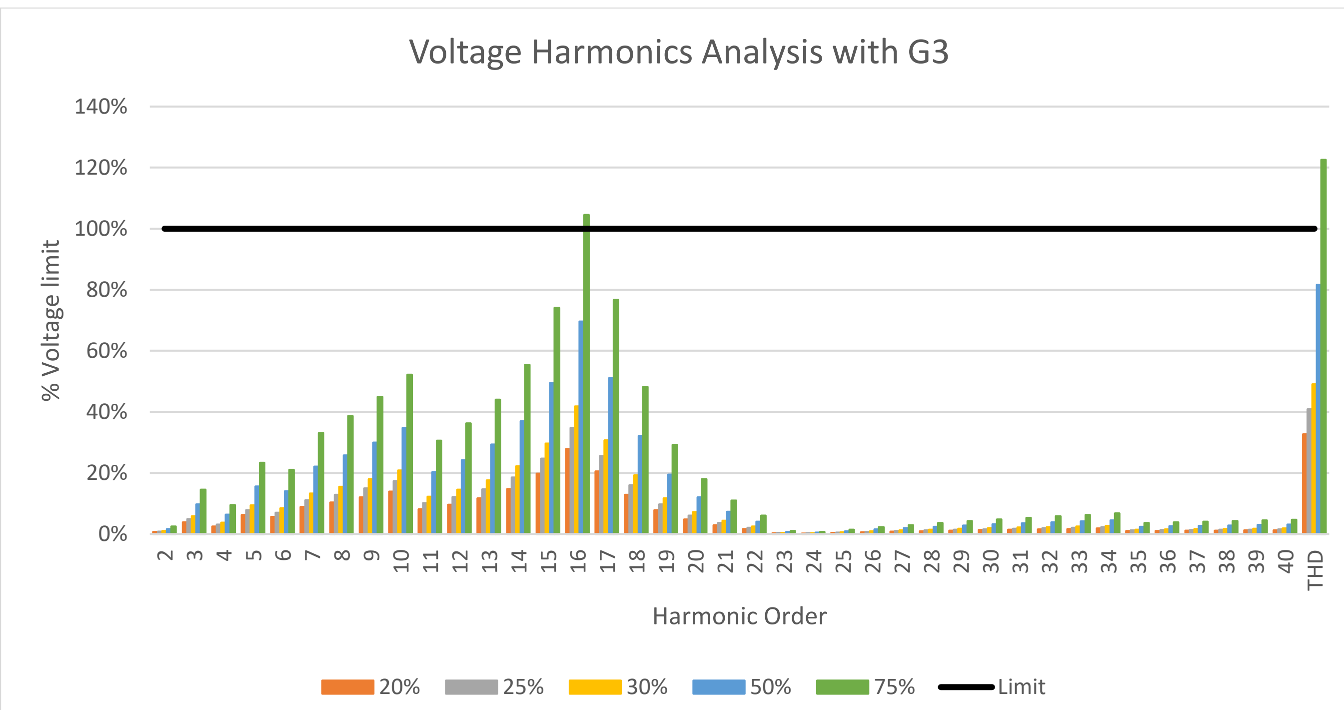


Figure 20: Voltage Harmonic Distortion Results – Inuvik with G3

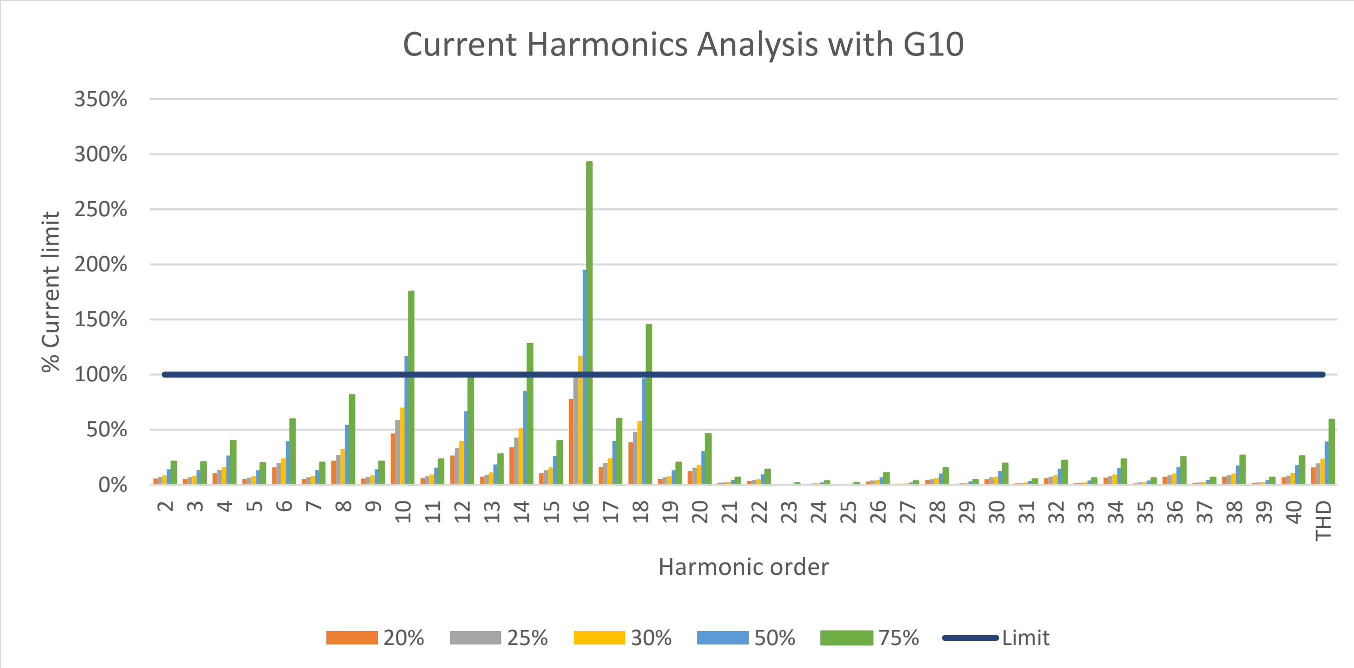


Figure 21: Current Harmonic Distortion Results – Inuvik with G10

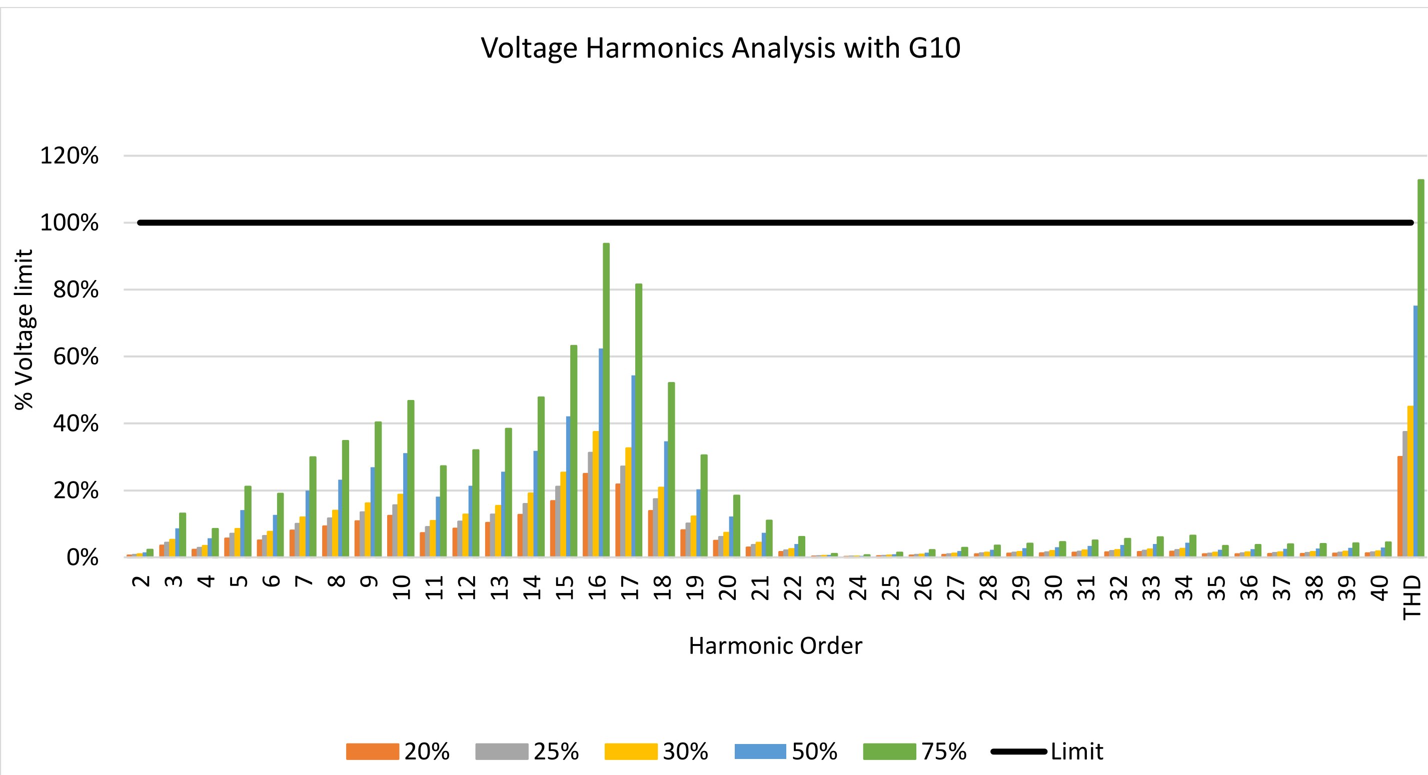


Figure 24: Current Harmonic Distortion Results – Inuvik with G10

E

Appendix E
Grid Stability Analysis Detailed Results

E.1. Fort Liard 20% Renewable Energy Penetration

E.1.1. Load Increase and Decrease

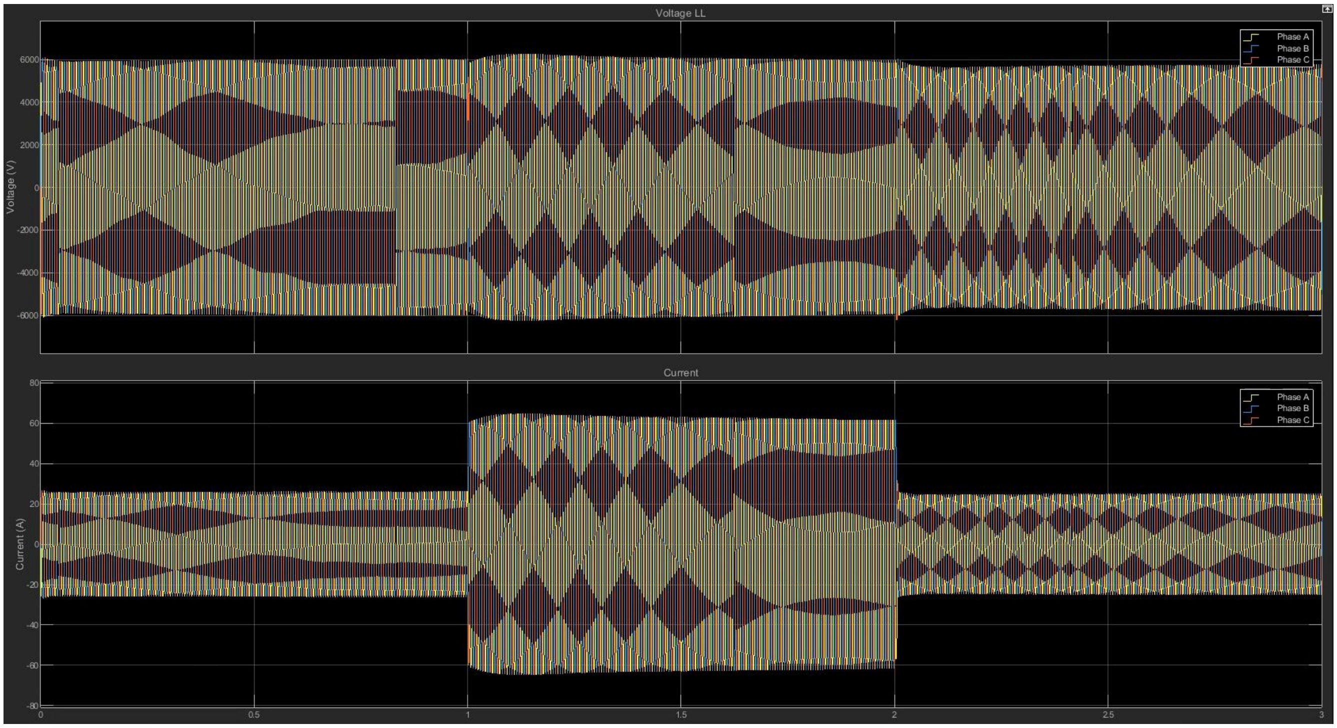


Figure 22: Dynamic Results – Fort Liard Load Variations – 20%

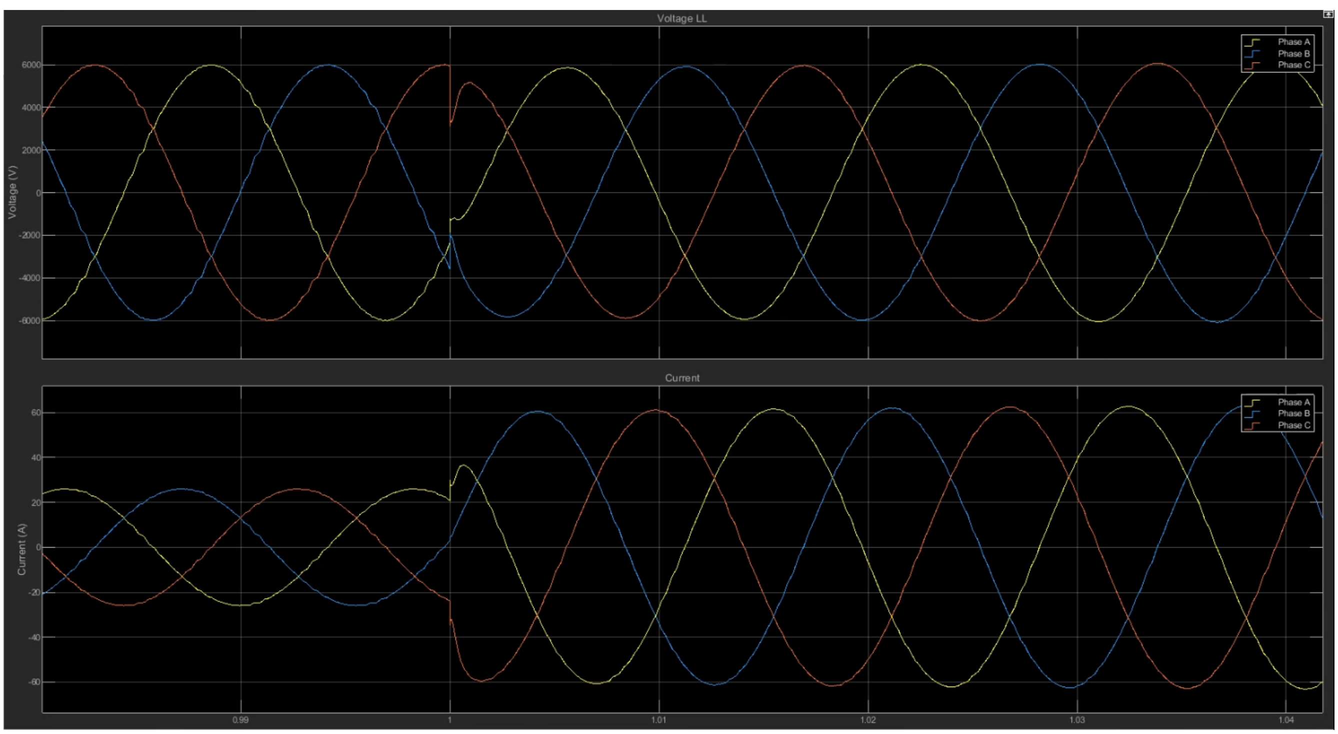


Figure 23: Dynamic Results – Fort Liard Load Increase – 20%

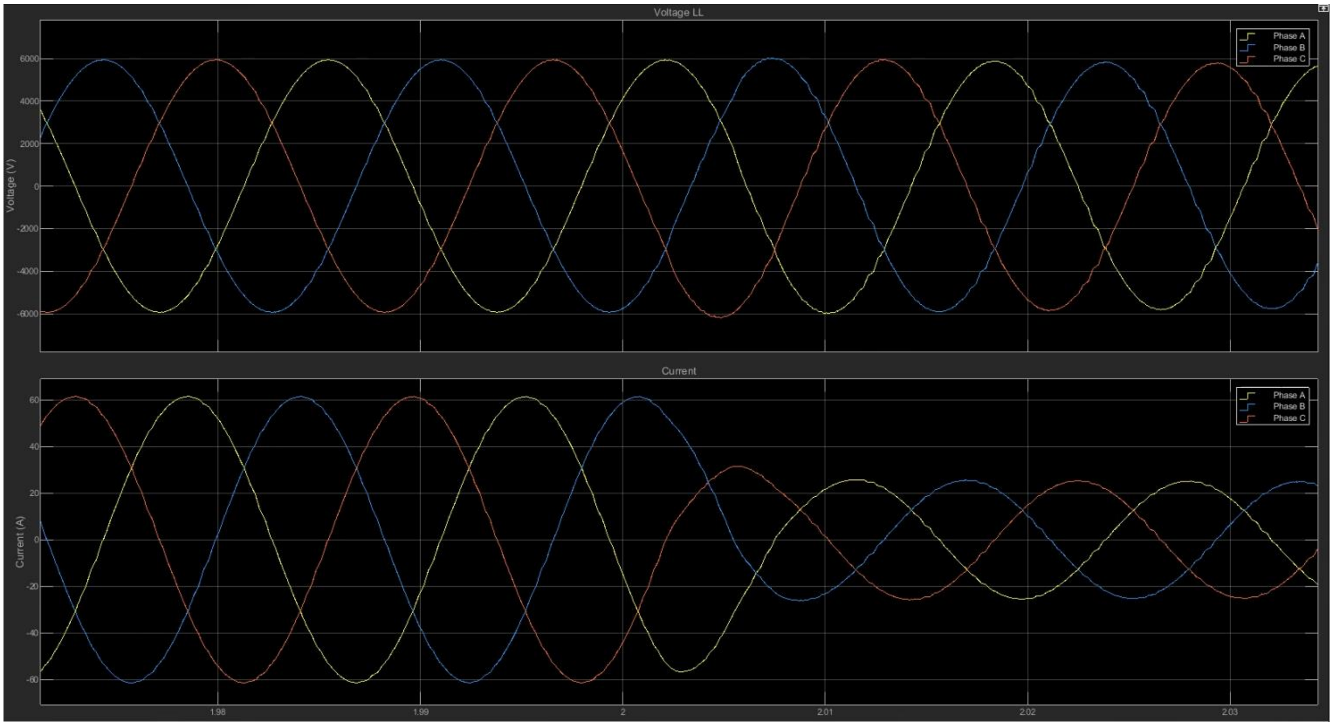


Figure 24: Dynamic Results – Fort Liard Load Decrease – 20%

E.1.2. Renewable Connection / Disconnection

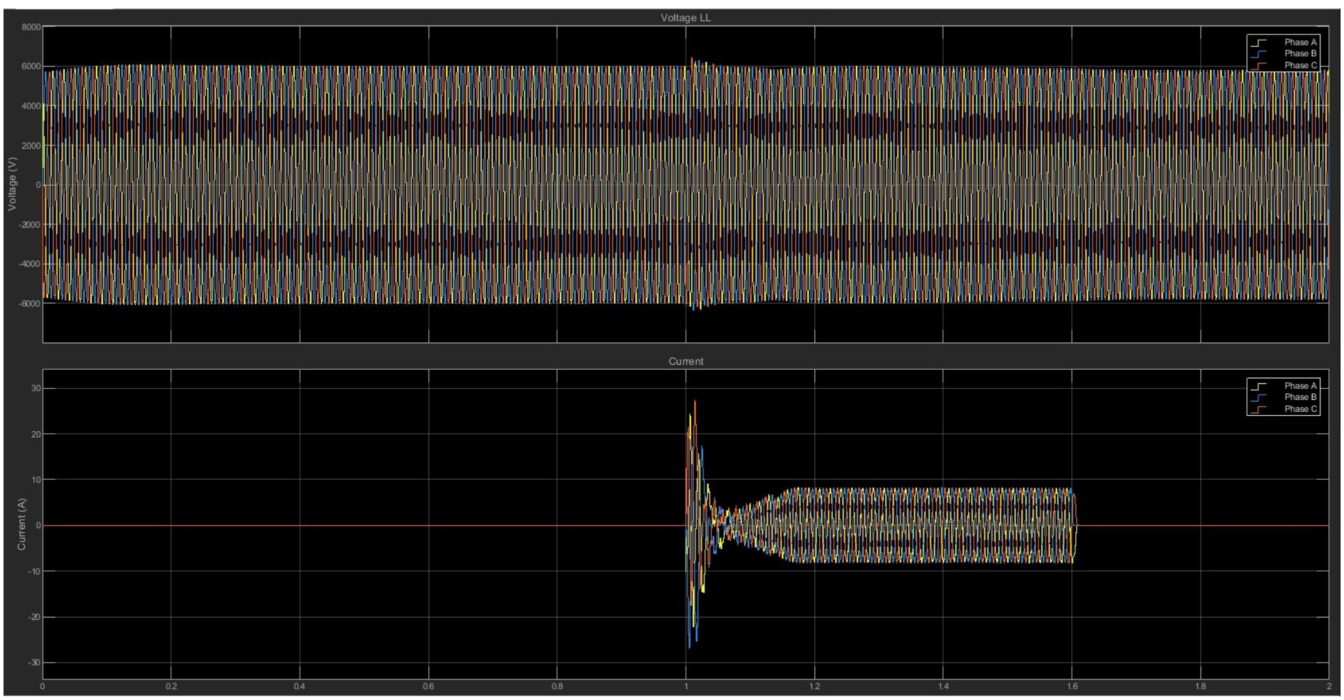


Figure 25: Dynamic Results – Fort Liard Renewable Sources Variation – 20% – PV

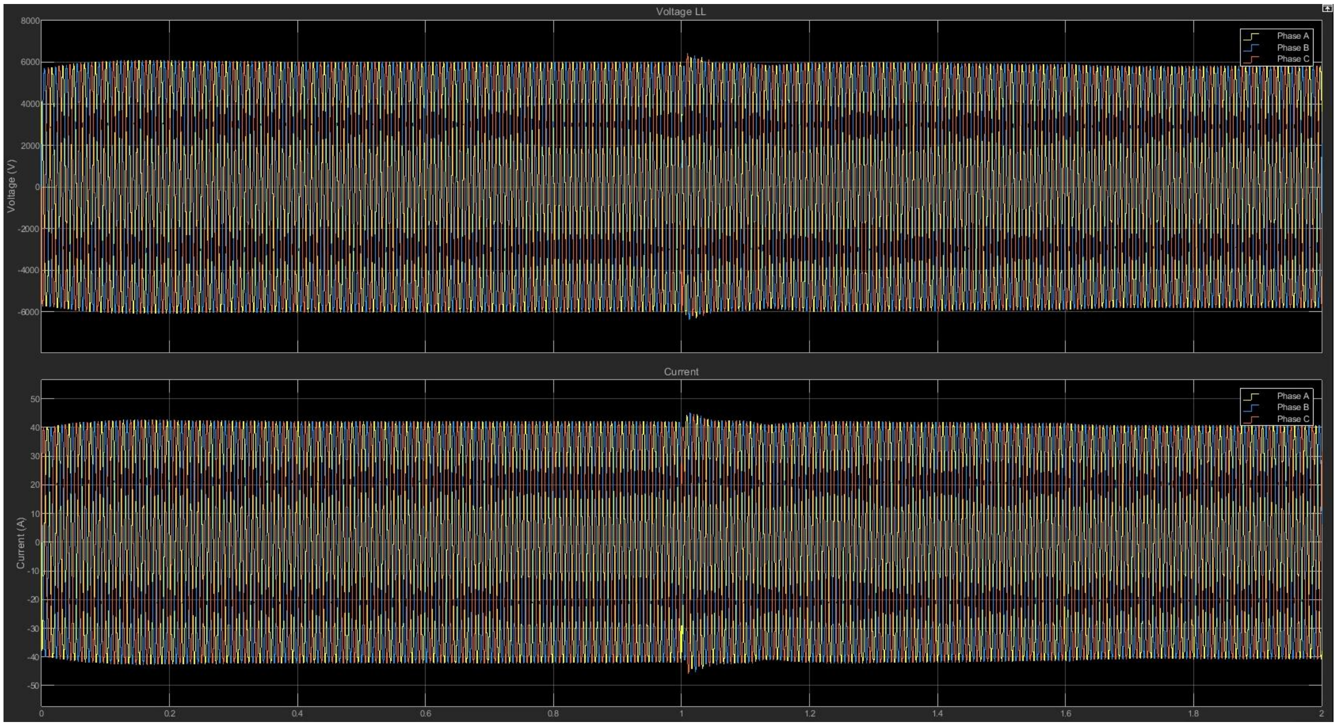


Figure 26: Dynamic Results – Fort Liard Renewable Sources Variation – 20% – Load

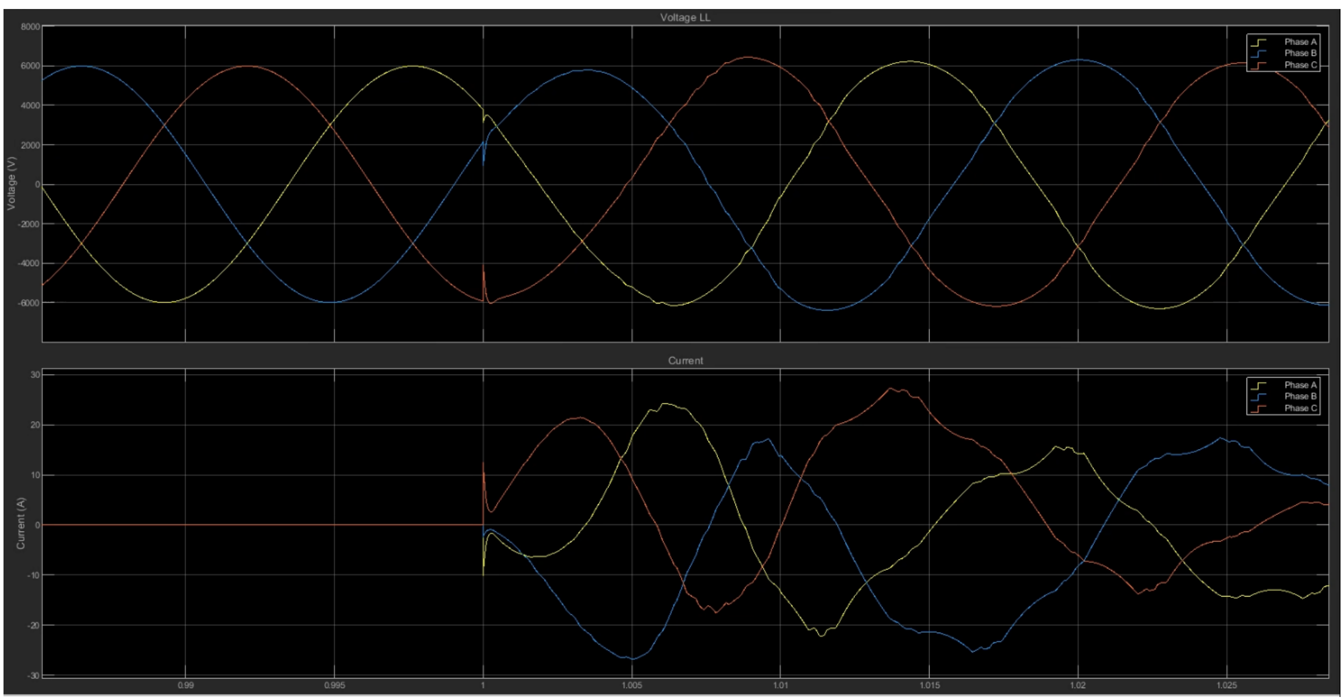


Figure 27: Dynamic Results – Fort Liard Renewable Sources Connection – 20% – PV

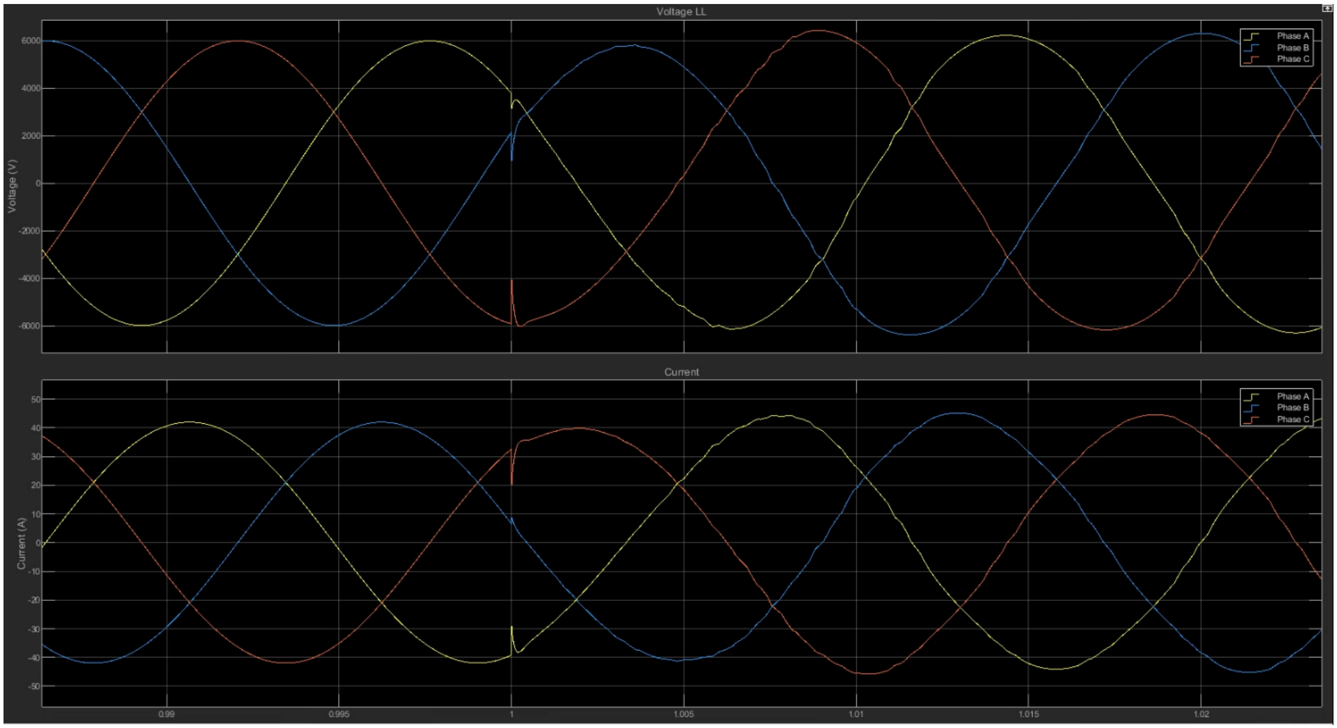


Figure 28: Dynamic Results – Fort Liard Renewable Sources Connection – 20% – Load

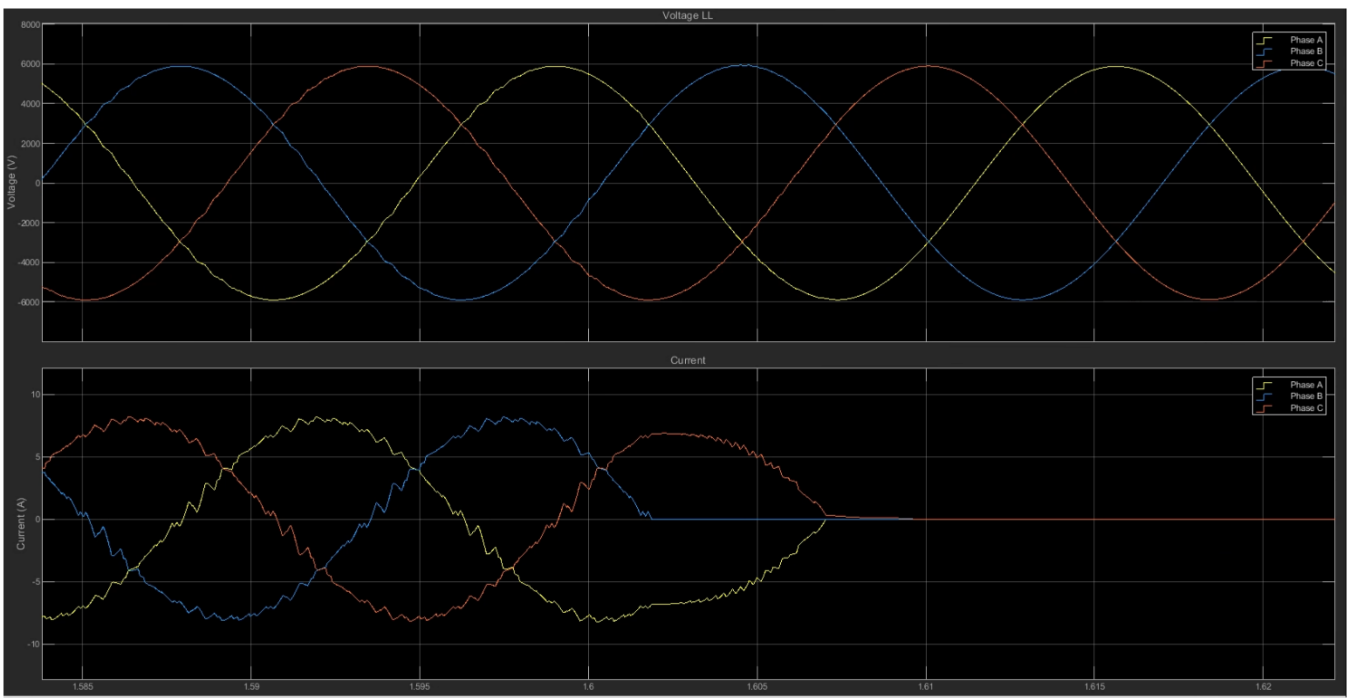


Figure 29: Dynamic Results – Fort Liard Renewable Sources Disconnection – 20% – PV

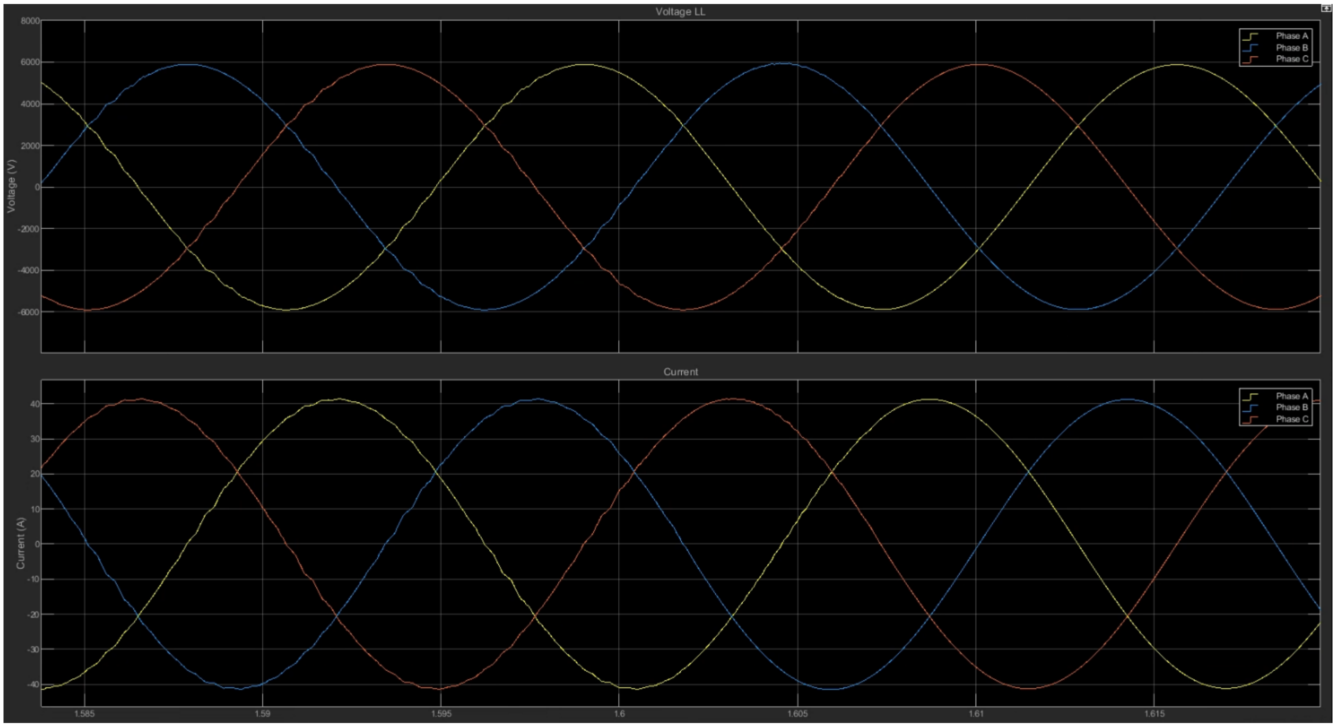


Figure 30: Dynamic Results – Fort Liard Renewable Sources Disconnection – 20% – Load

E.2. Fort Liard 25% Renewable Energy Penetration

E.2.1. Load Increase and Decrease

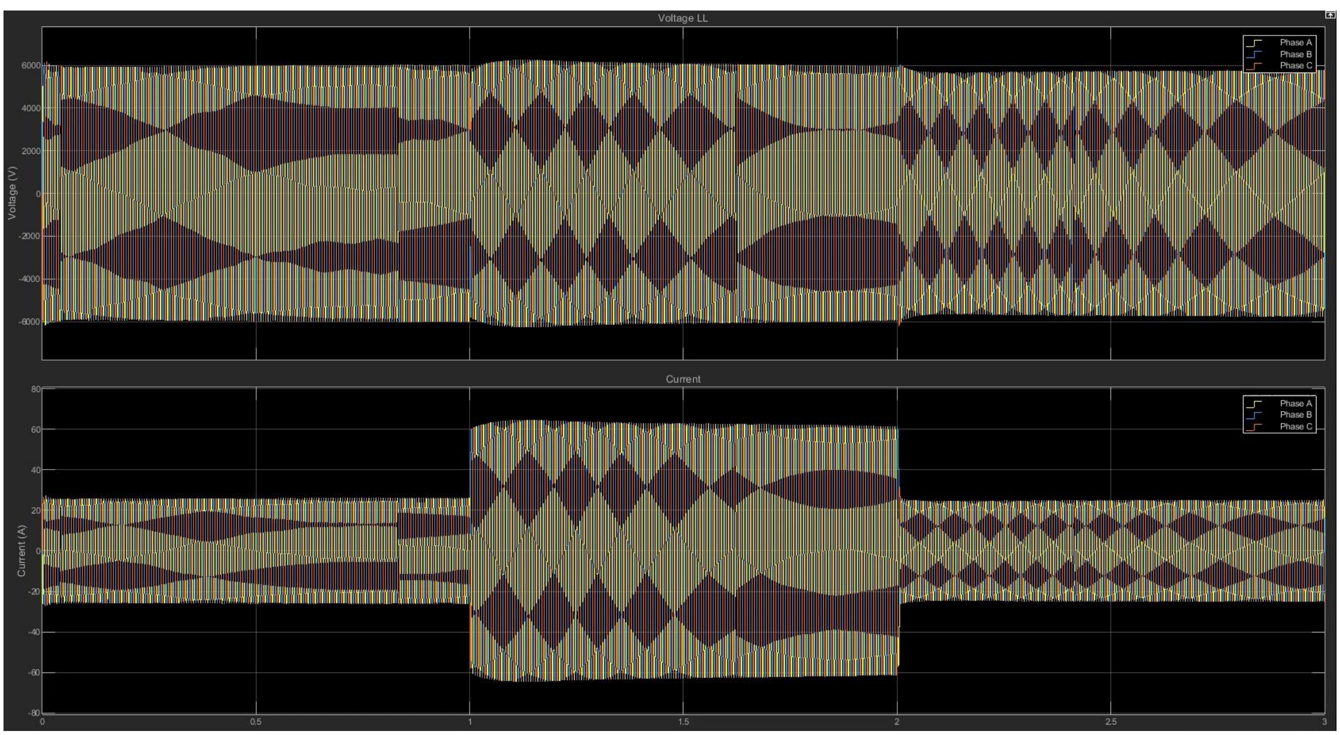


Figure 31: Dynamic Results – Fort Liard Load Variations – 25%

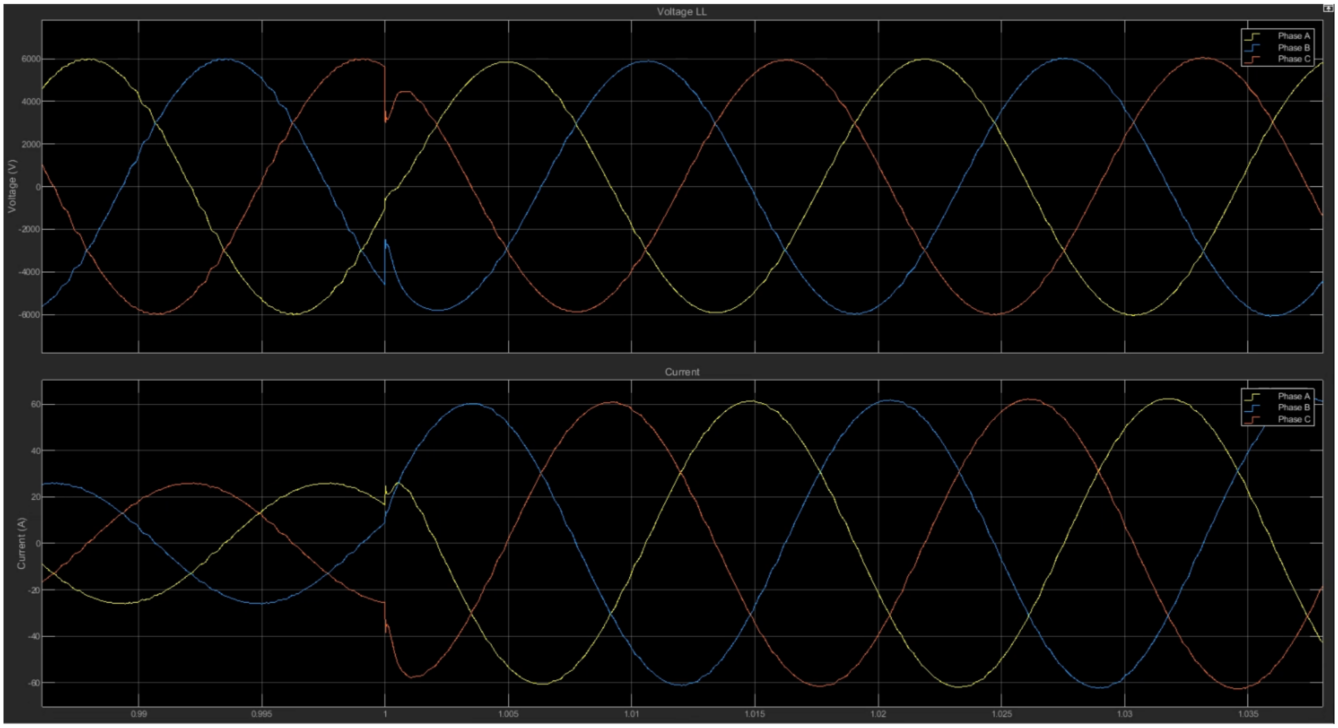


Figure 32: Dynamic Results – Fort Liard Load Increase – 25%

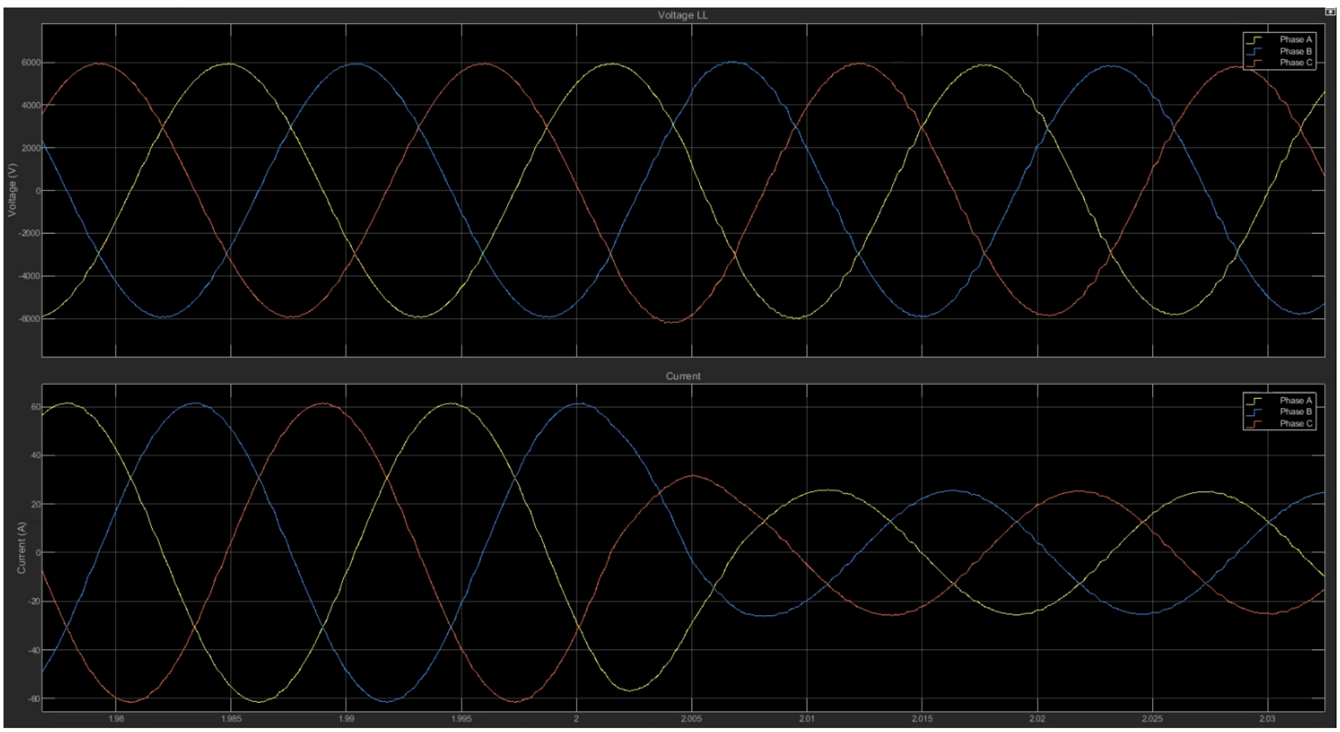


Figure 33: Dynamic Results – Fort Liard Load Decrease – 25%

E.2.2. Renewable Connection / Disconnection

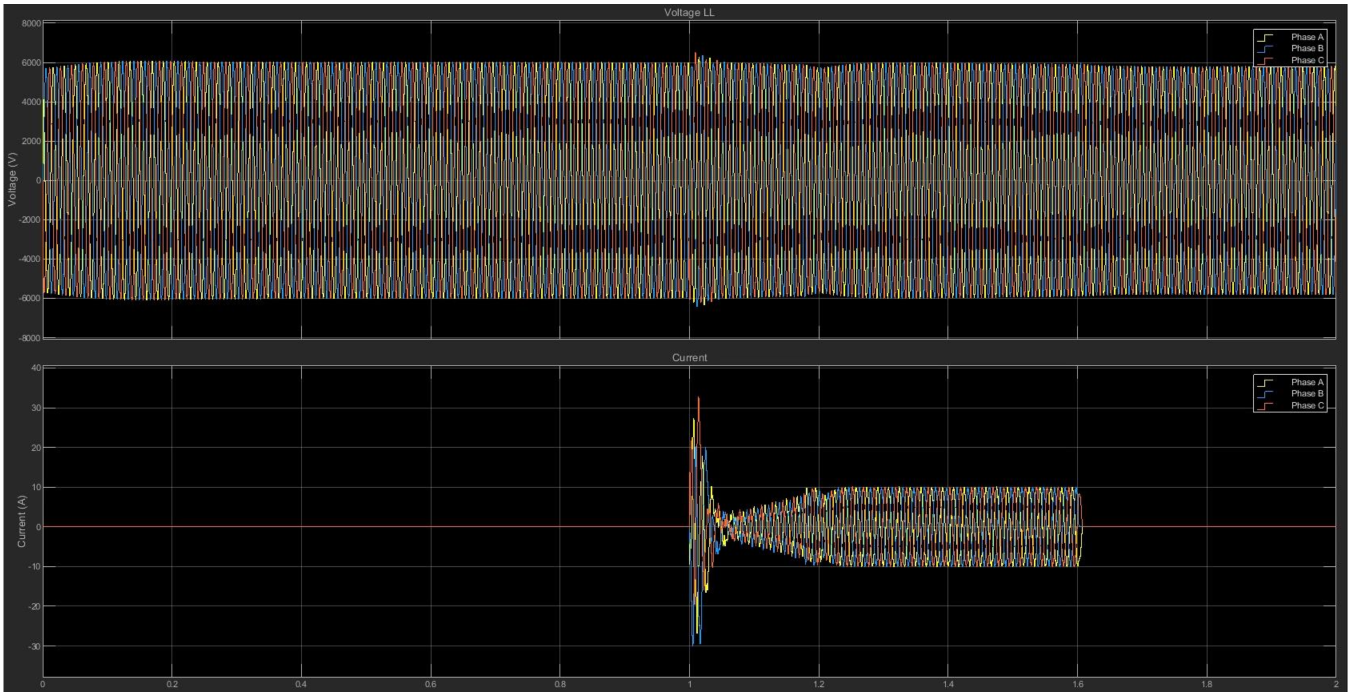


Figure 34: Dynamic Results – Fort Liard Renewable Sources Variation – 25% – PV

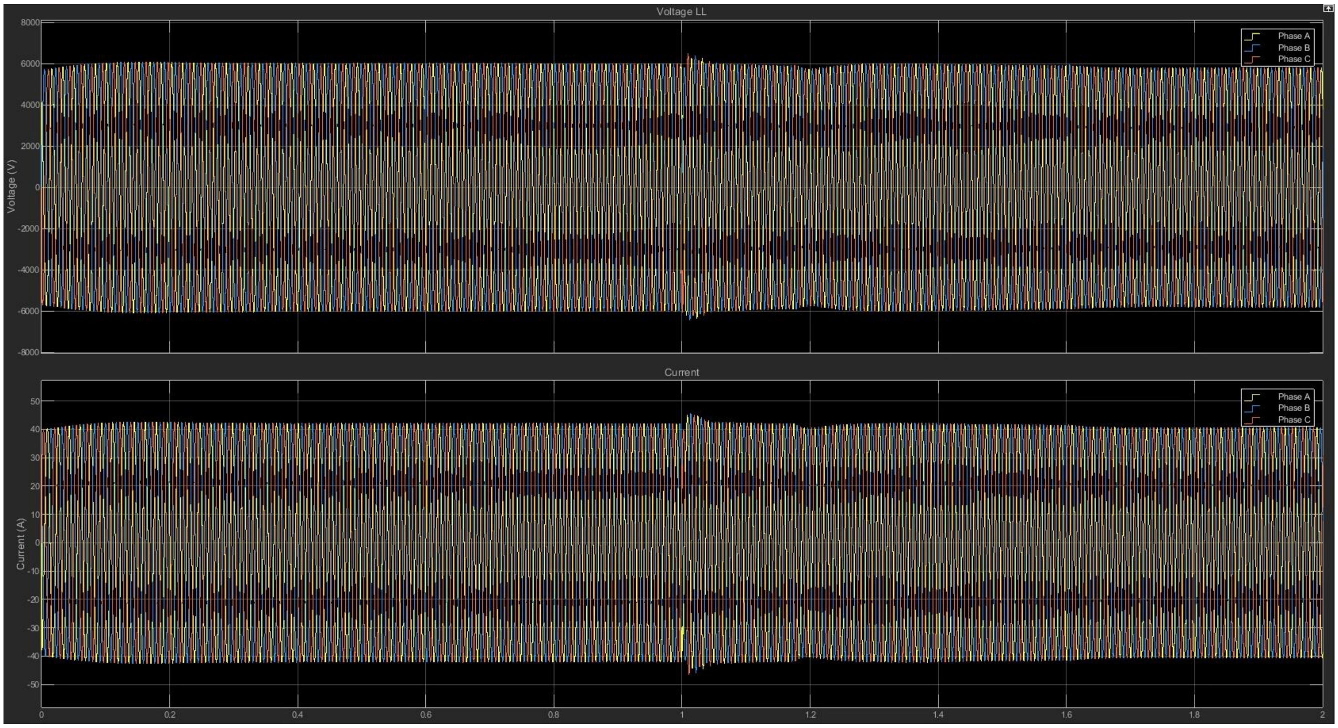


Figure 35: Dynamic Results – Fort Liard Renewable Sources Variation – 25% – Load

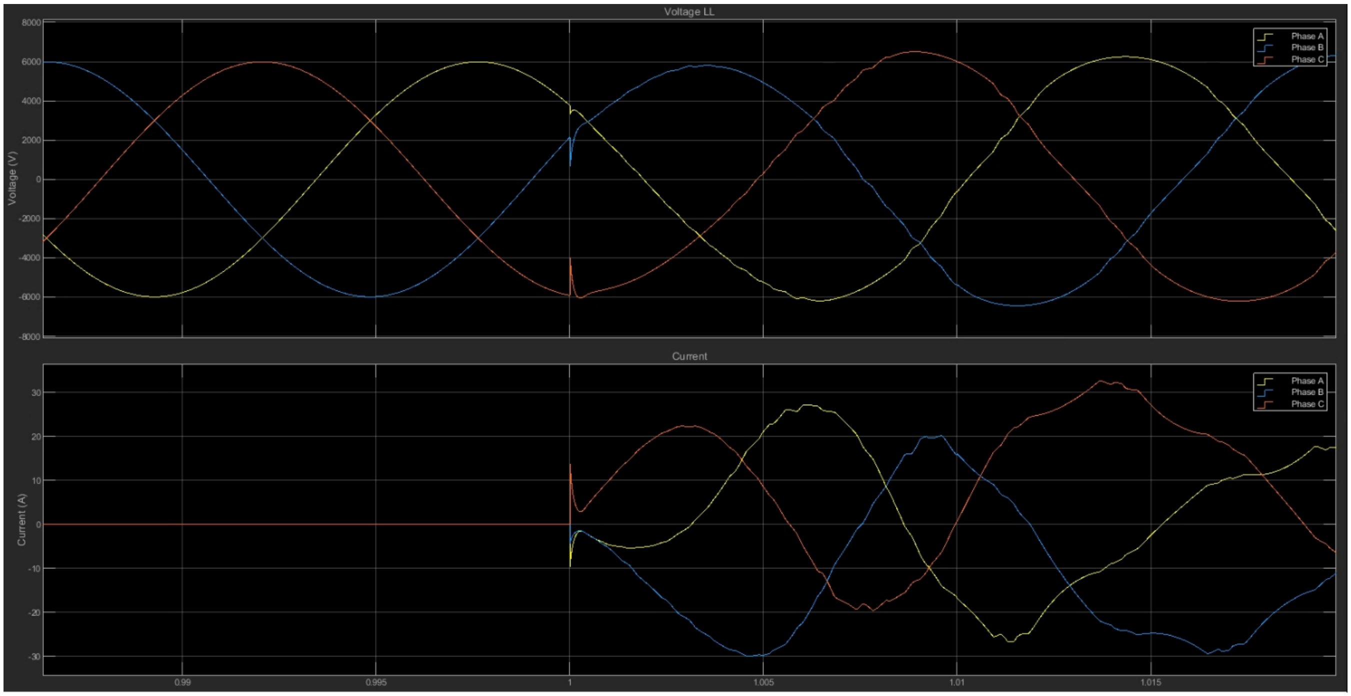


Figure 36: Dynamic Results – Fort Liard Renewable Sources Connection – 25% – PV

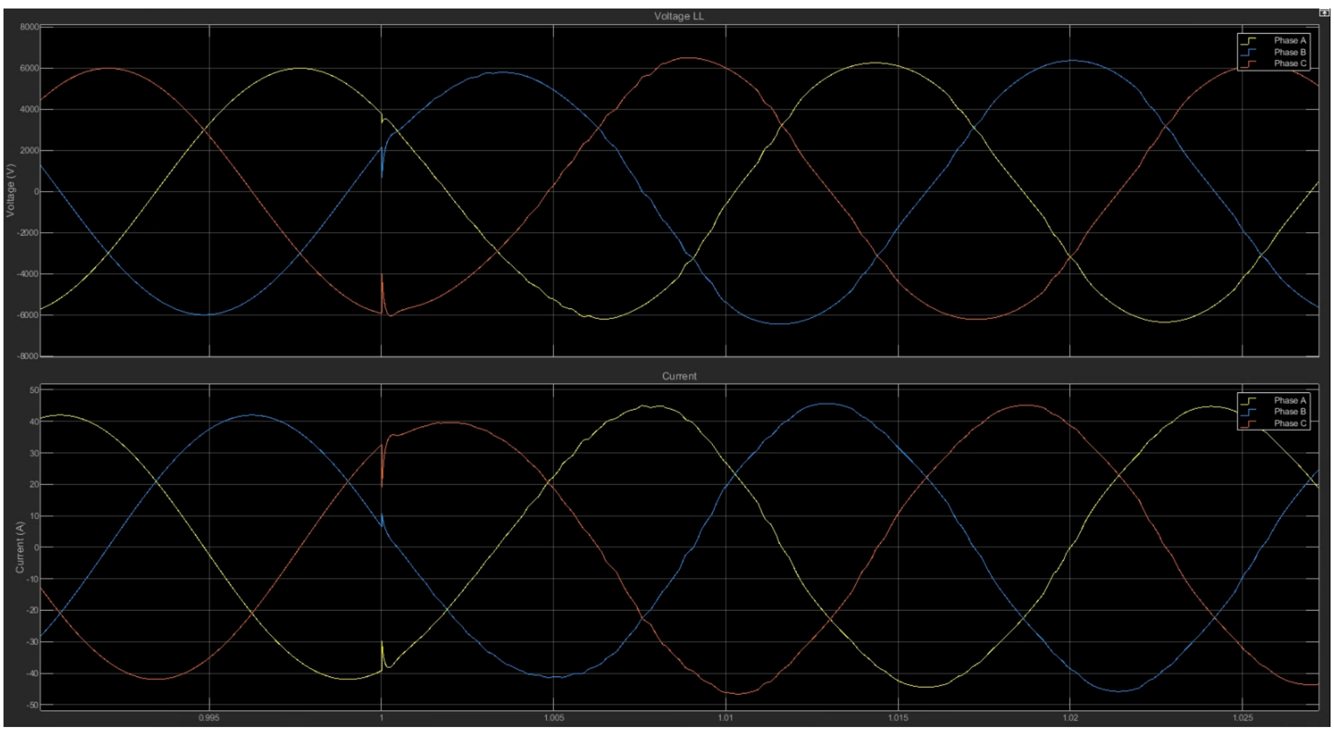


Figure 37: Dynamic Results – Fort Liard Renewable Sources Connection – 25% – Load

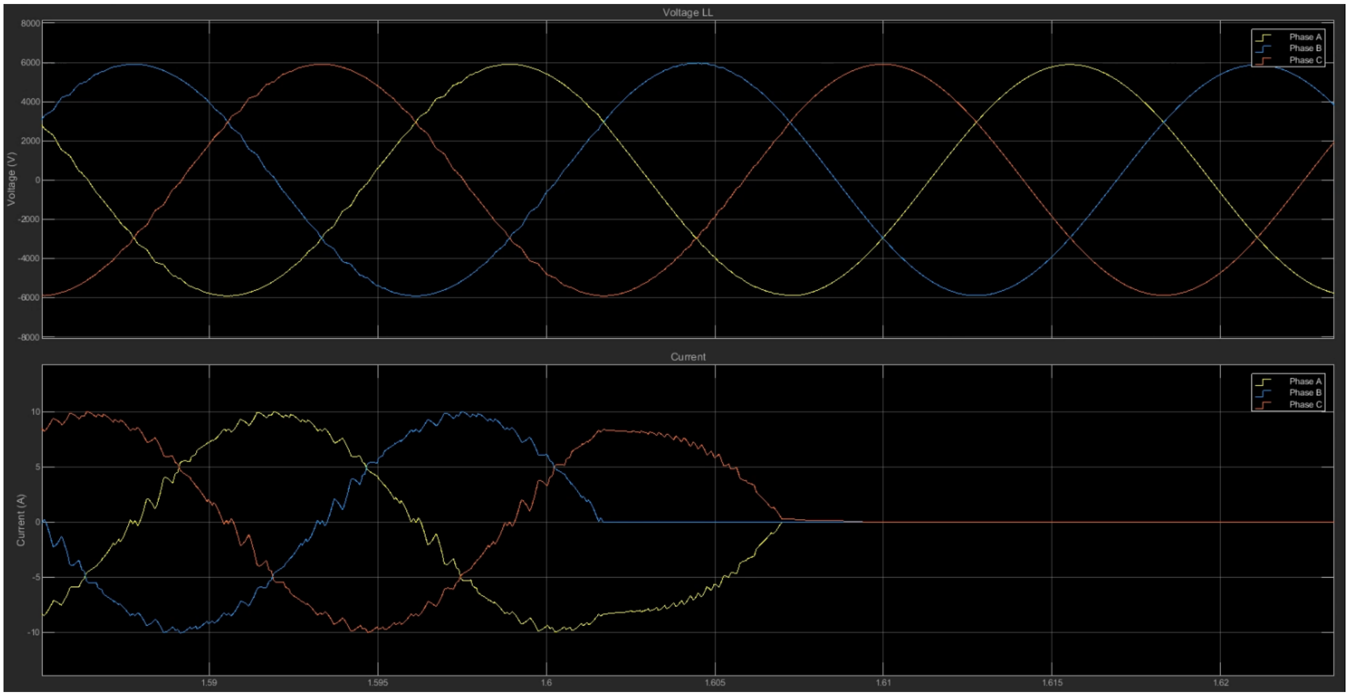


Figure 38: Dynamic Results – Fort Liard Renewable Sources Disconnection – 25% – PV

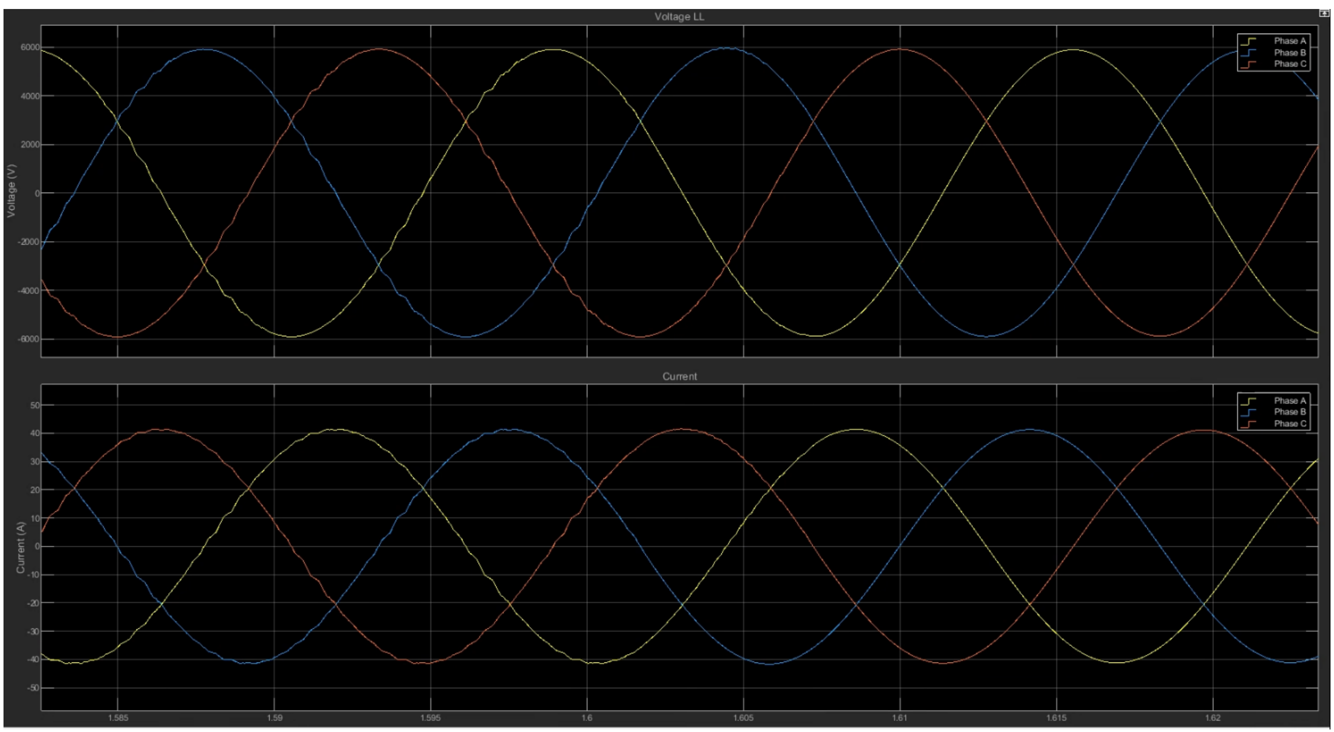


Figure 39: Dynamic Results – Fort Liard Renewable Sources Disconnection – 25% – Load

E.3. Fort Liard 30% Renewable Energy Penetration

E.3.1. Load Increase and Decrease

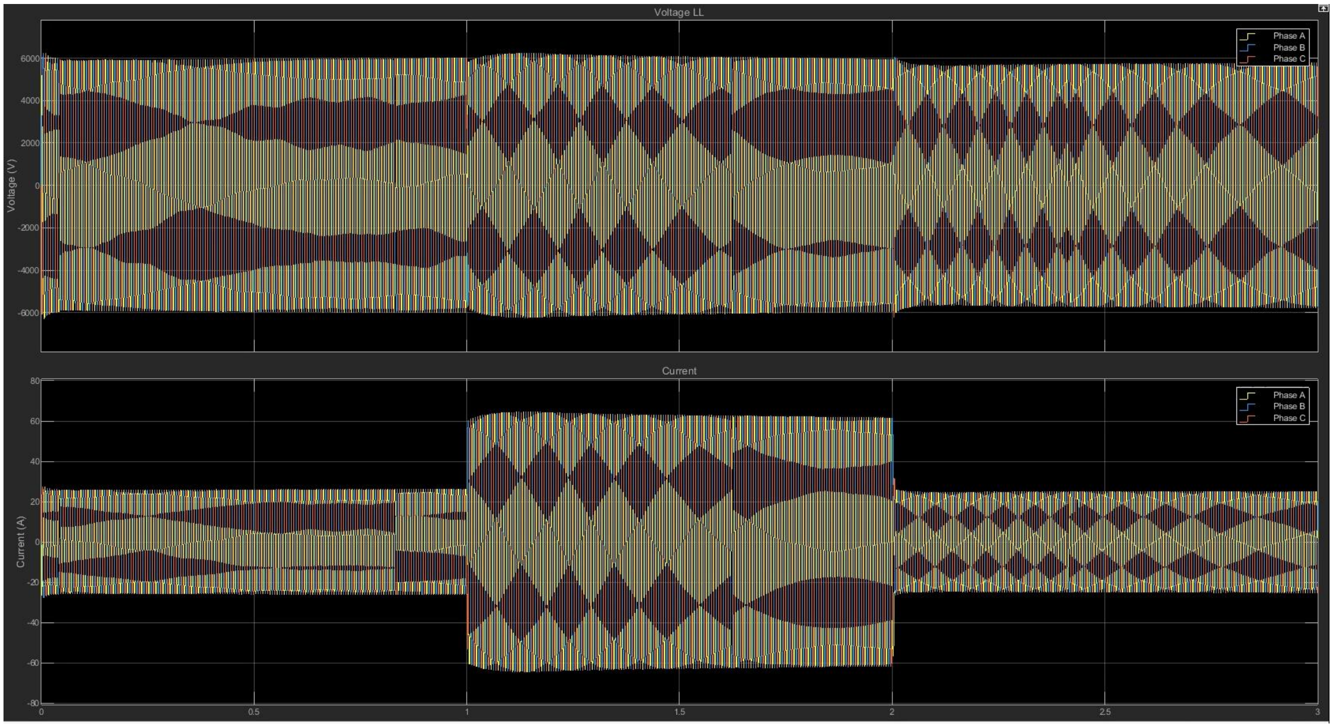


Figure 40: Dynamic Results – Fort Liard Load Variations – 30%

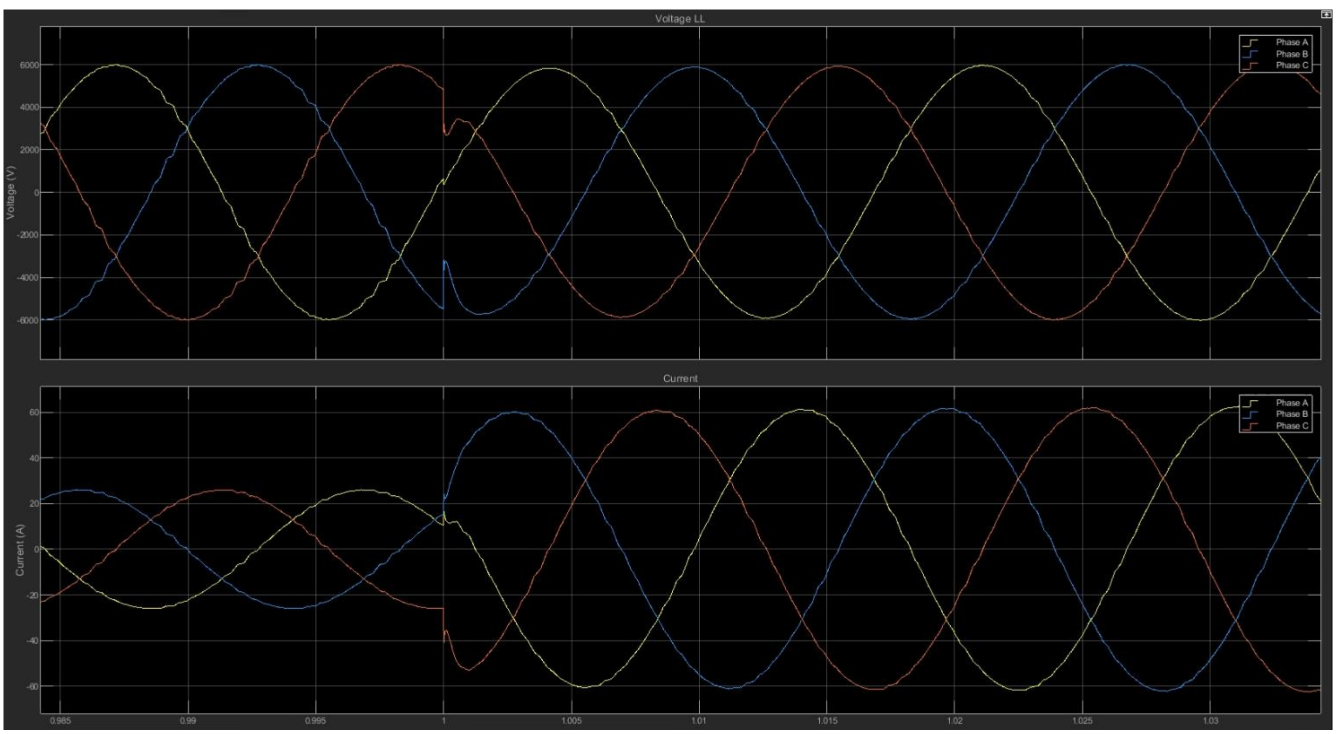


Figure 41: Dynamic Results – Fort Liard Load Increase – 30%

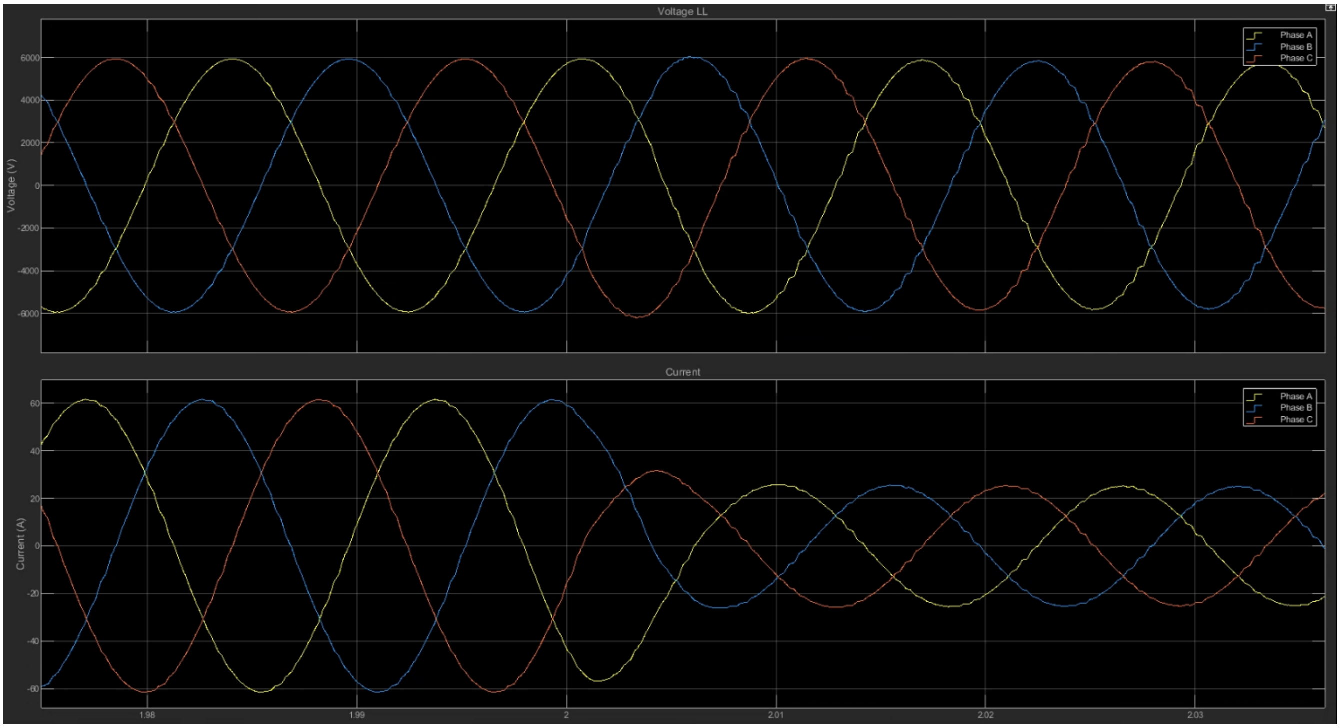


Figure 42: Dynamic Results – Fort Liard Load Decrease – 30%

E.3.2. Renewable Connection / Disconnection

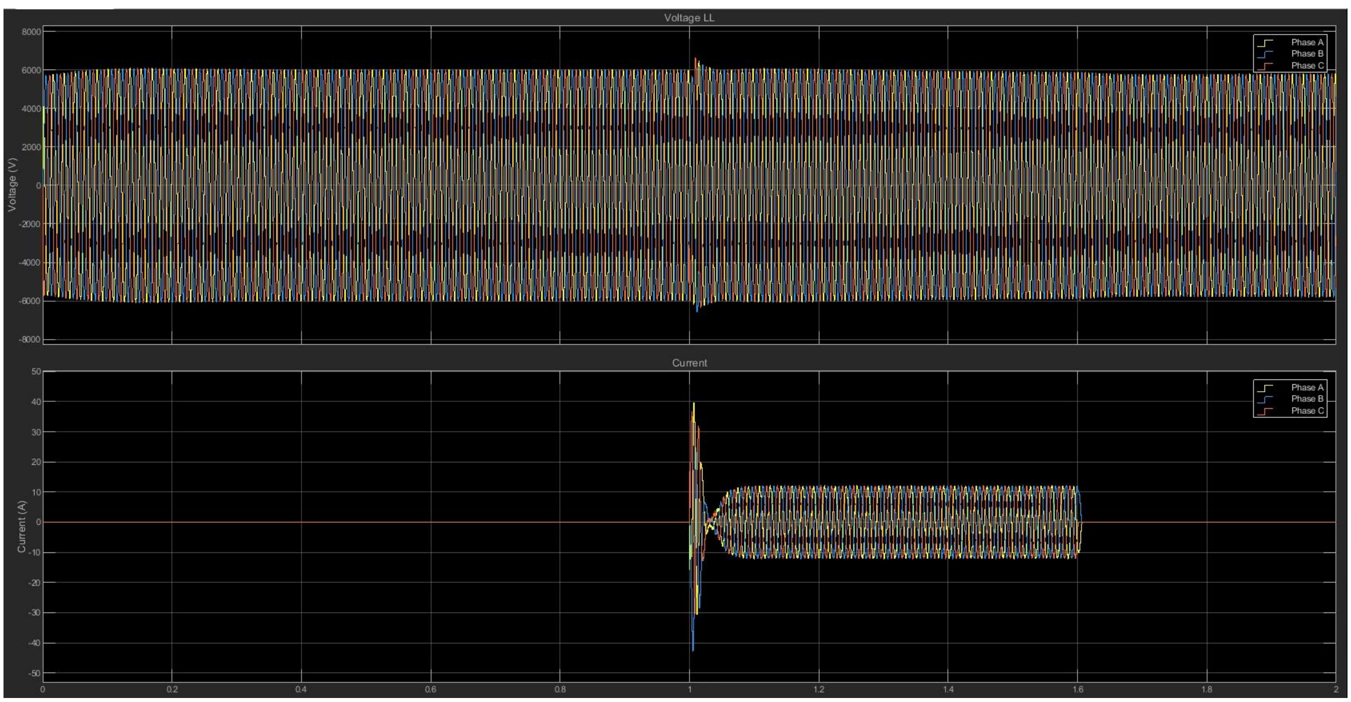


Figure 43: Dynamic Results – Fort Liard Renewable Sources Variation – 30% – PV

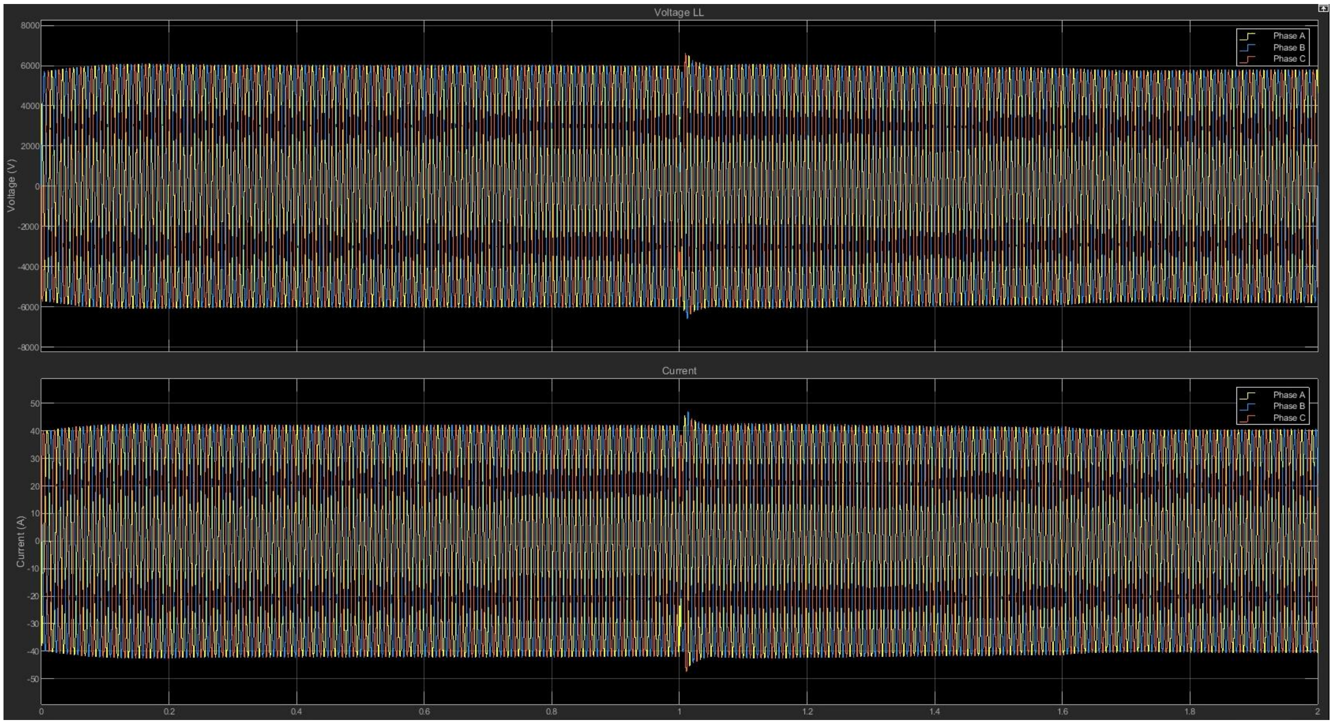


Figure 44: Dynamic Results – Fort Liard Renewable Sources Variation – 30% – Load

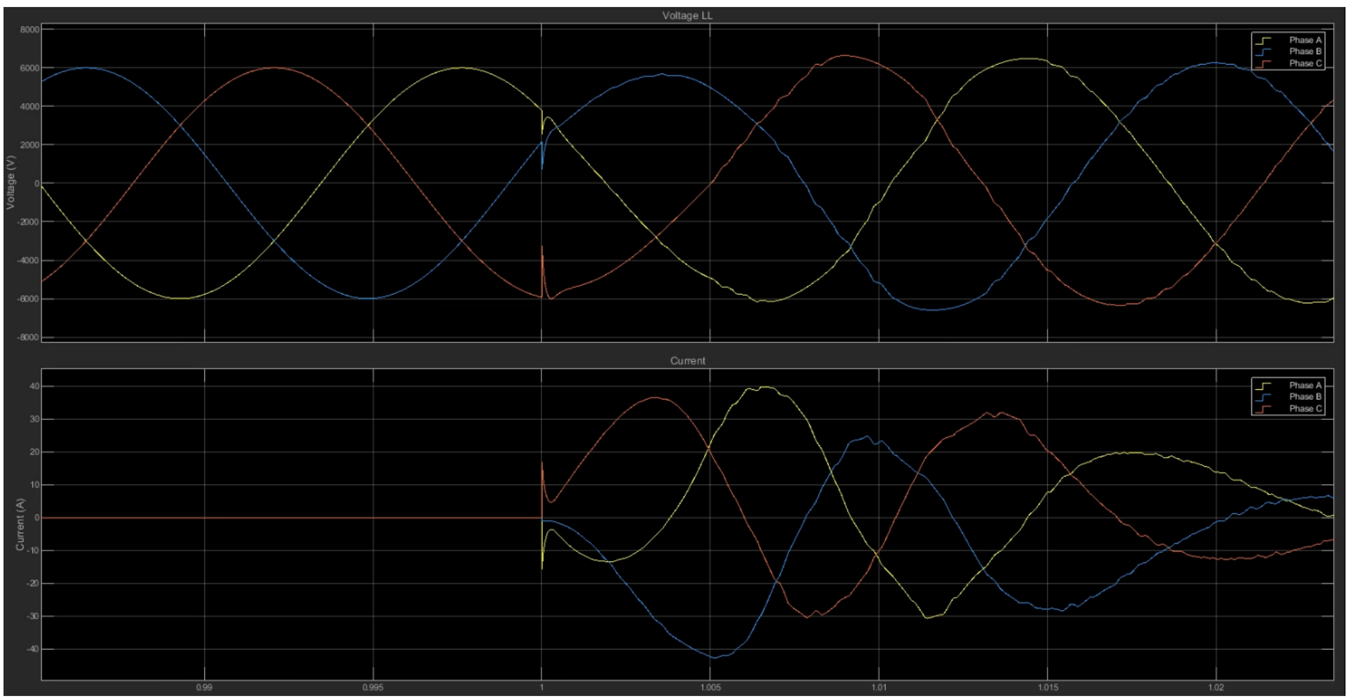


Figure 45: Dynamic Results – Fort Liard Renewable Sources Connection – 30% – PV

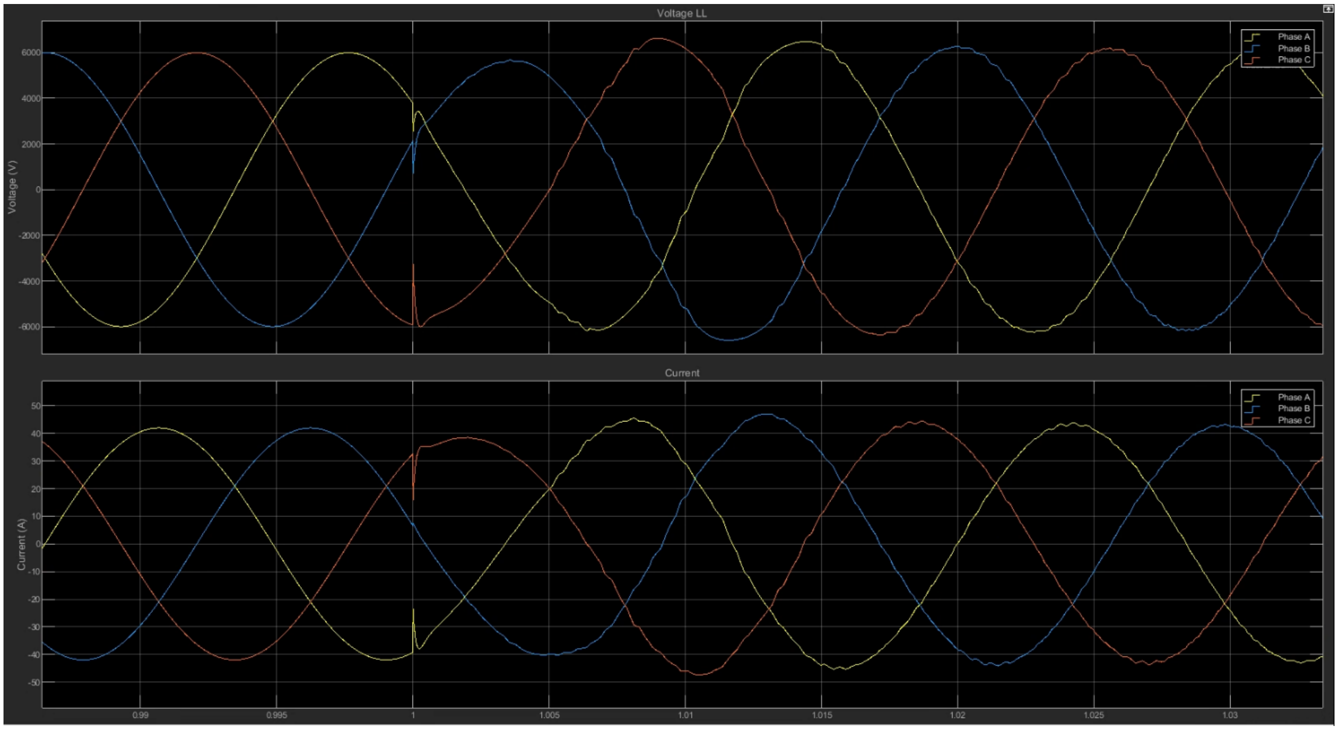


Figure 46: Dynamic Results – Fort Liard Renewable Sources Connection – 30% – Load

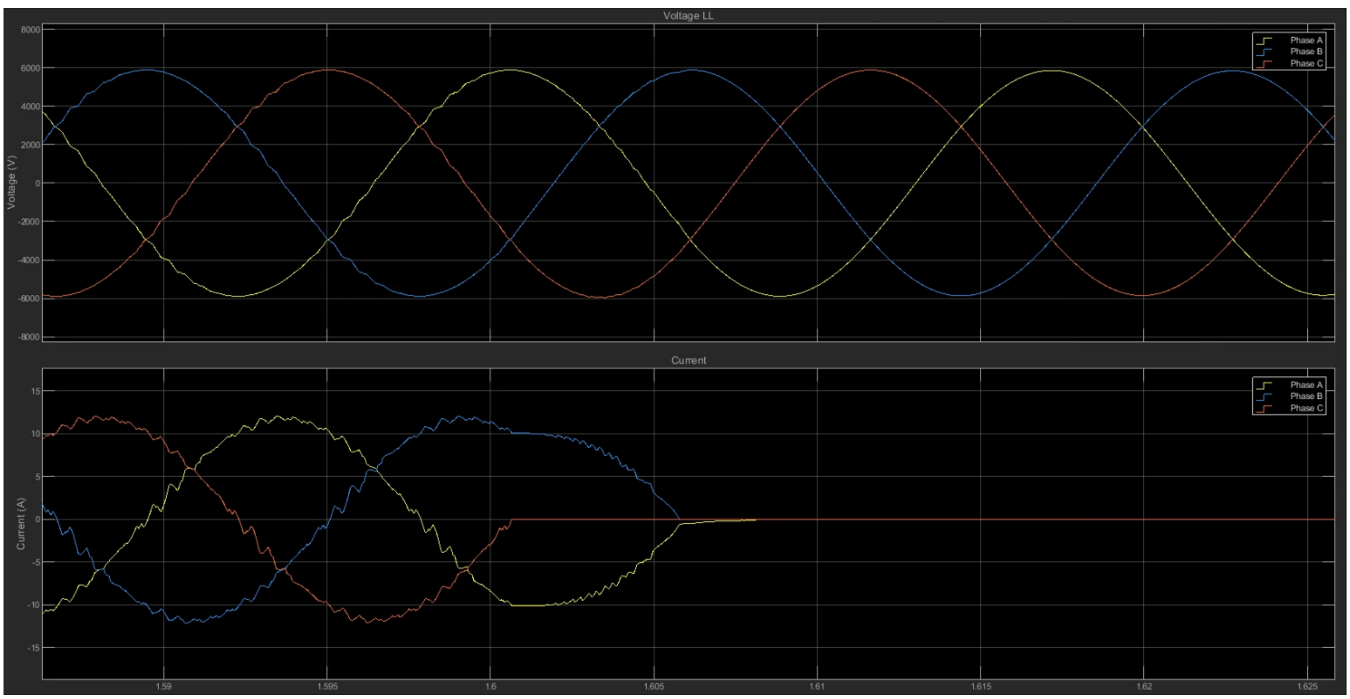


Figure 47: Dynamic Results – Fort Liard Renewable Sources Disconnection – 30% – PV

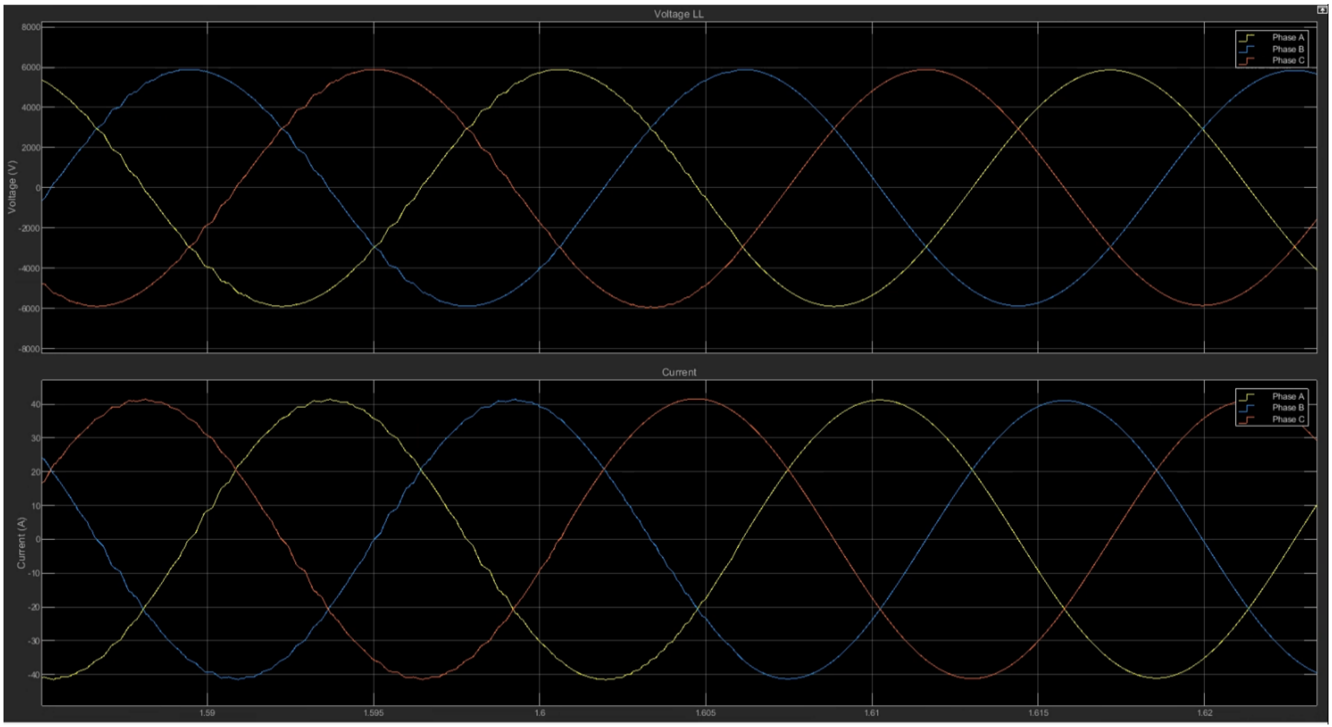


Figure 48: Dynamic Results – Fort Liard Renewable Sources Disconnection – 30% – Load

E.4. Fort Liard 50% Renewable Energy Penetration

E.4.1. Load Increase and Decrease

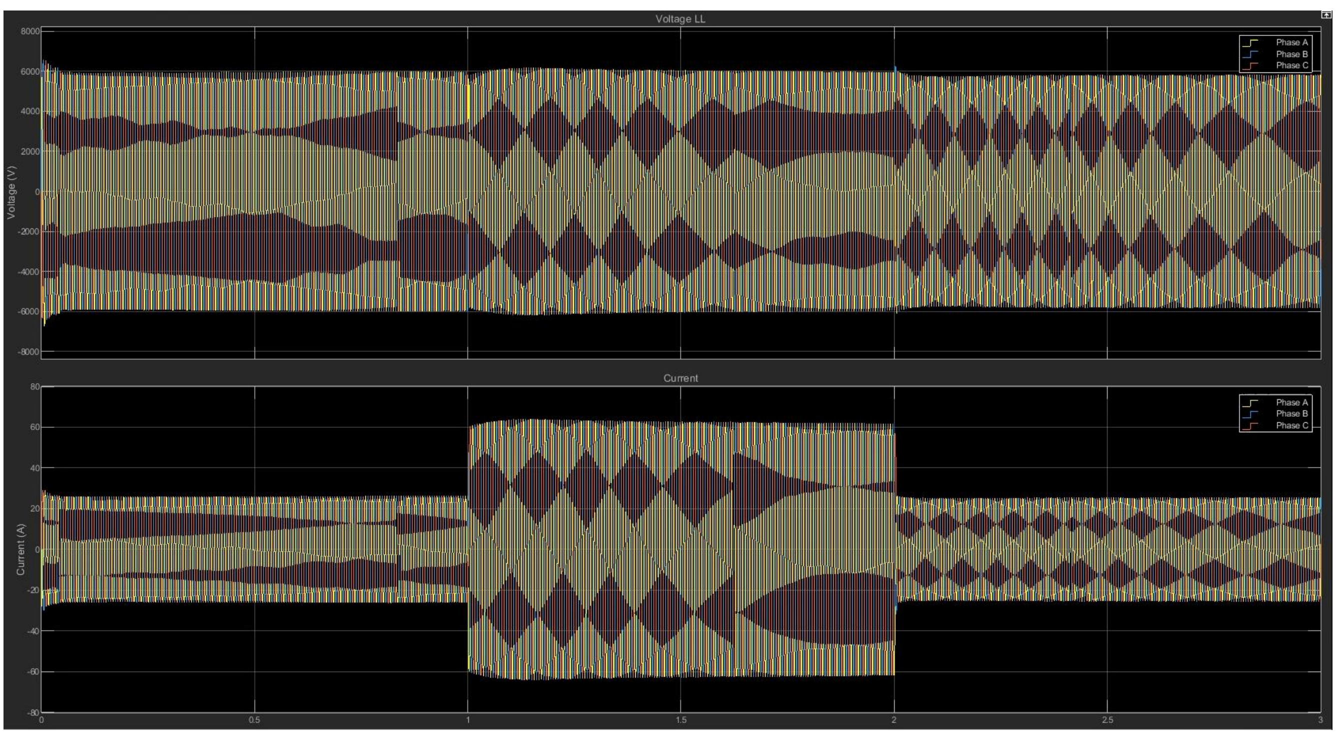


Figure 49: Dynamic Results – Fort Liard Load Variations – 50%

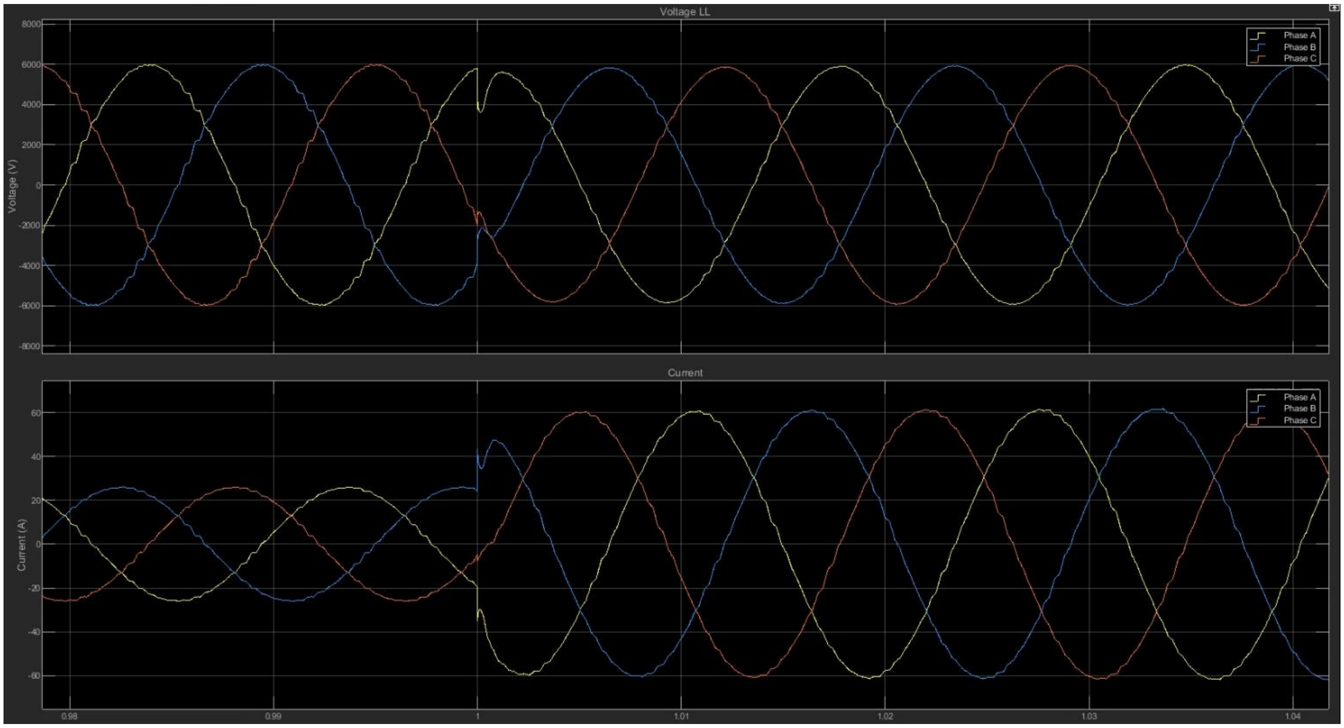


Figure 50: Dynamic Results – Fort Liard Load Increase – 50%

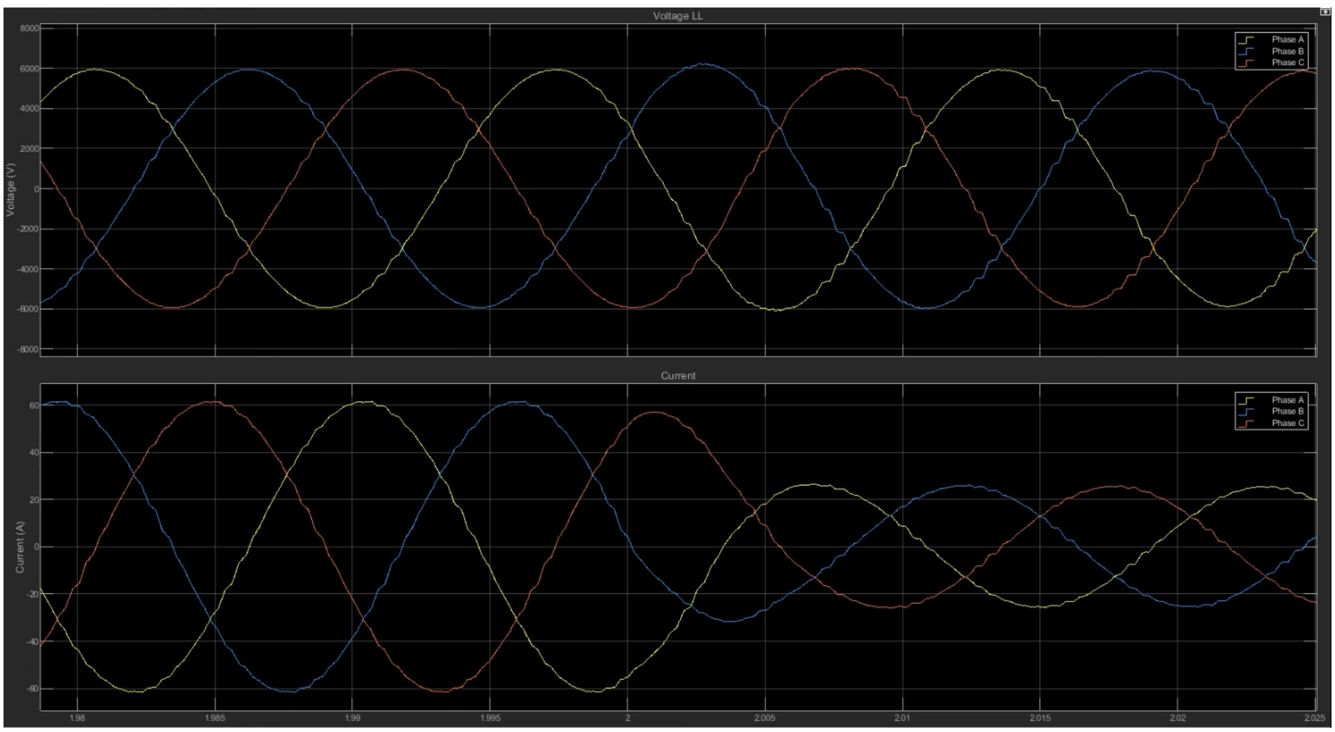


Figure 51: Dynamic Results – Fort Liard Load Decrease – 50%

E.4.2. Renewable Connection / Disconnection

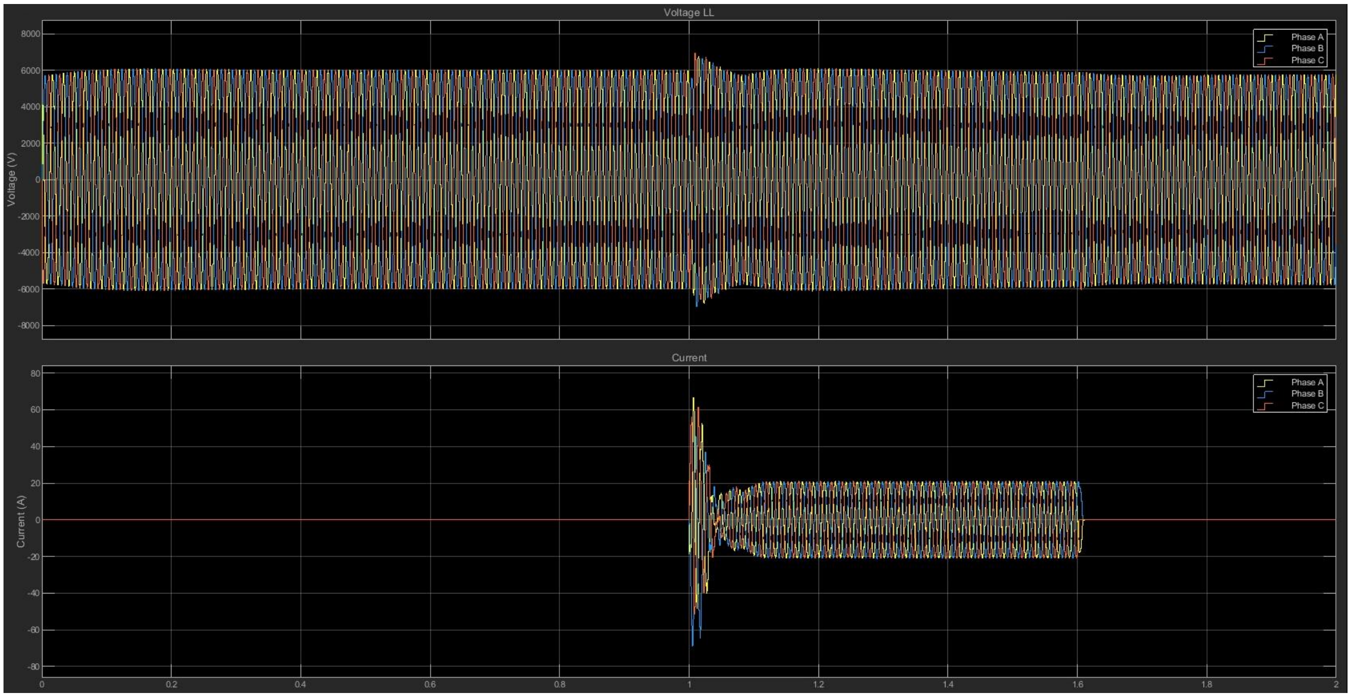


Figure 52: Dynamic Results – Fort Liard Renewable Sources Variation – 50% – PV

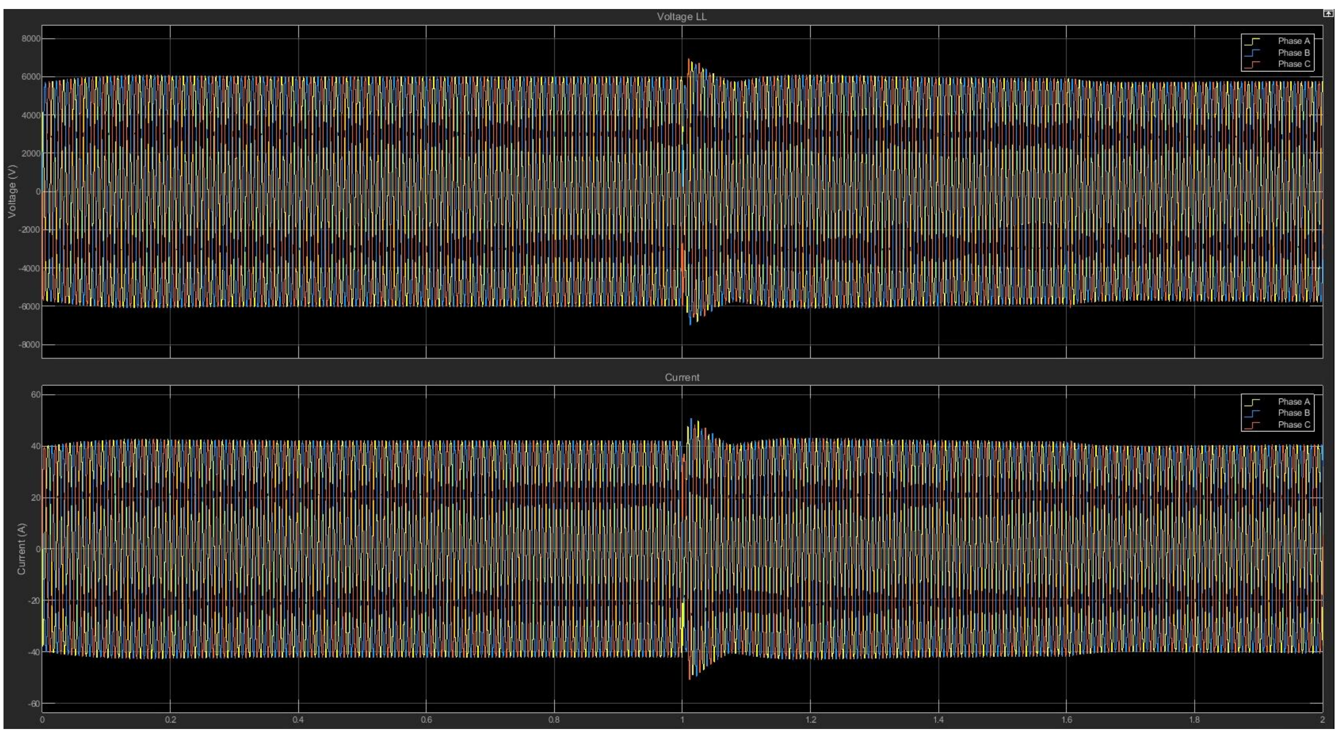


Figure 53: Dynamic Results – Fort Liard Renewable Sources Variation – 50% – Load

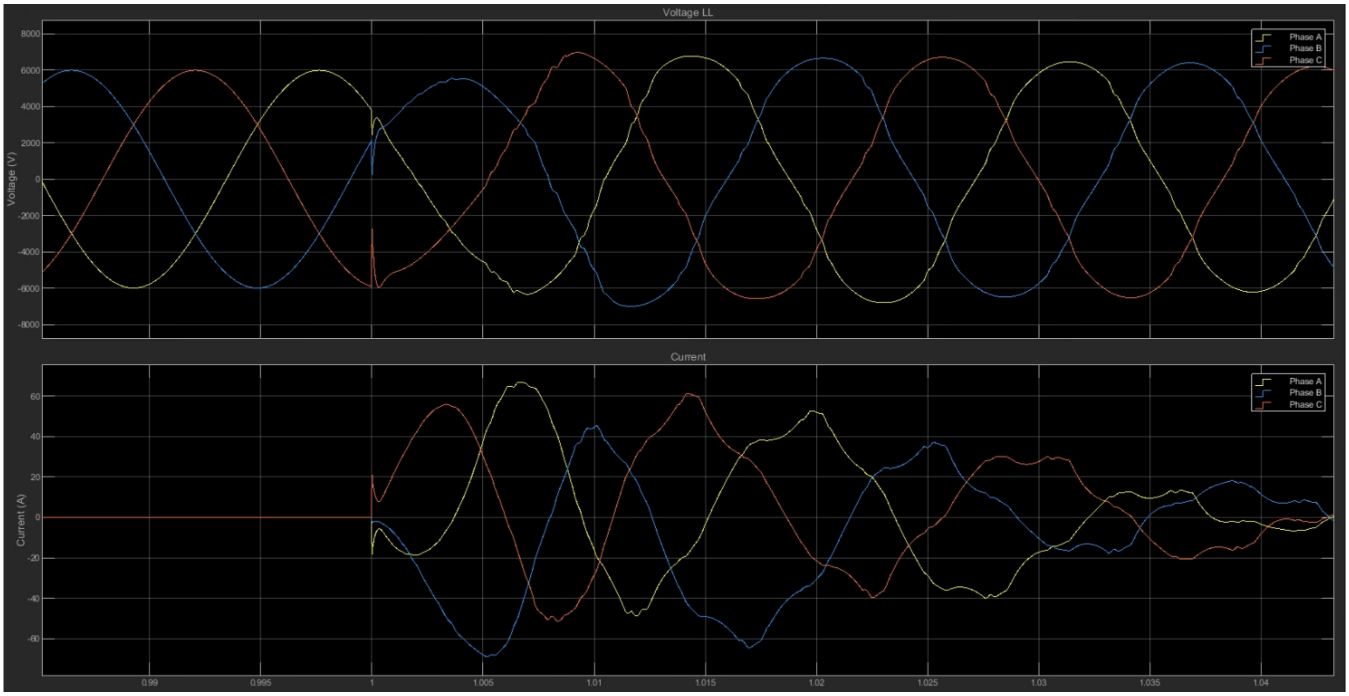


Figure 54: Dynamic Results – Fort Liard Renewable Sources Connection – 50% – PV

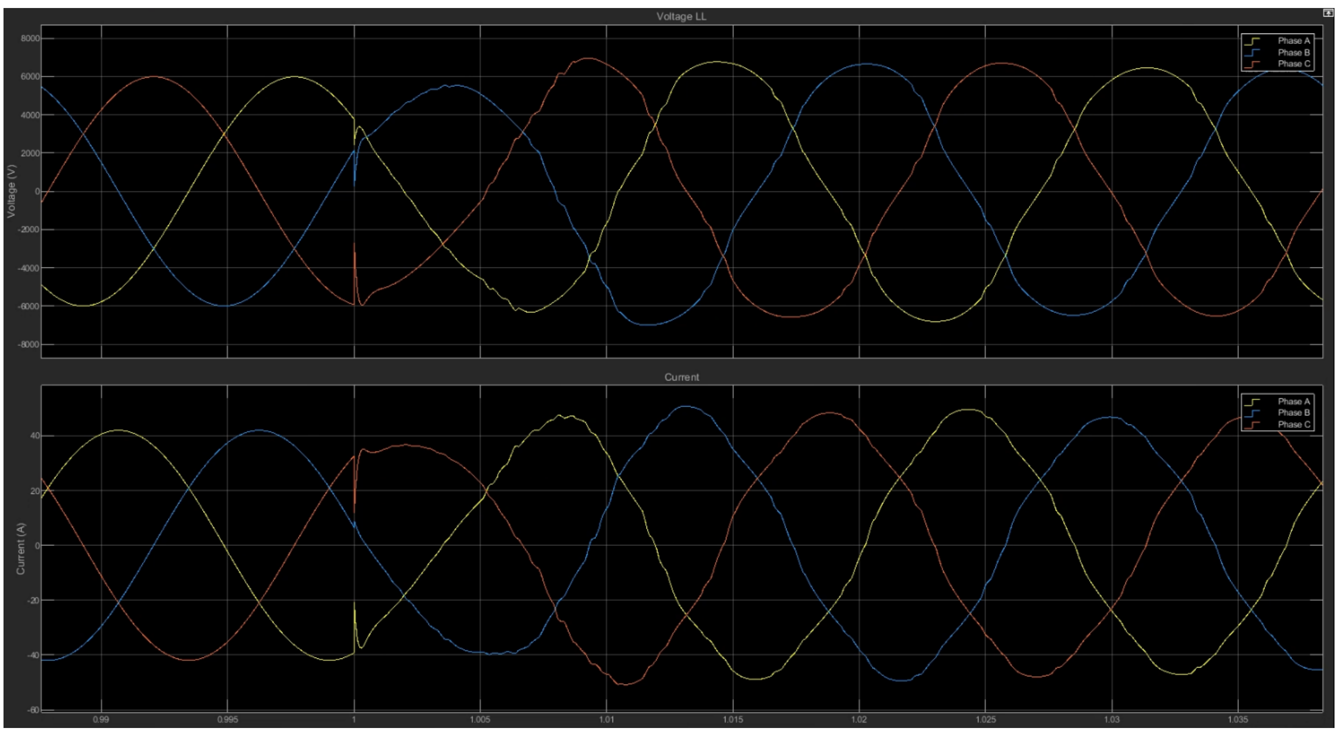


Figure 55: Dynamic Results – Fort Liard Renewable Sources Connection – 50% – Load

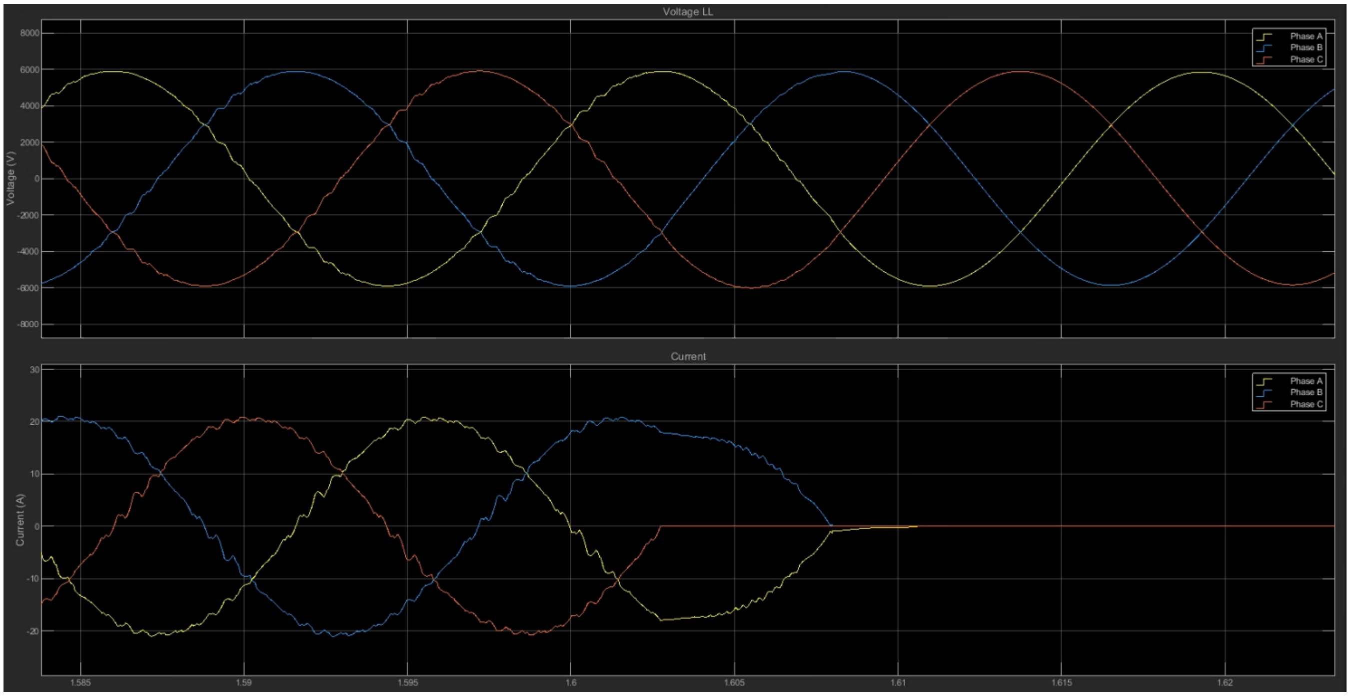


Figure 56: Dynamic Results – Fort Liard Renewable Sources Disconnection – 50% – PV

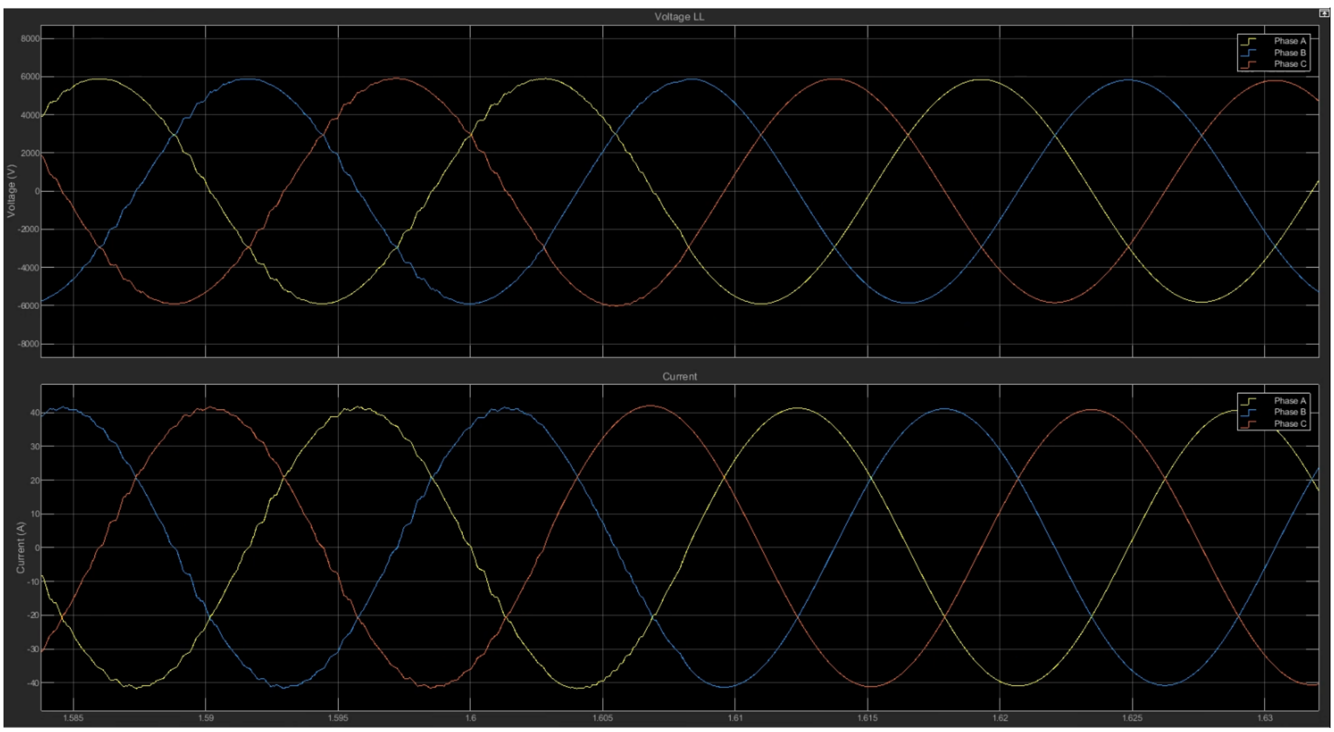


Figure 57: Dynamic Results – Fort Liard Renewable Sources Disconnection – 50% – Load

E.5. Tulita 20% Renewable Energy Penetration

E.5.1. Load Increase and Decrease

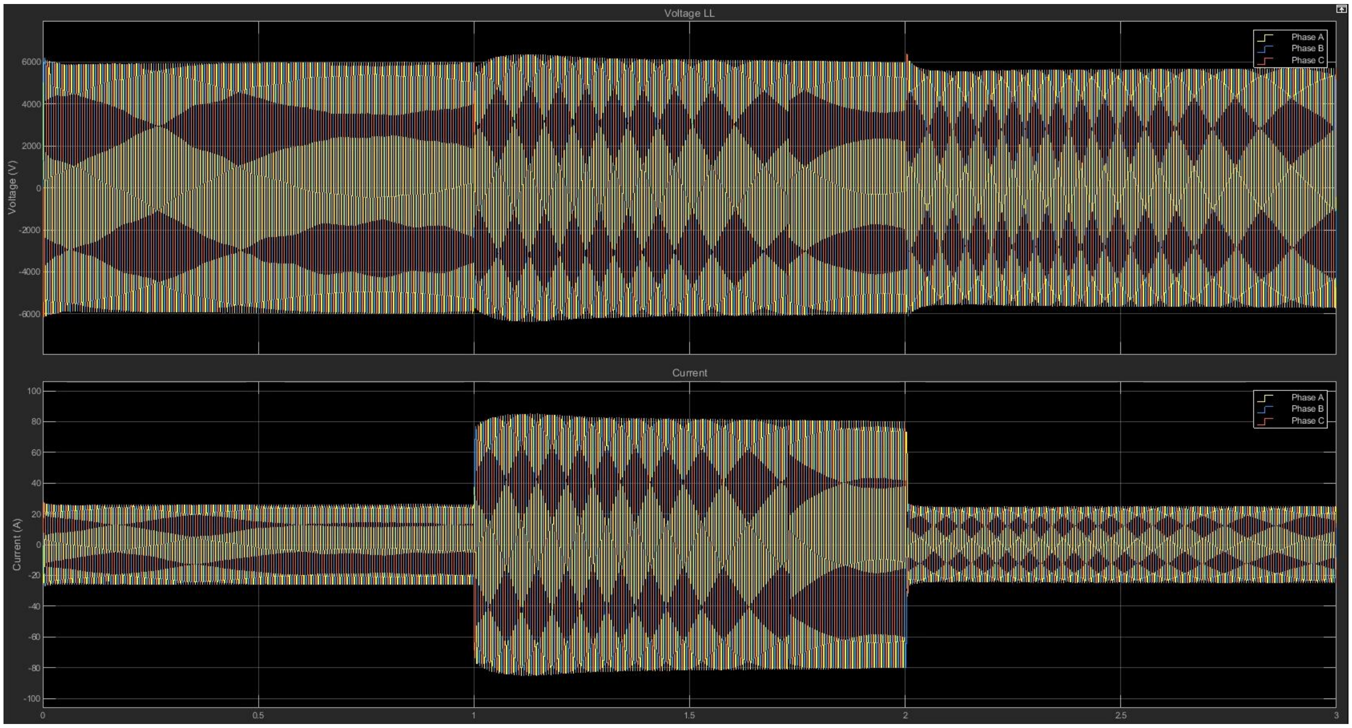


Figure 58: Dynamic Results – Tulita Load Variations – 20%

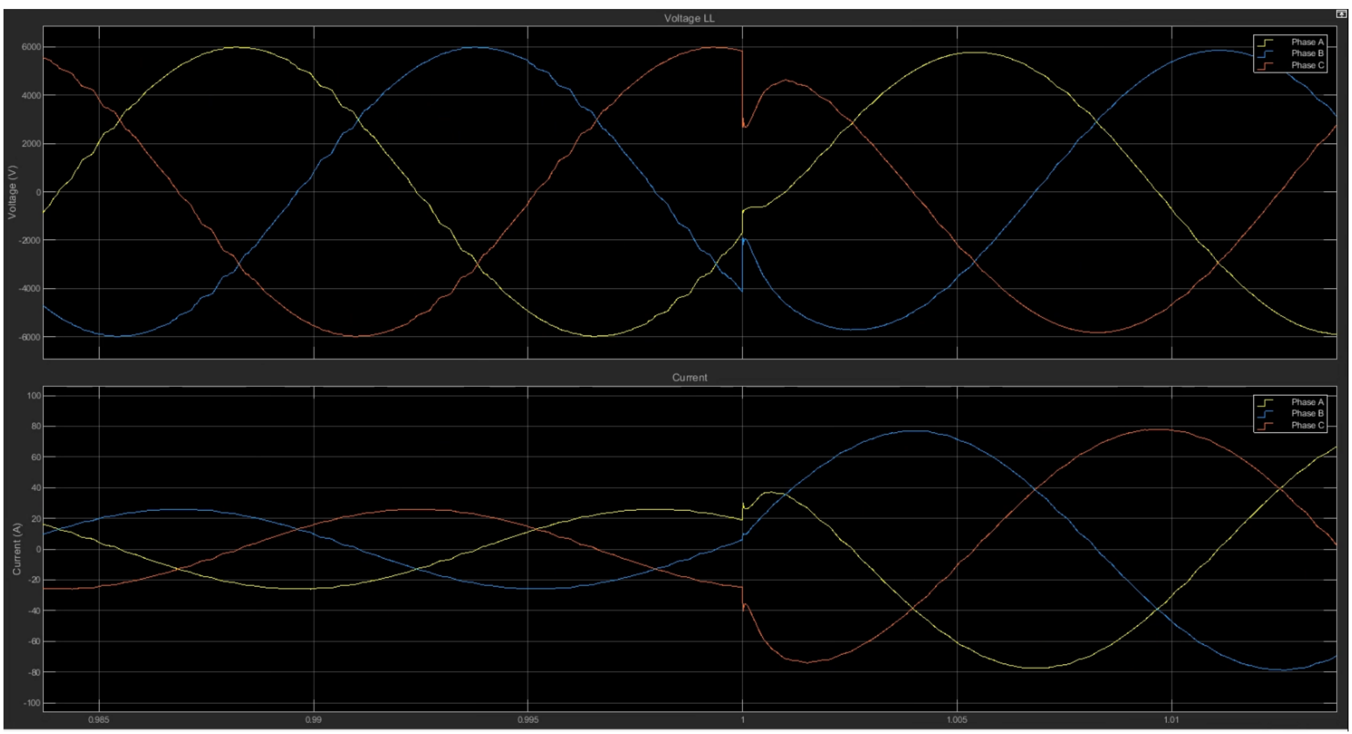


Figure 59: Dynamic Results – Tulita Load Increase – 20%

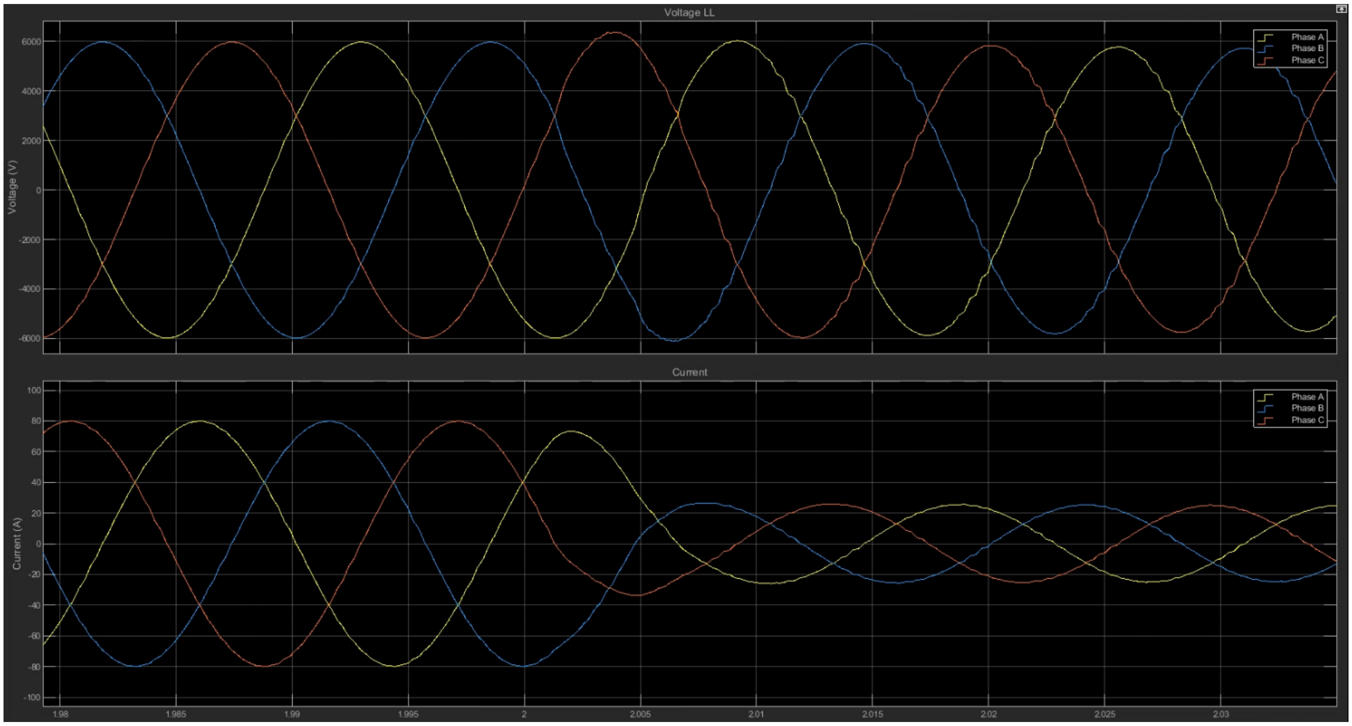


Figure 60: Dynamic Results – Tulita Load Decrease – 20%

E.5.2. Renewable Connection / Disconnection

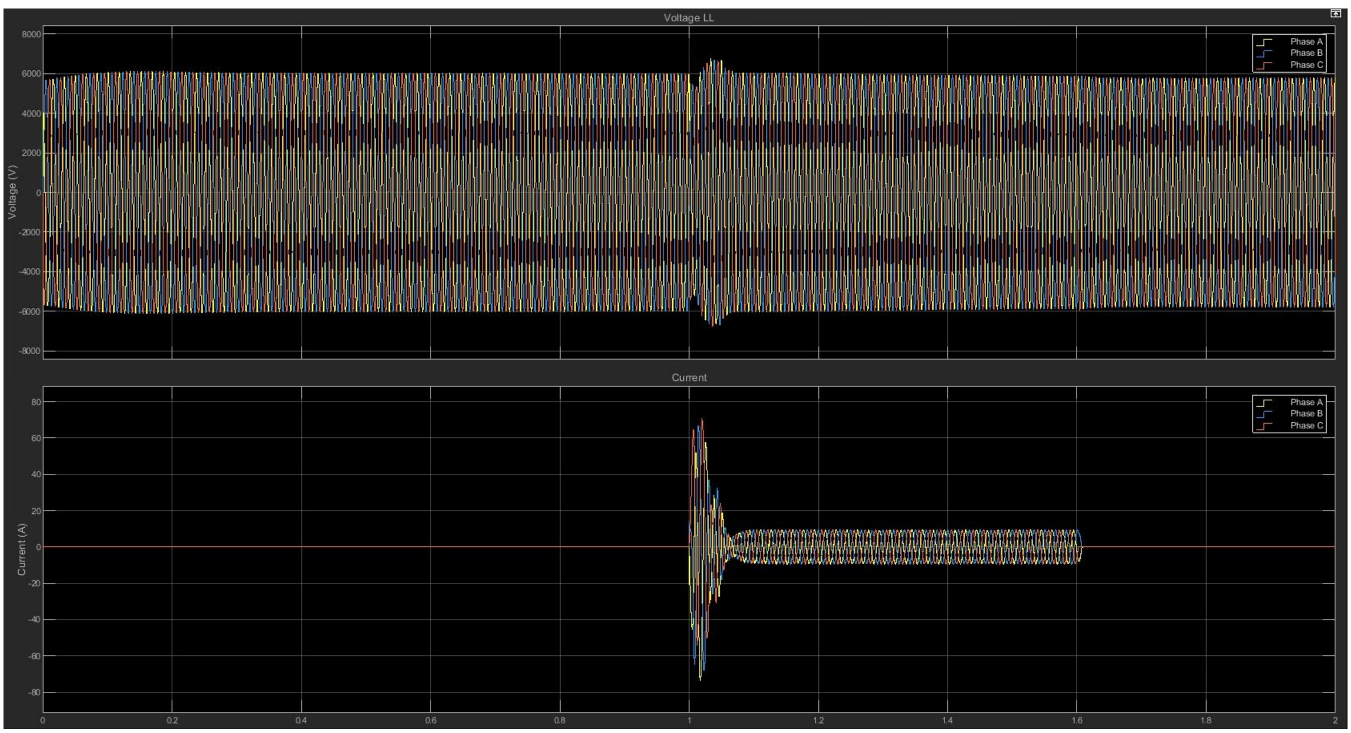


Figure 61: Dynamic Results – Tulita Renewable Sources Variation – 20% – PV

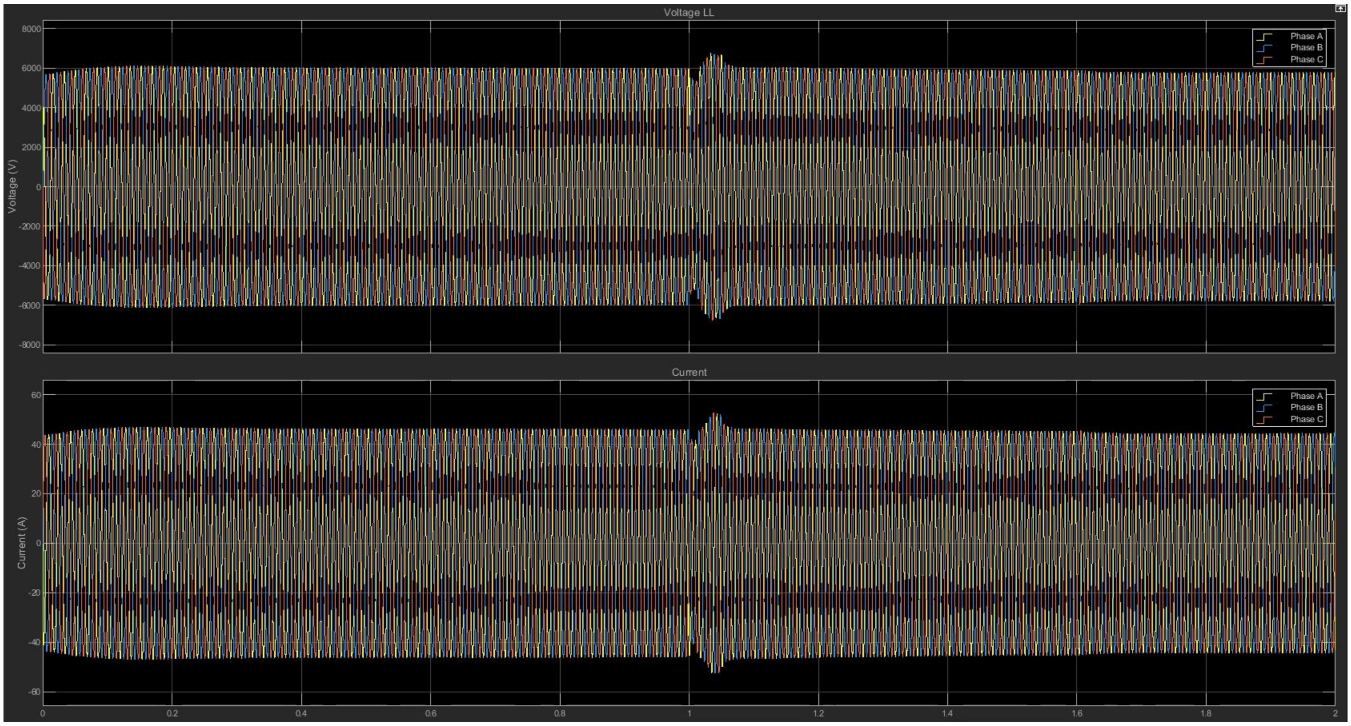


Figure 62: Dynamic Results – Tulita Renewable Sources Variation – 20% – Load

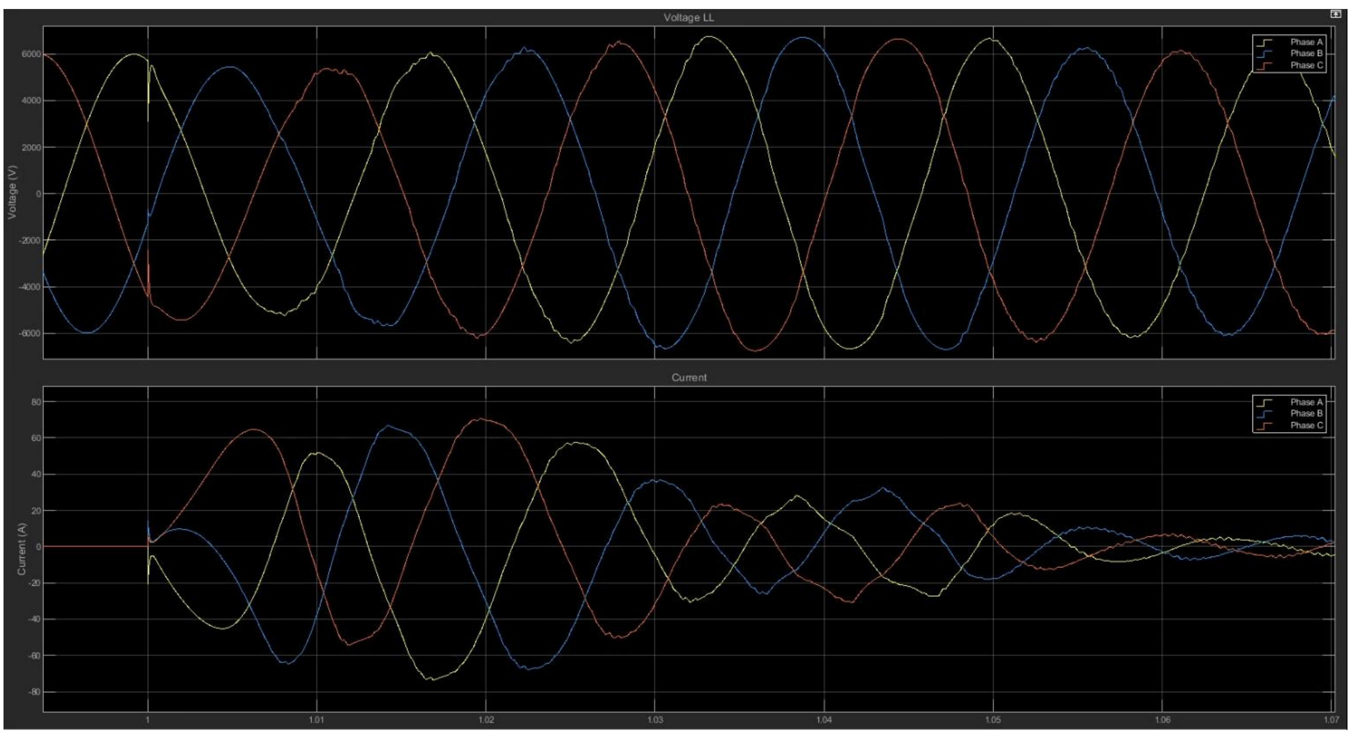


Figure 63: Dynamic Results – Tulita Renewable Sources Connection – 20% – PV

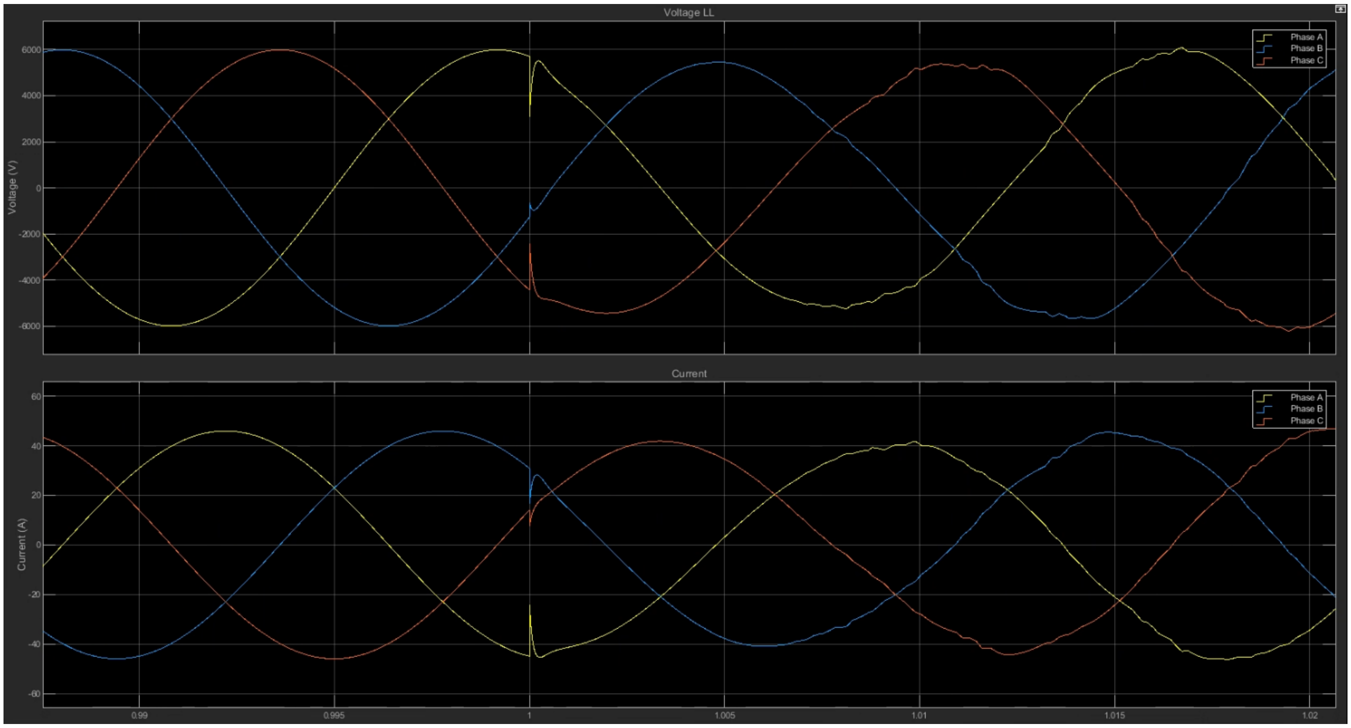


Figure 64: Dynamic Results – Tulita Renewable Sources Connection – 20% – Load

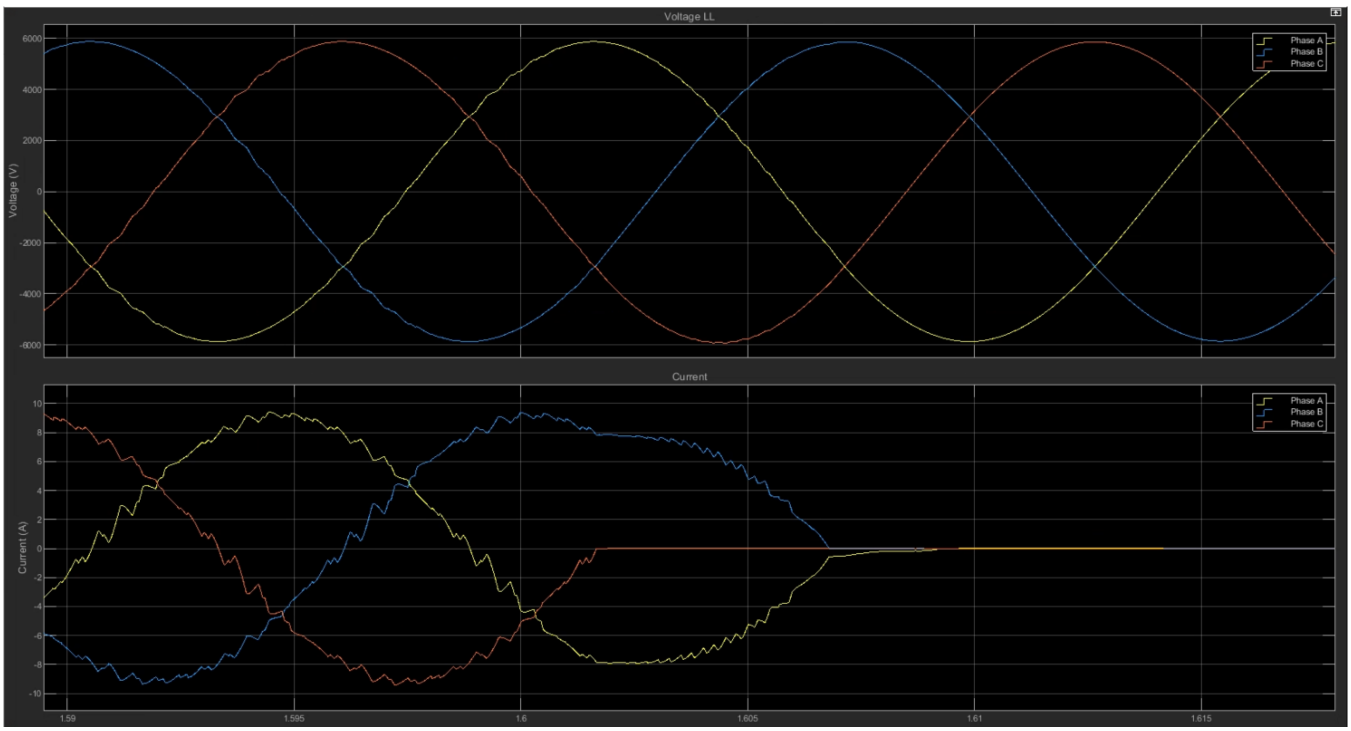


Figure 65: Dynamic Results – Tulita Renewable Sources Disconnection – 20% – PV

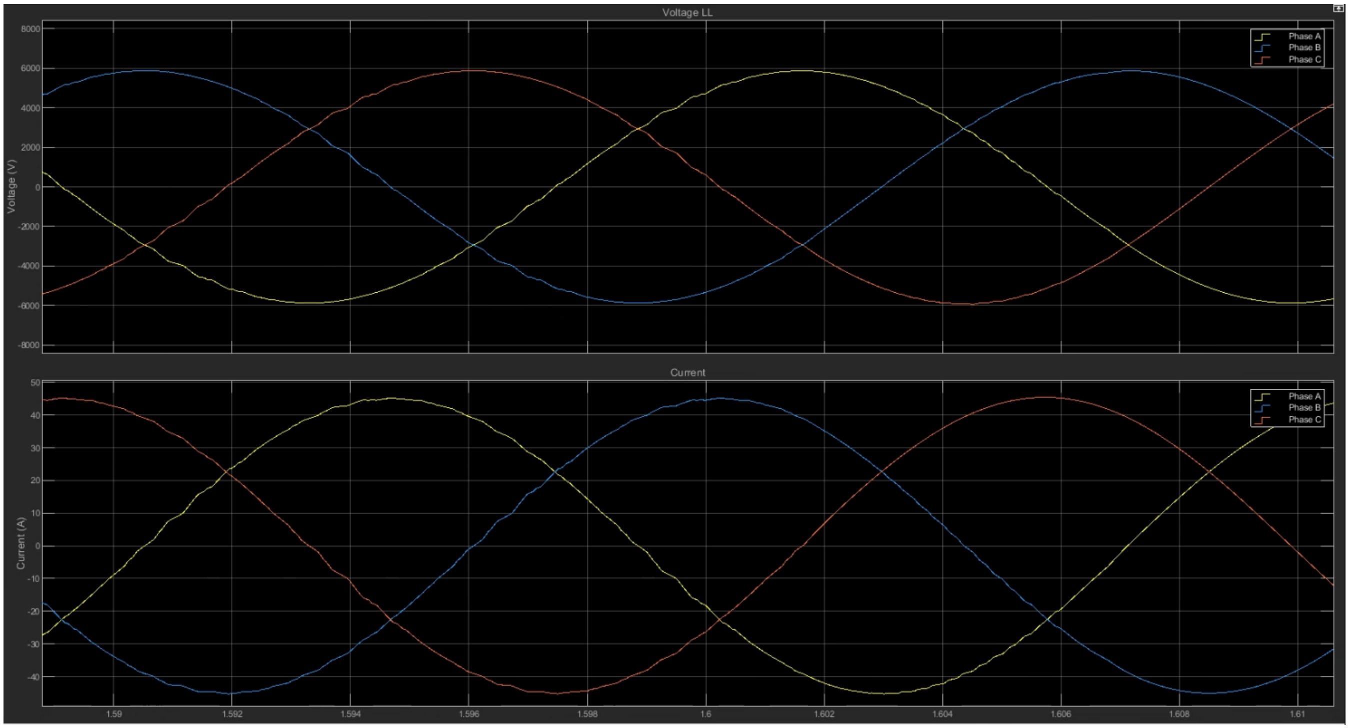


Figure 66: Dynamic Results – Tulita Renewable Sources Disconnection – 20% – Load

E.6. Tulita 25% Renewable Energy Penetration

E.6.1. Load Increase and Decrease

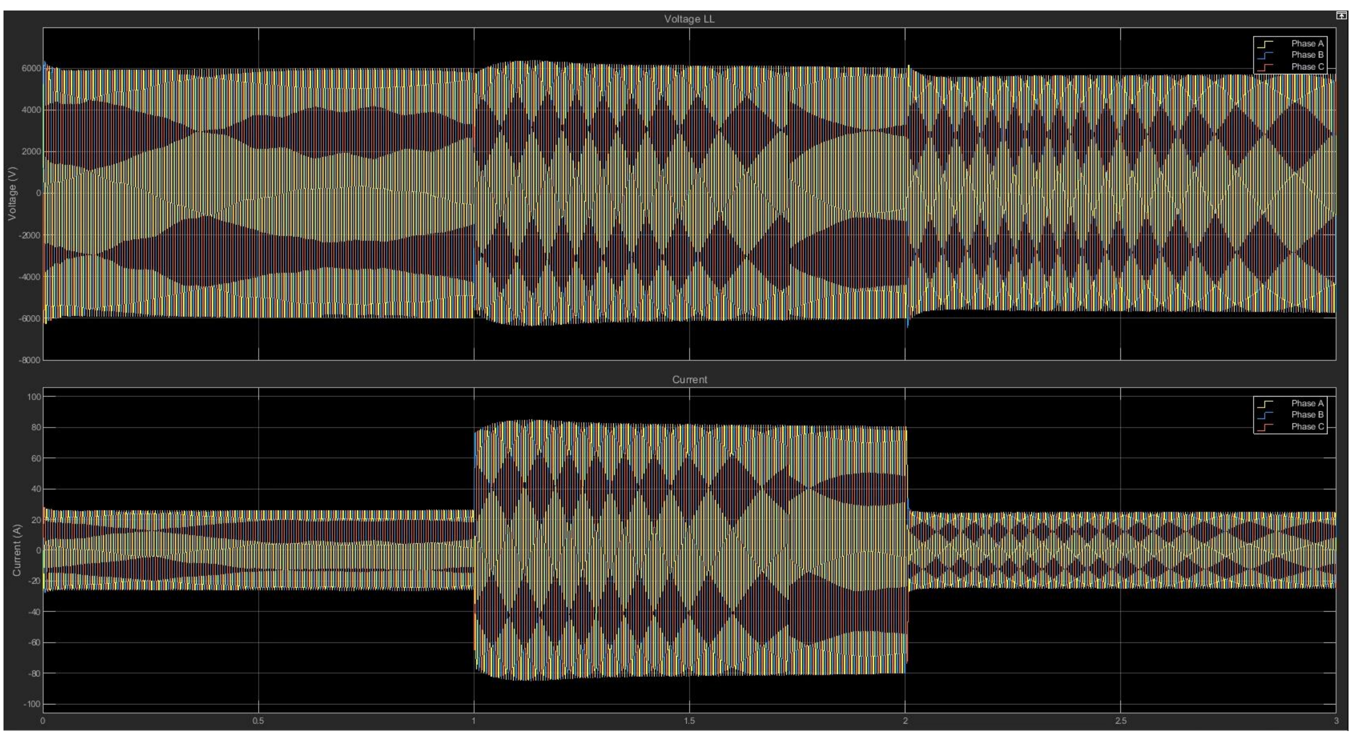


Figure 67: Dynamic Results – Tulita Load Variations – 25%

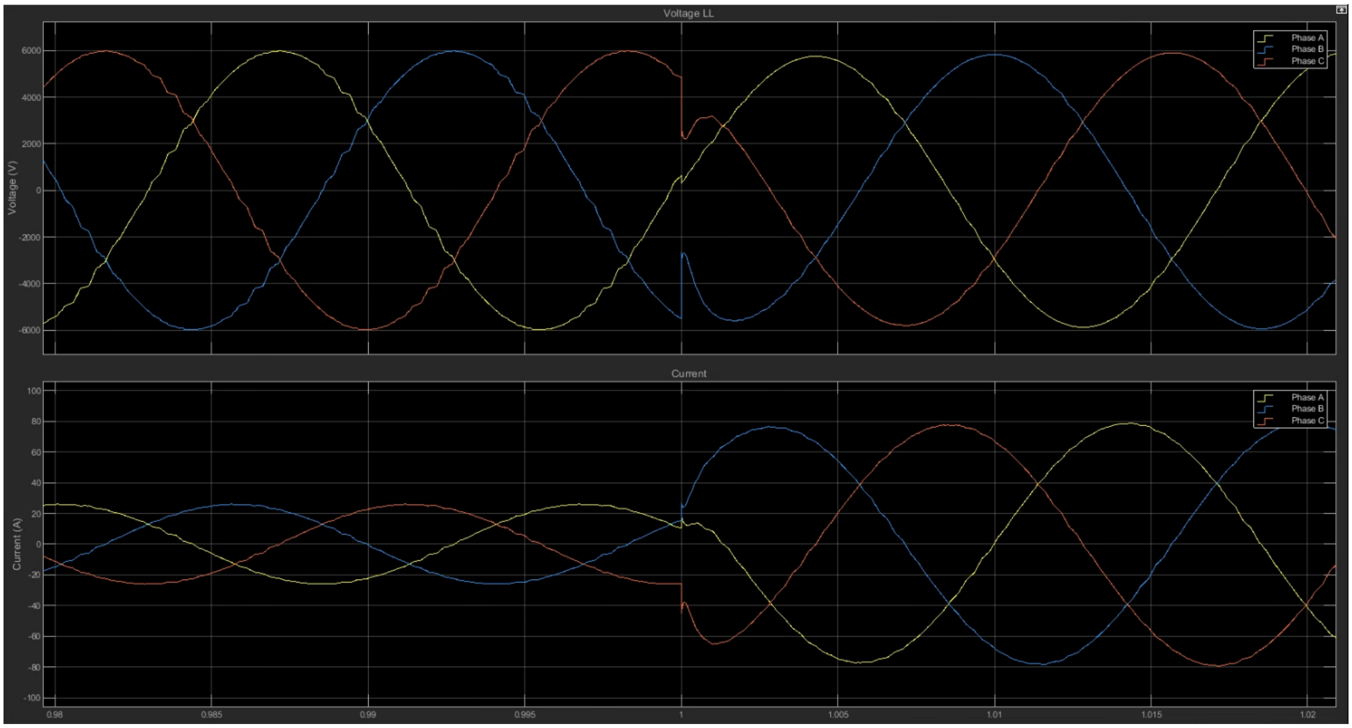


Figure 68: Dynamic Results – Tulita Load Increase – 25%

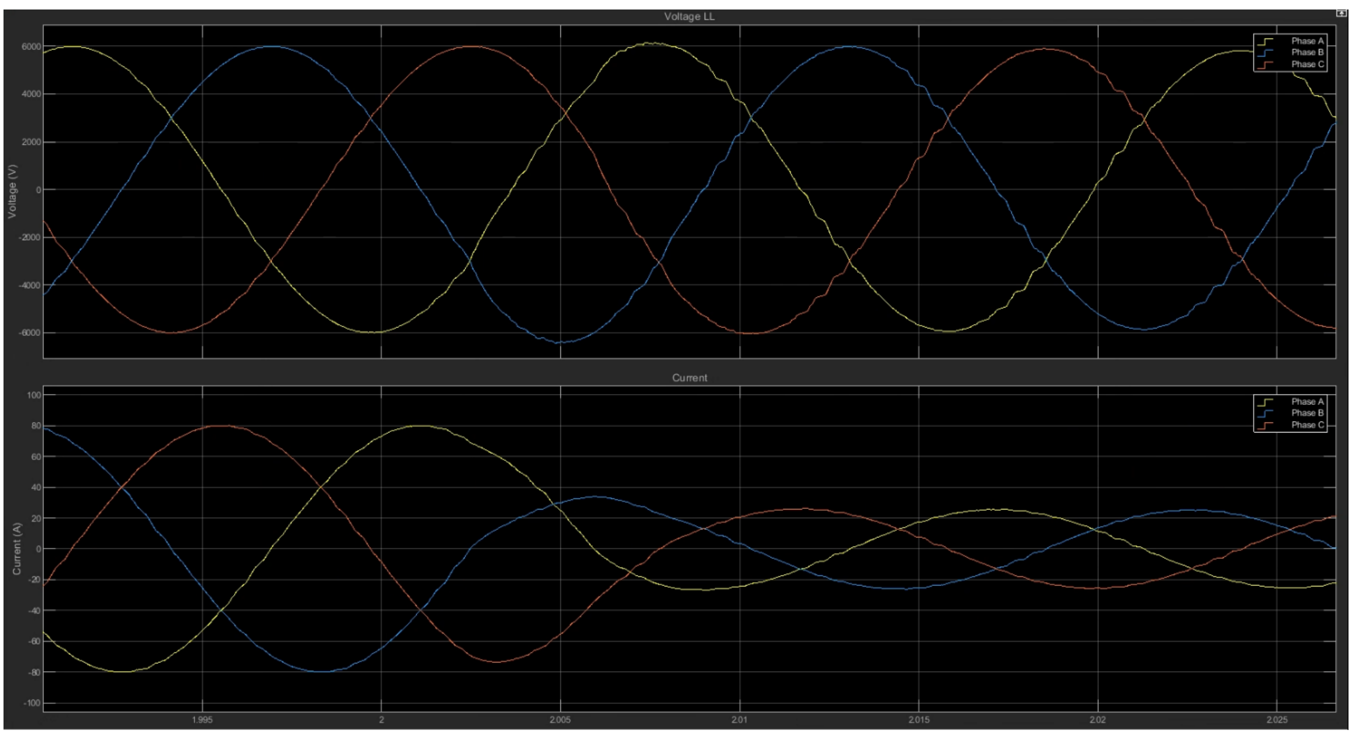


Figure 69: Dynamic Results – Tulita Load Decrease – 25%

E.6.2. Renewable Connection / Disconnection

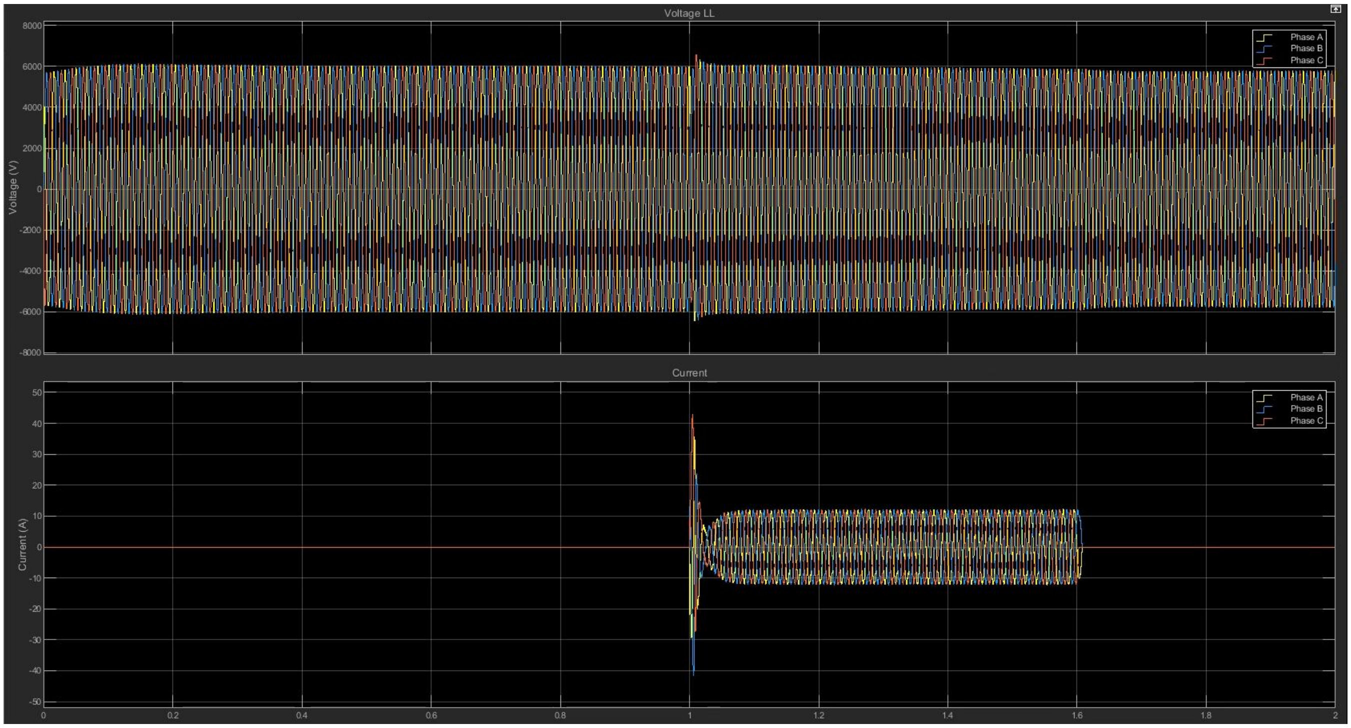


Figure 70: Dynamic Results – Tulita Renewable Sources Variation – 25% – PV

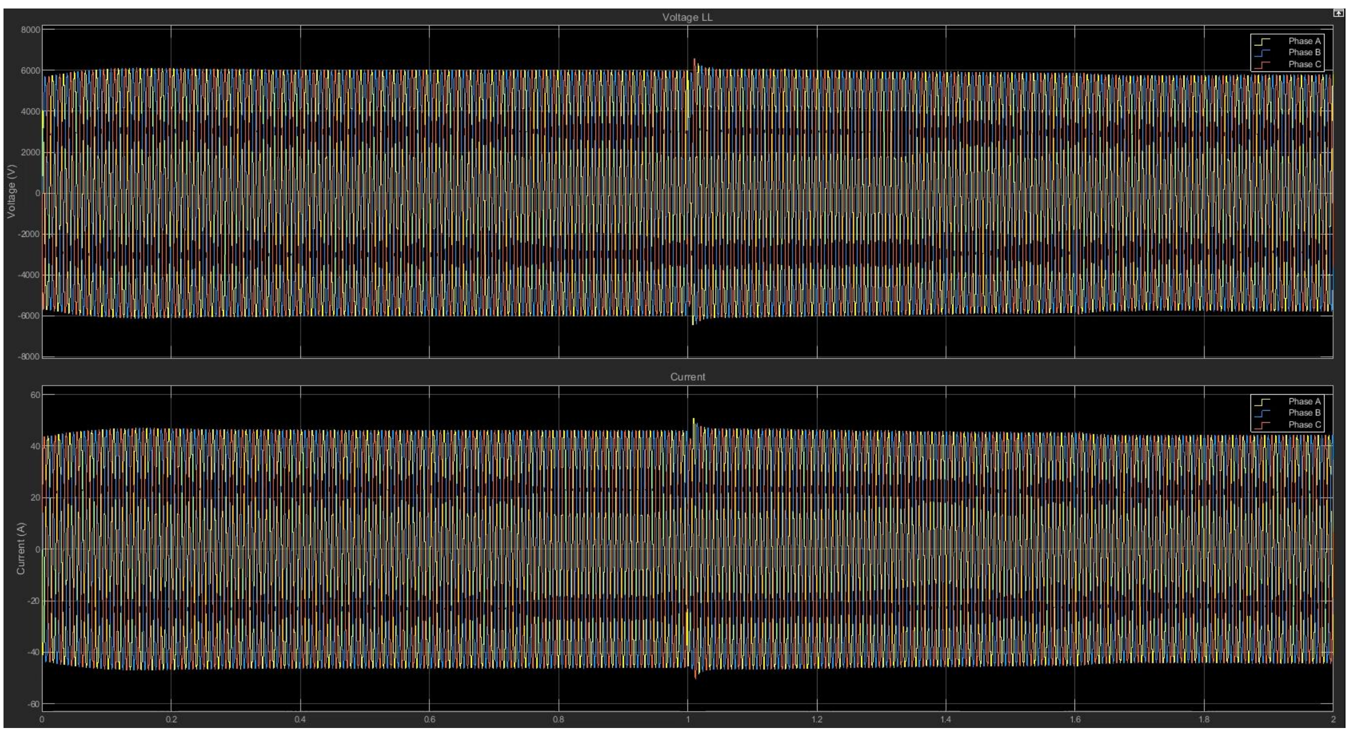


Figure 71: Dynamic Results – Tulita Renewable Sources Variation – 25% – Load

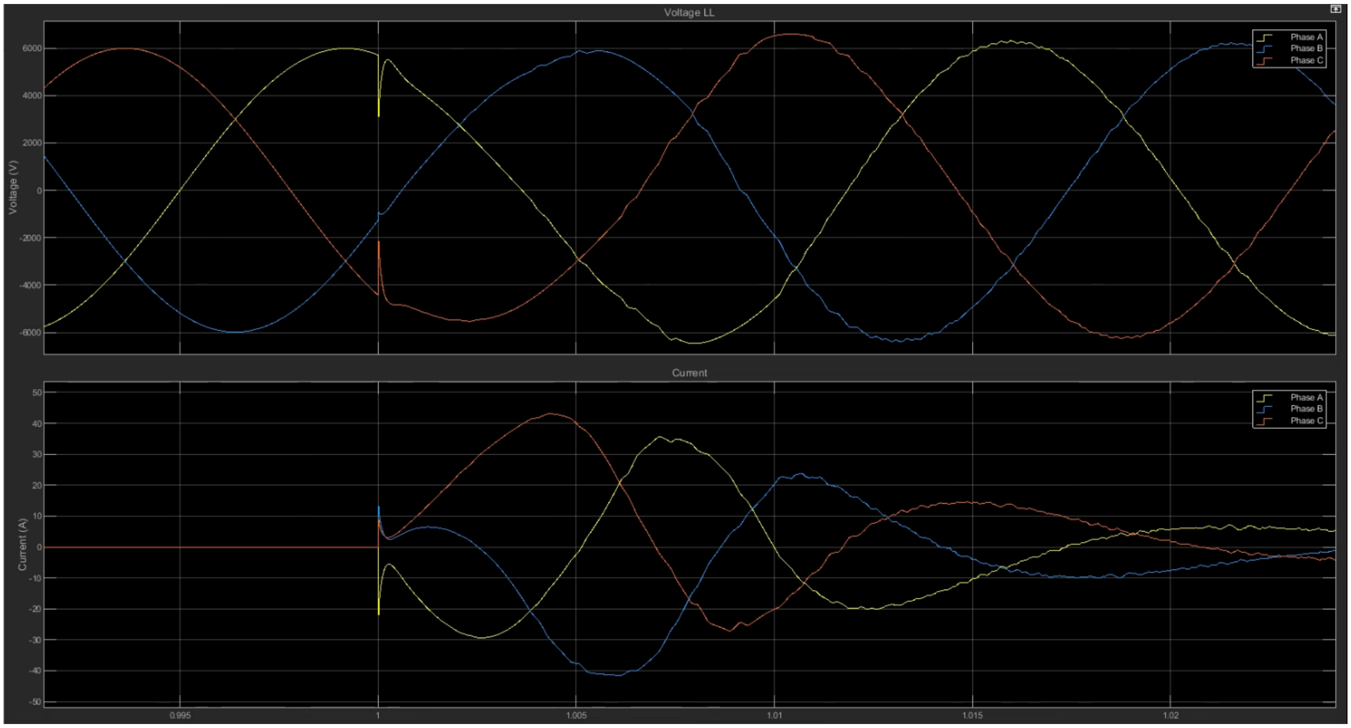


Figure 72: Dynamic Results – Tulita Renewable Sources Connection – 25% – PV

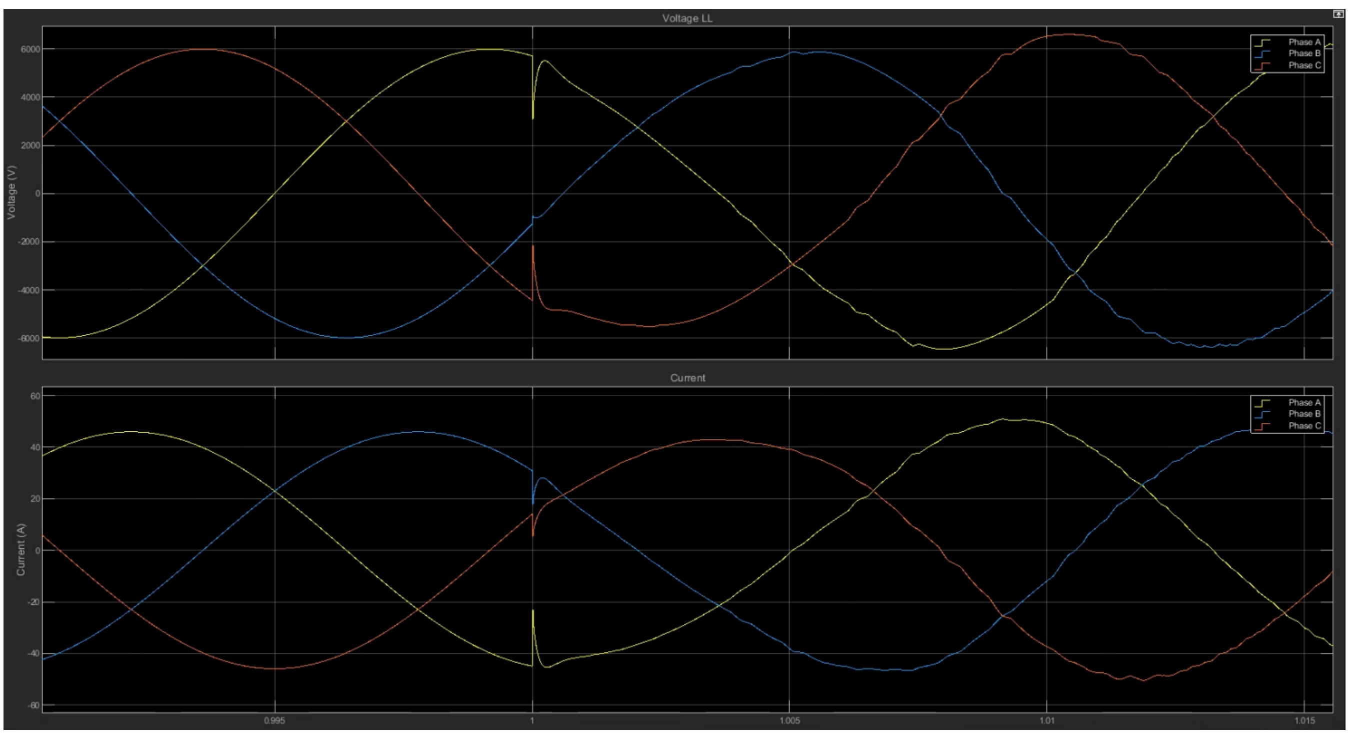


Figure 73: Dynamic Results – Tulita Renewable Sources Connection – 25% – Load

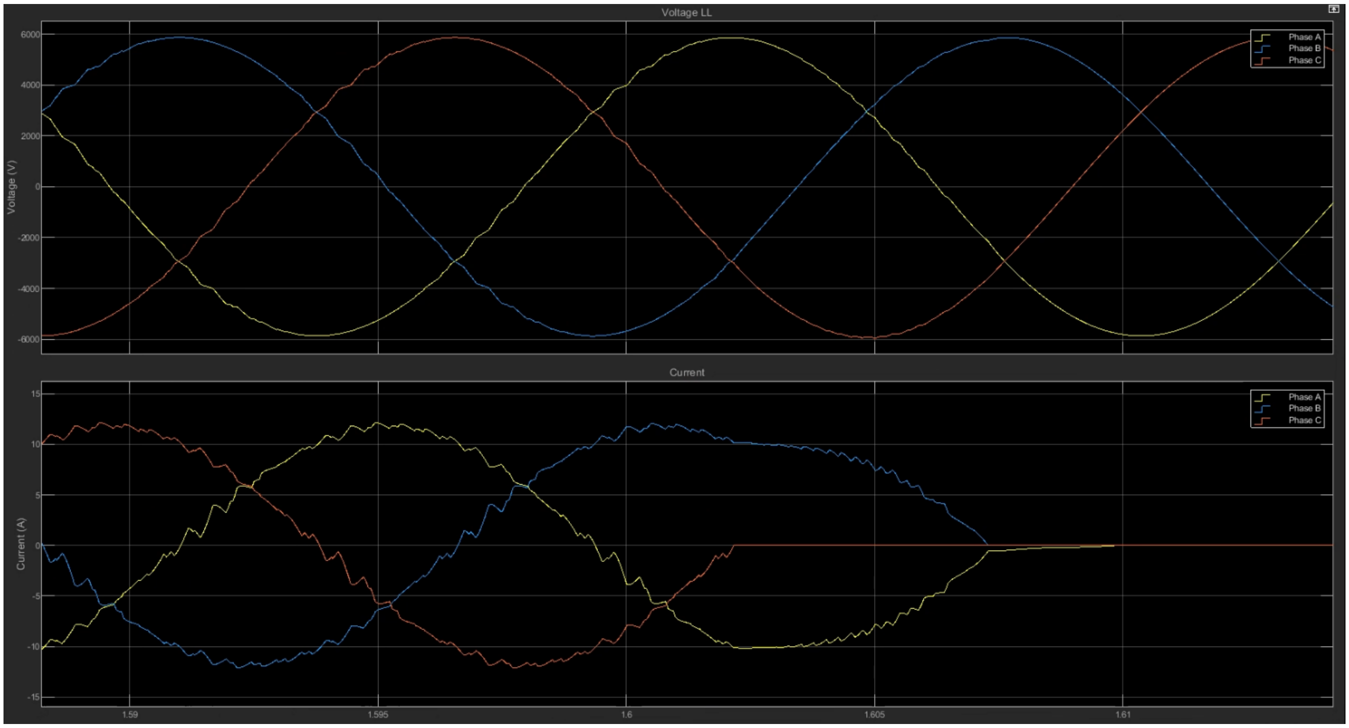


Figure 74: Dynamic Results – Tulita Renewable Sources Disconnection – 25% – PV

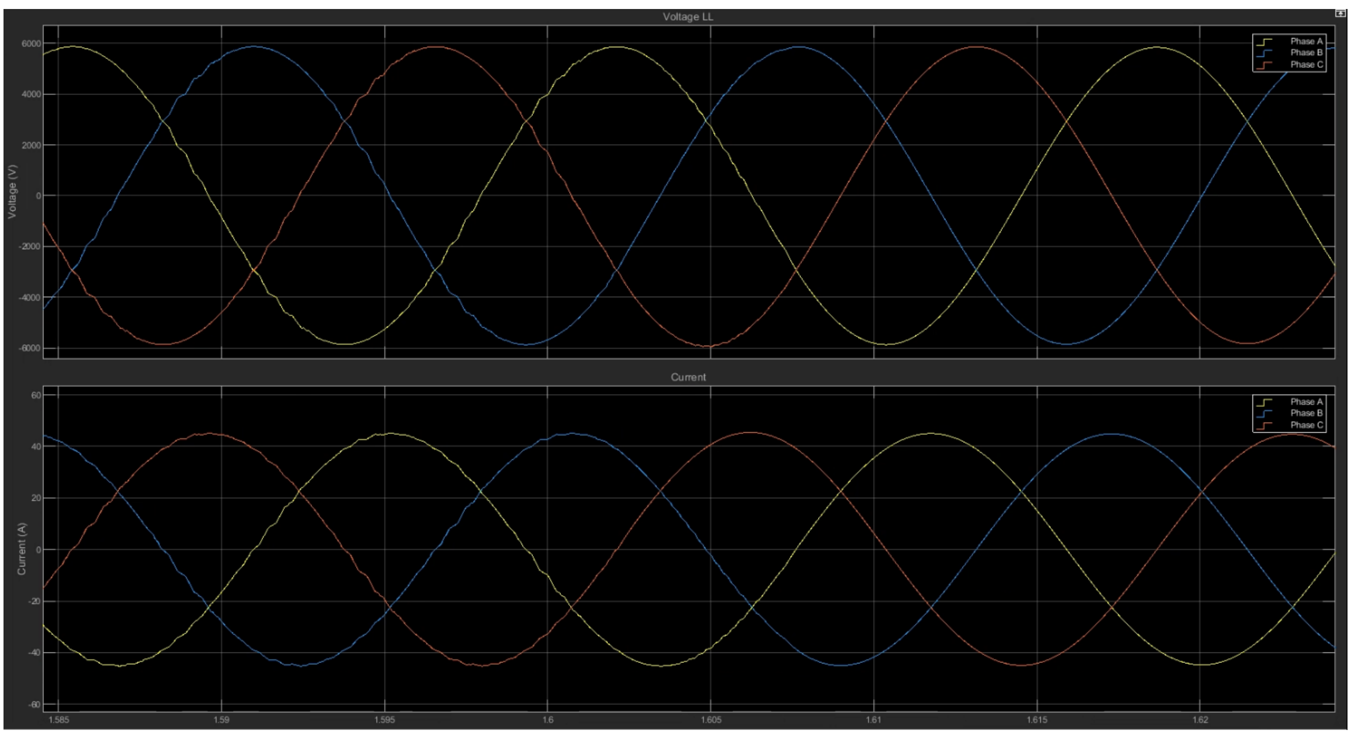


Figure 75: Dynamic Results – Tulita Renewable Sources Disconnection – 25% – Load

E.7. Tulita 30% Renewable Energy Penetration

E.7.1. Load Increase and Decrease

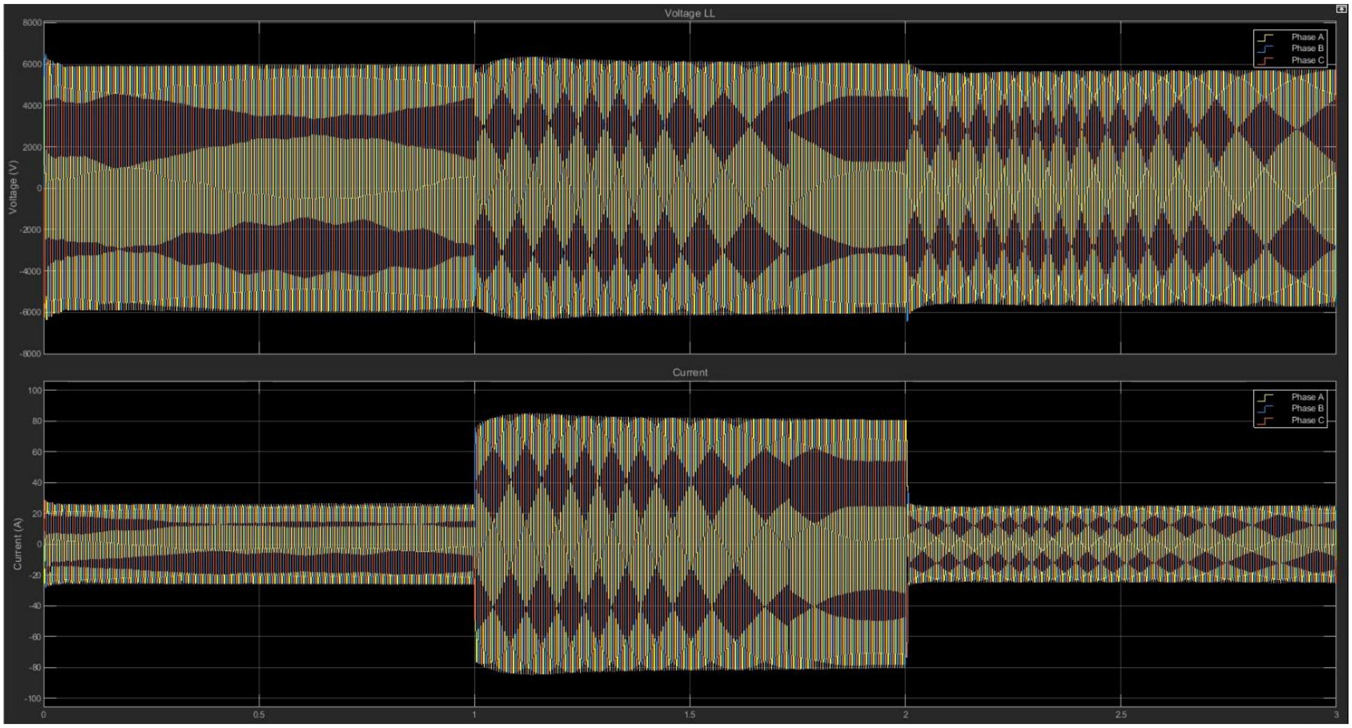


Figure 76: Dynamic Results – Tulita Load Variations – 30%

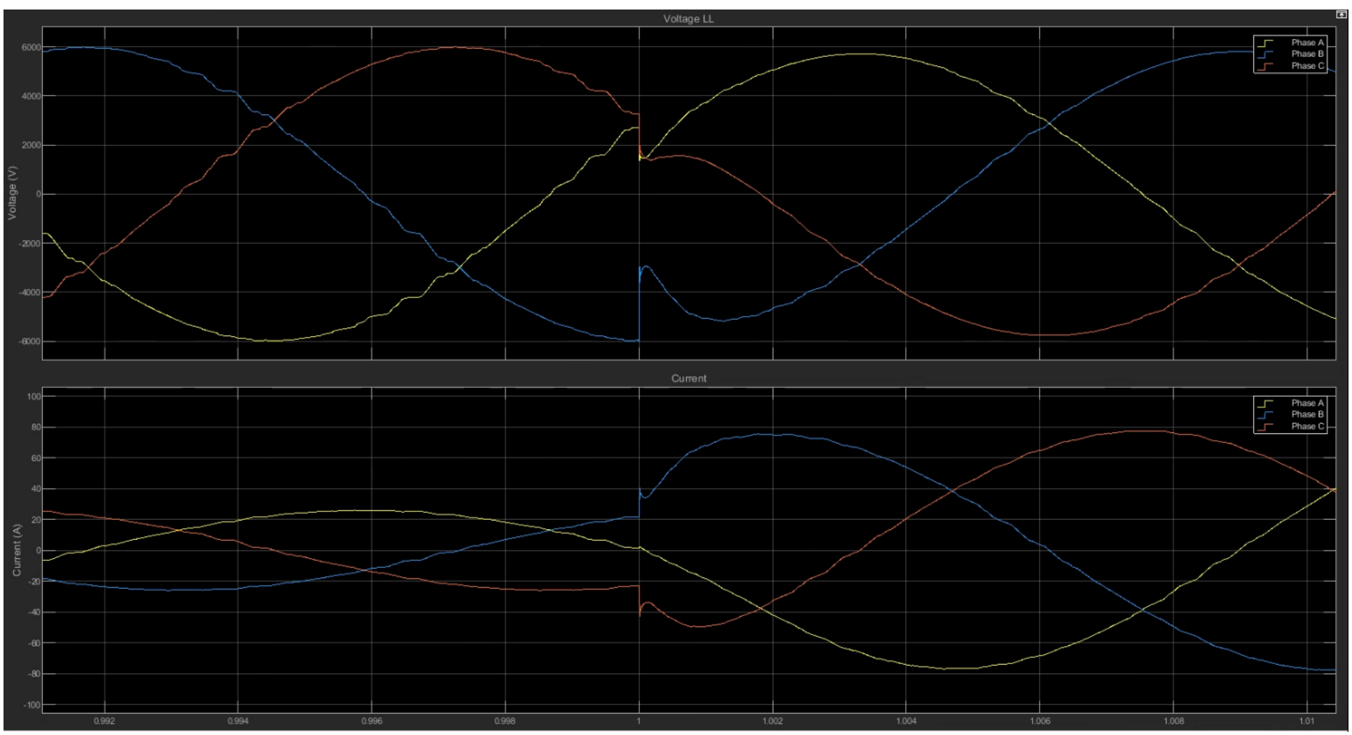


Figure 77: Dynamic Results – Tulita Load Increase – 30%

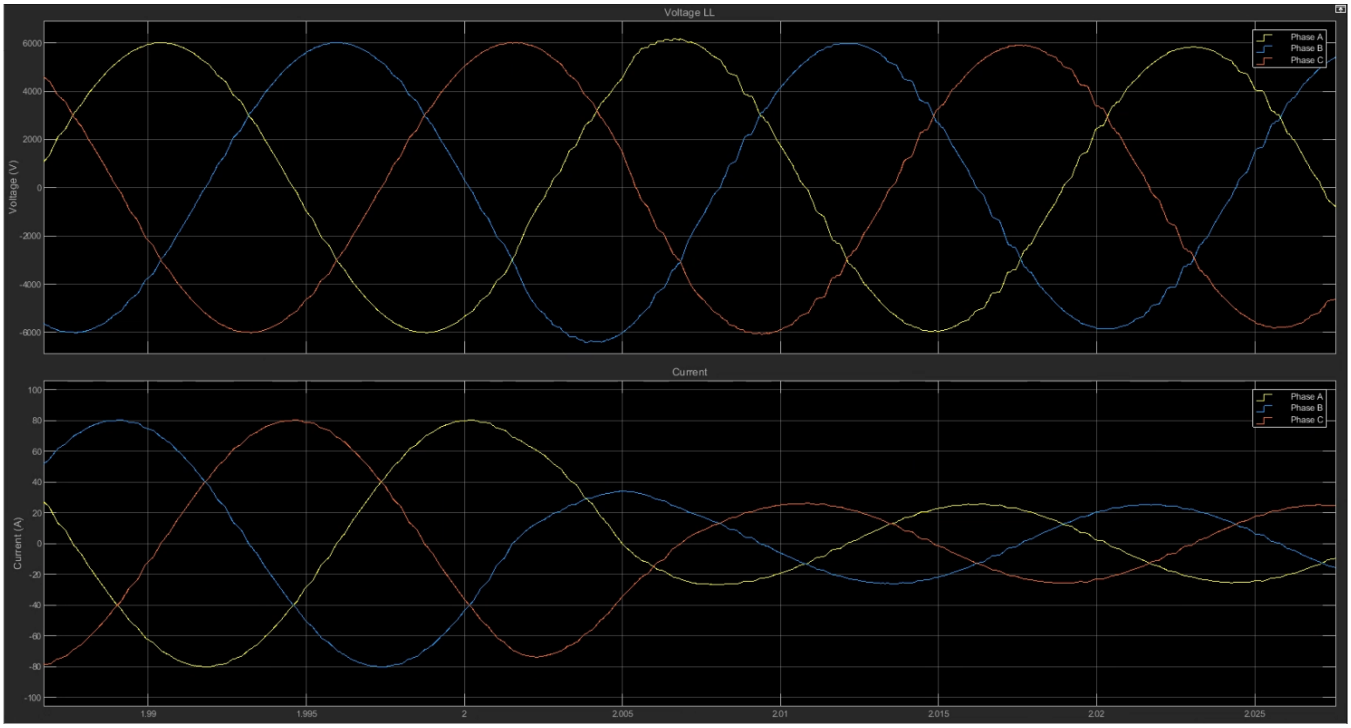


Figure 78: Dynamic Results – Tulita Load Decrease – 30%

E.7.2. Renewable Connection / Disconnection

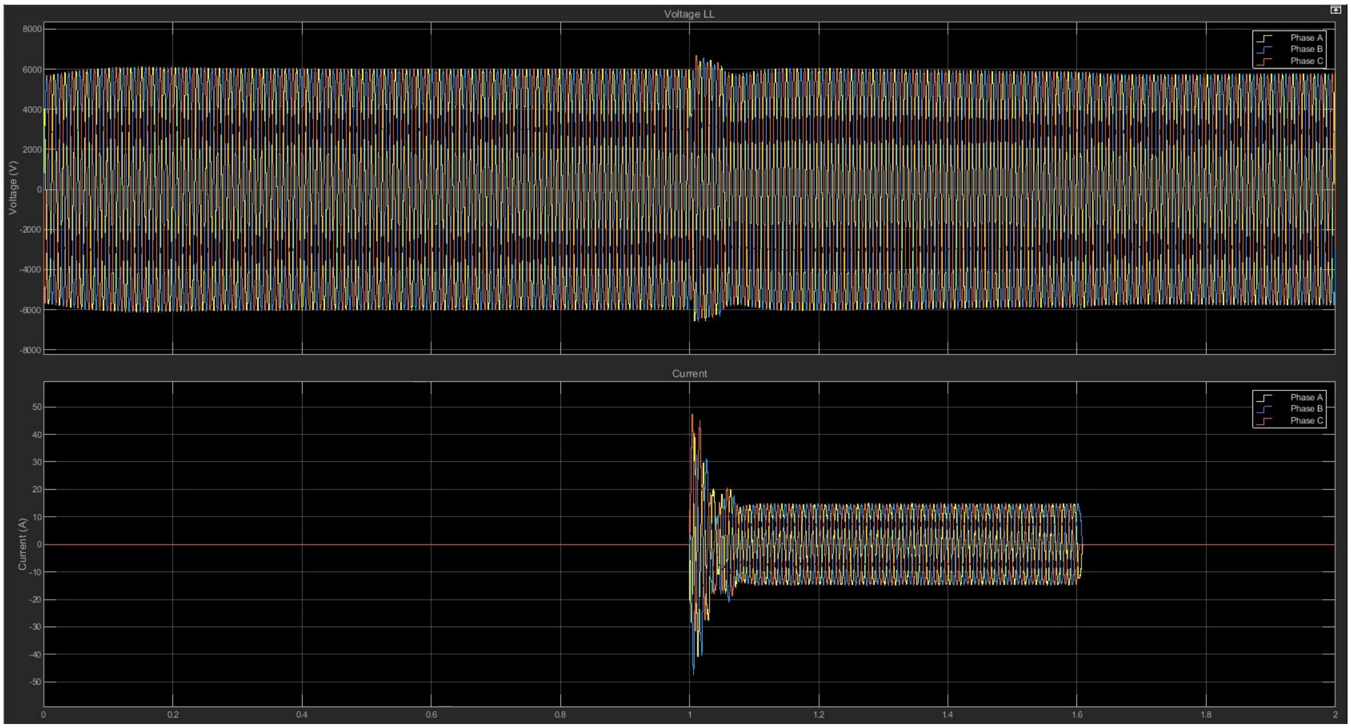


Figure 79: Dynamic Results – Tulita Renewable Sources Variation – 30% – PV

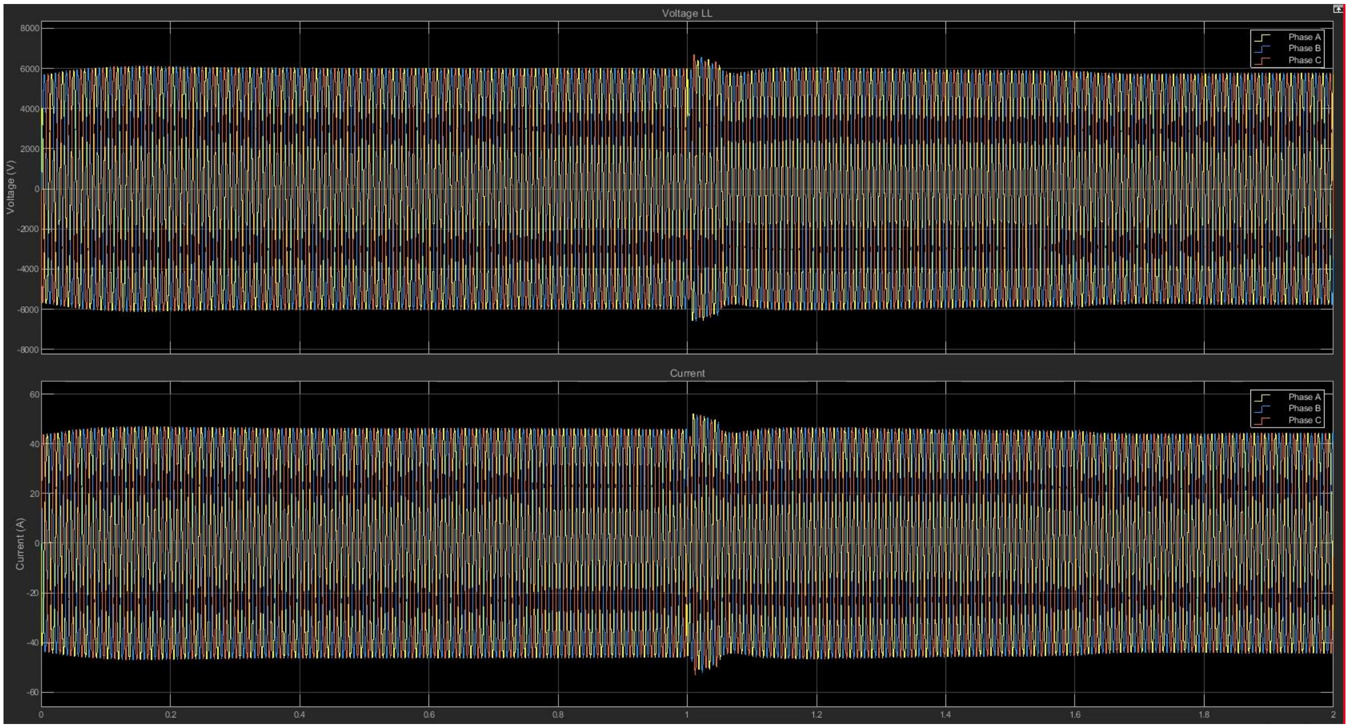


Figure 80: Dynamic Results – Tulita Renewable Sources Variation – 30% – Load

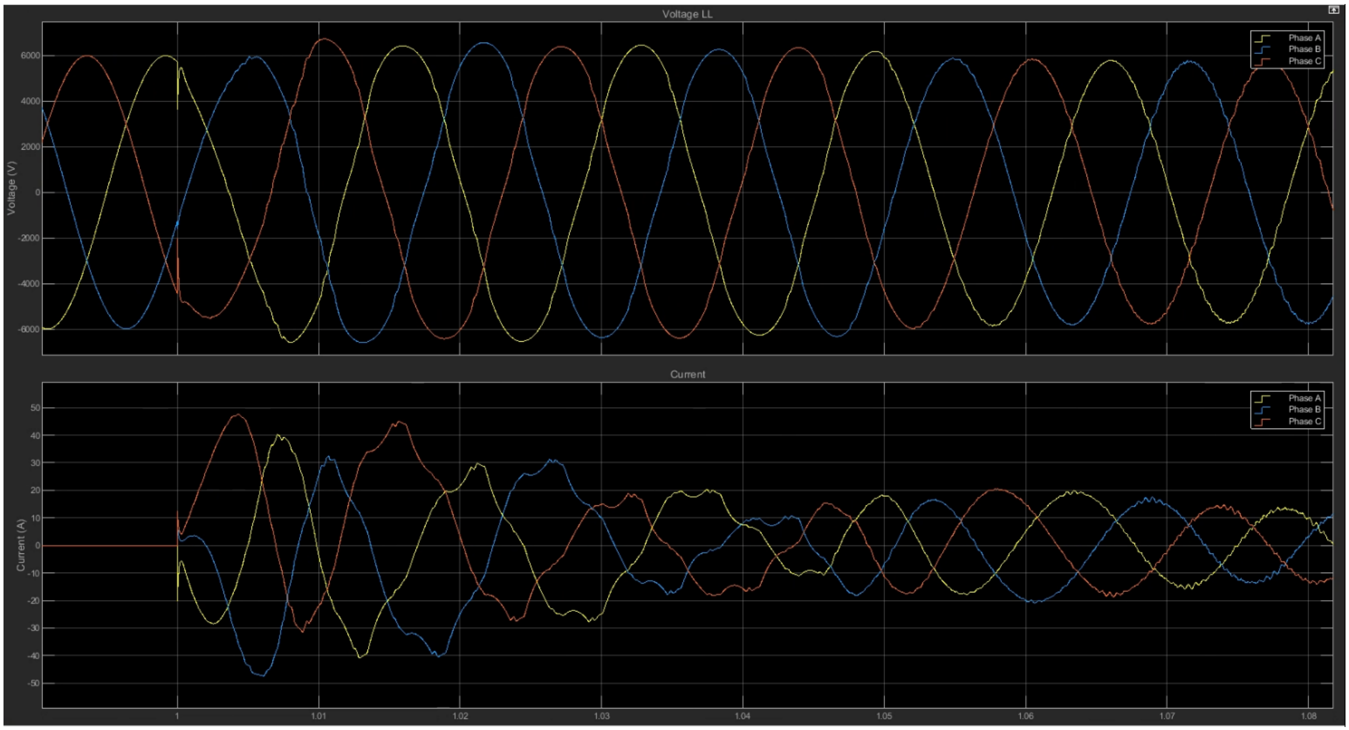


Figure 81: Dynamic Results – Tulita Renewable Sources Connection – 30% – PV

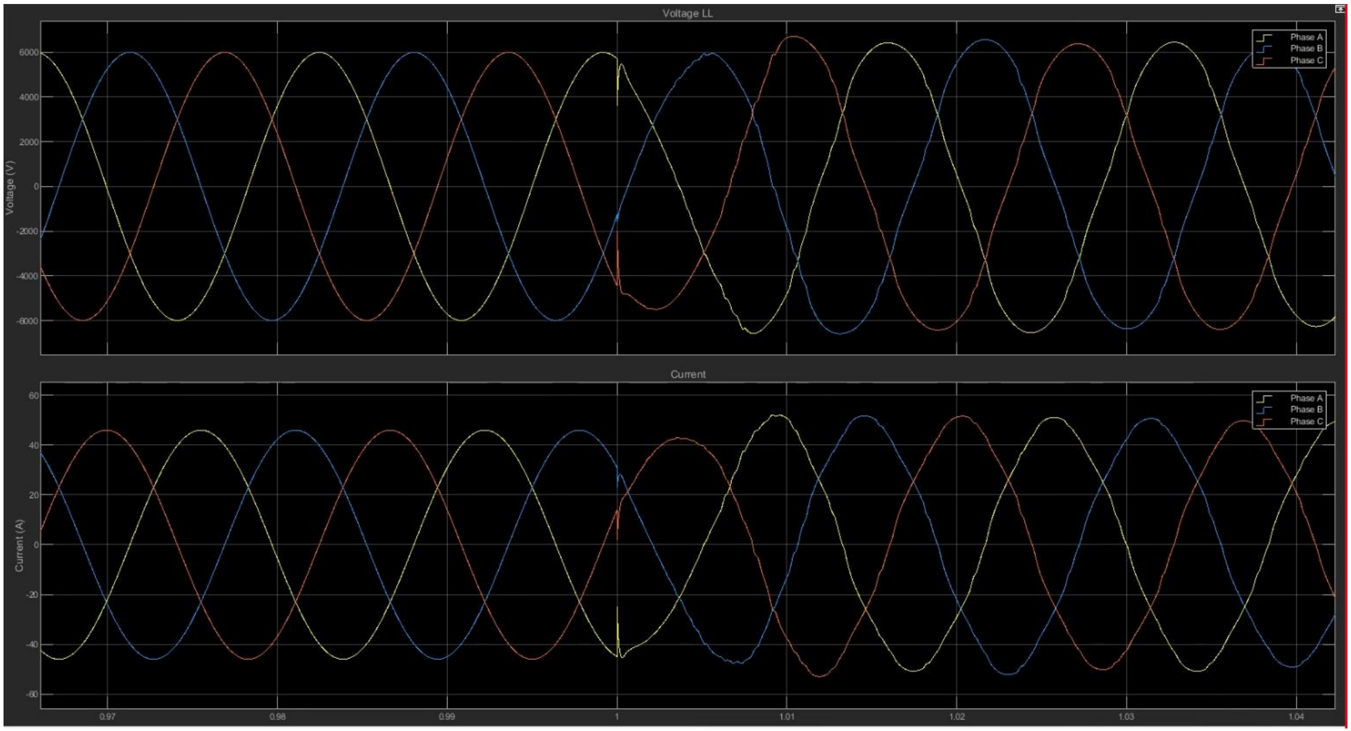


Figure 82: Dynamic Results – Tulita Renewable Sources Connection – 30% – Load

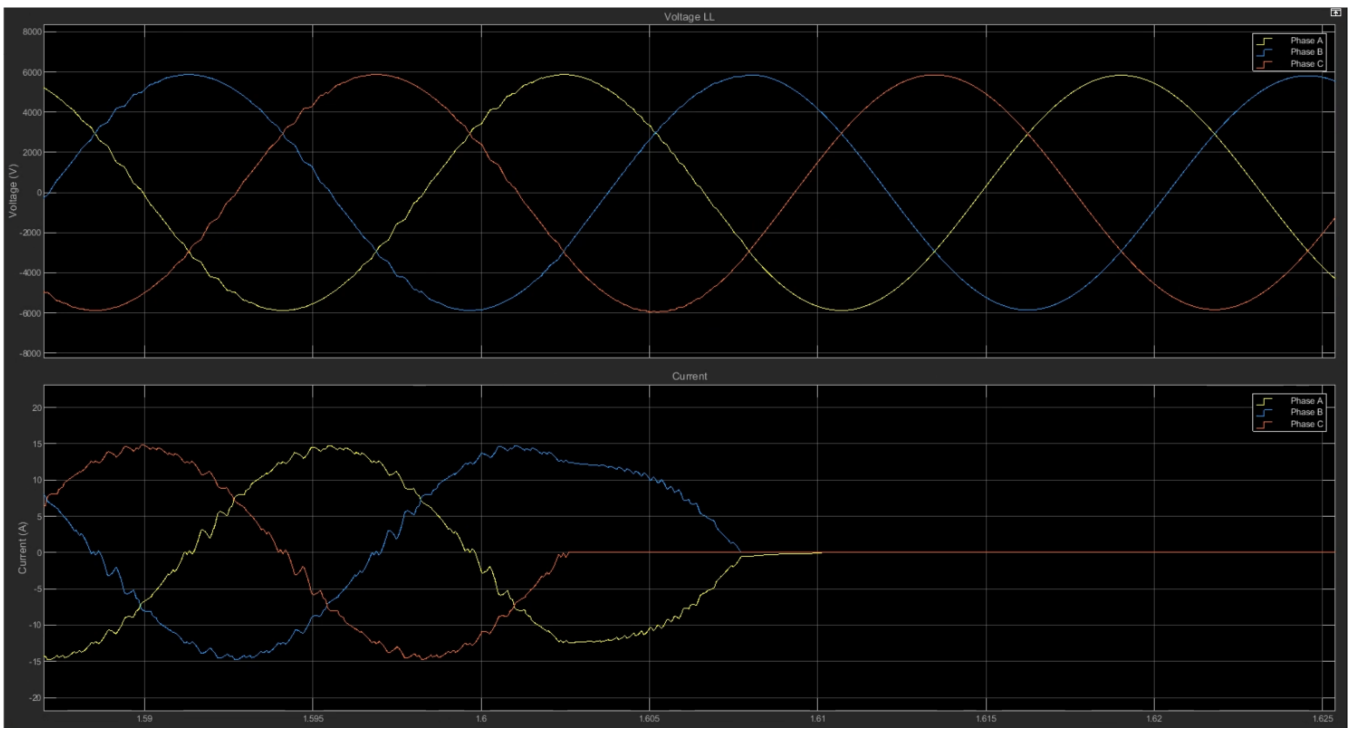


Figure 83: Dynamic Results – Tulita Renewable Sources Disconnection – 30% – PV

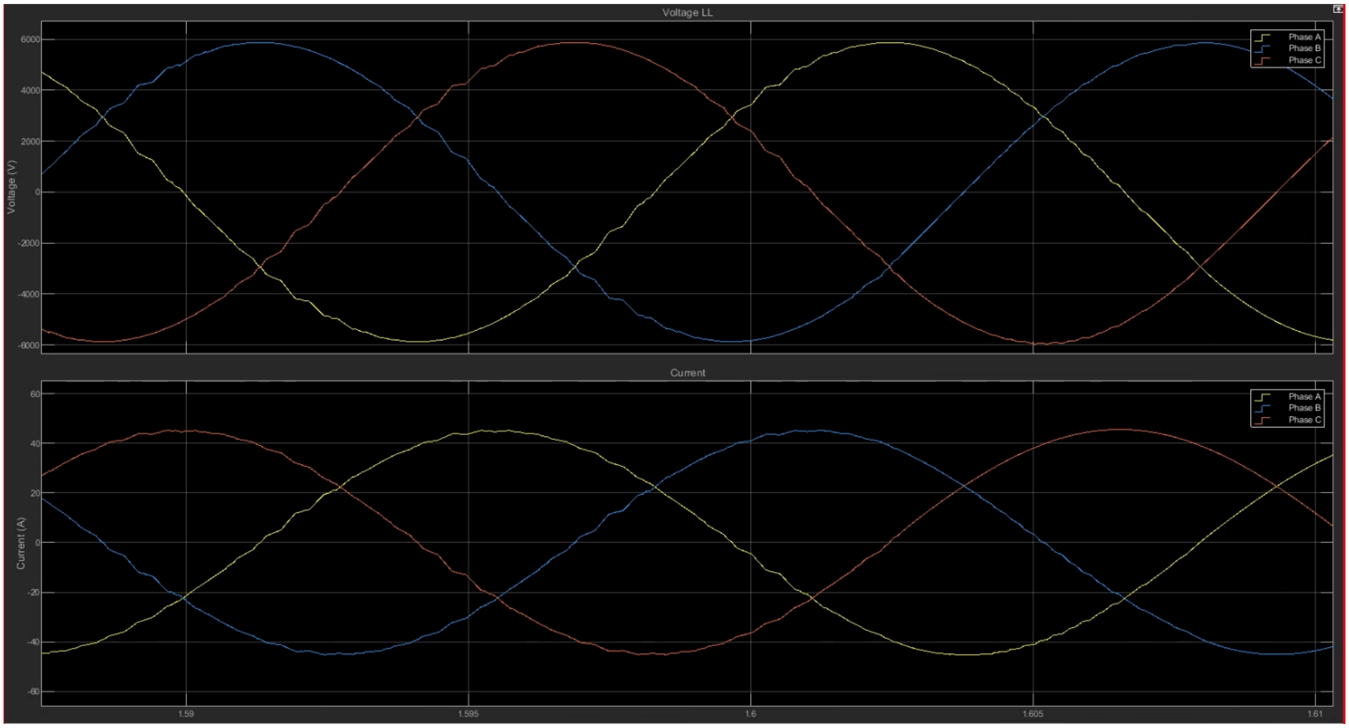


Figure 84: Dynamic Results – Tulita Renewable Sources Disconnection – 30% – Load

E.8. Tulita 50% Renewable Energy Penetration

E.8.1. Load Increase and Decrease

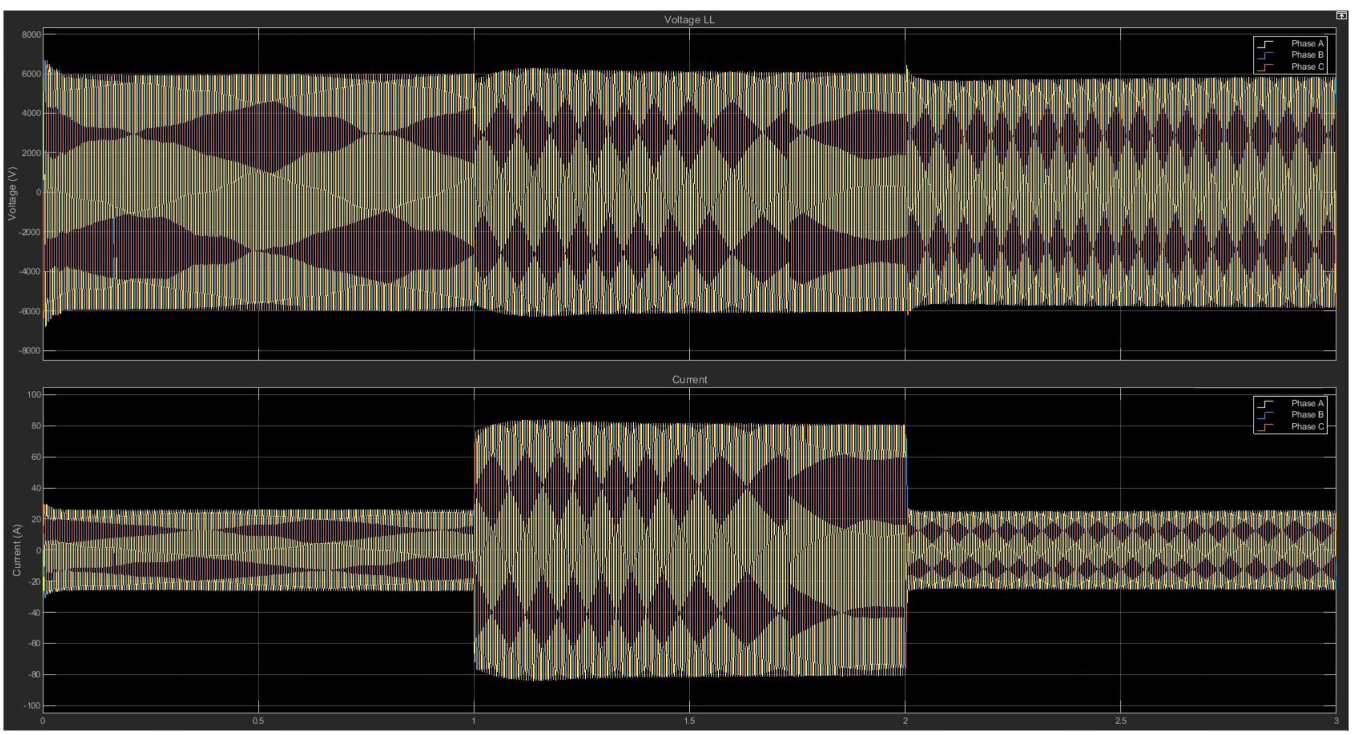


Figure 85: Dynamic Results – Tulita Load Variations – 50%

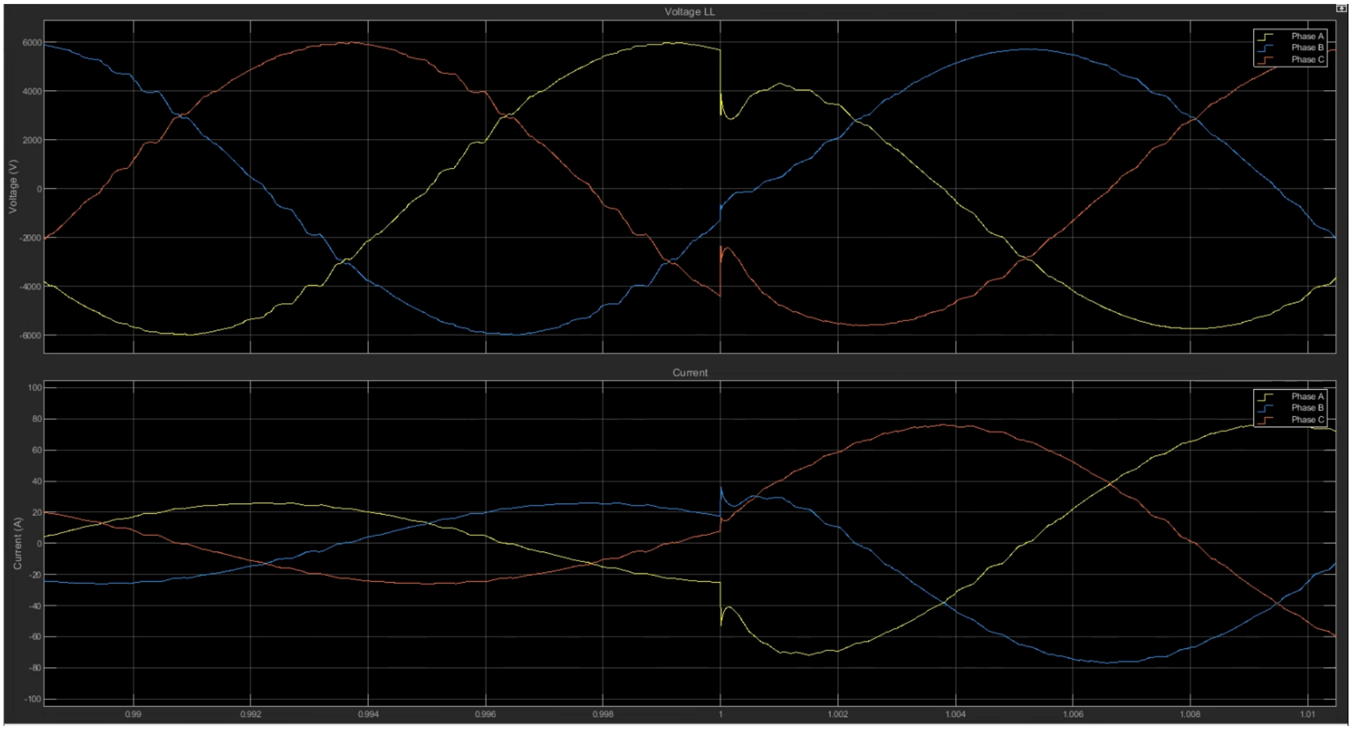


Figure 86: Dynamic Results – Tulita Load Increase – 50%

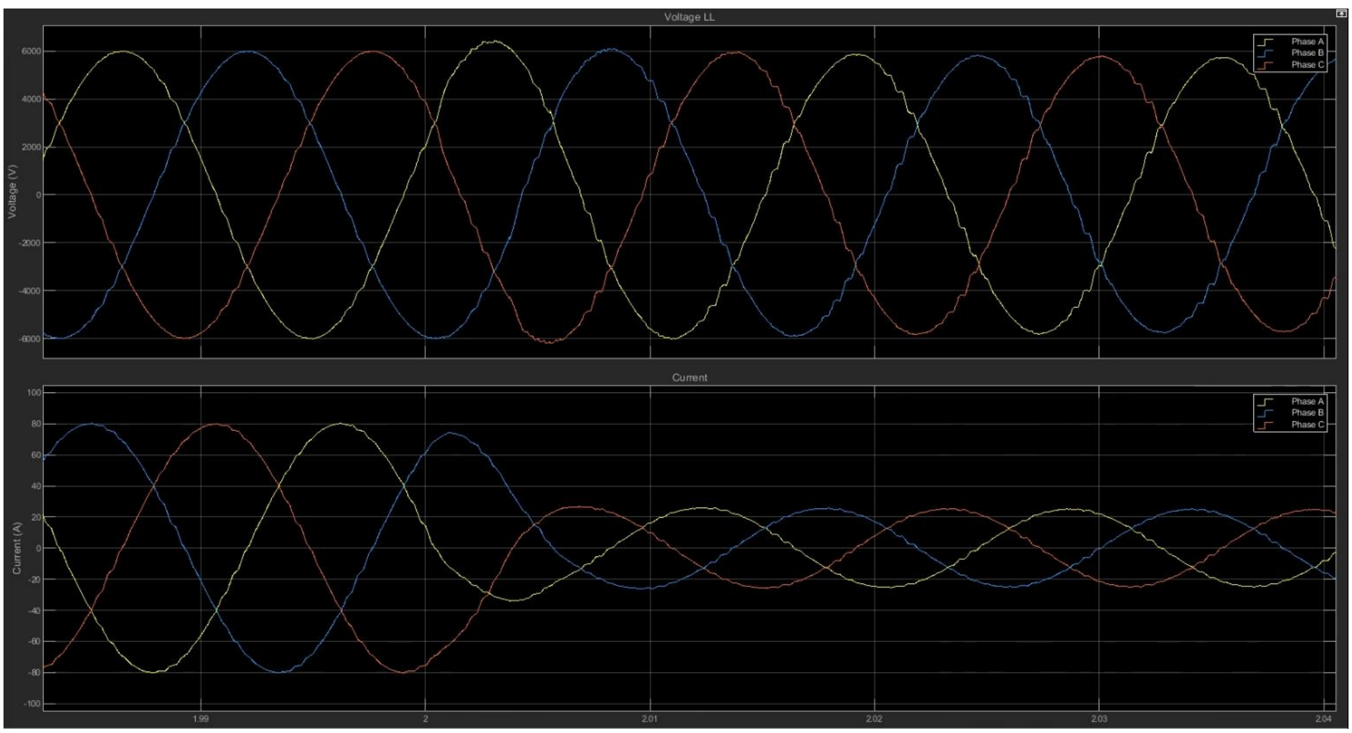


Figure 87: Dynamic Results – Tulita Load Decrease – 50%

E.8.2. Renewable Connection / Disconnection

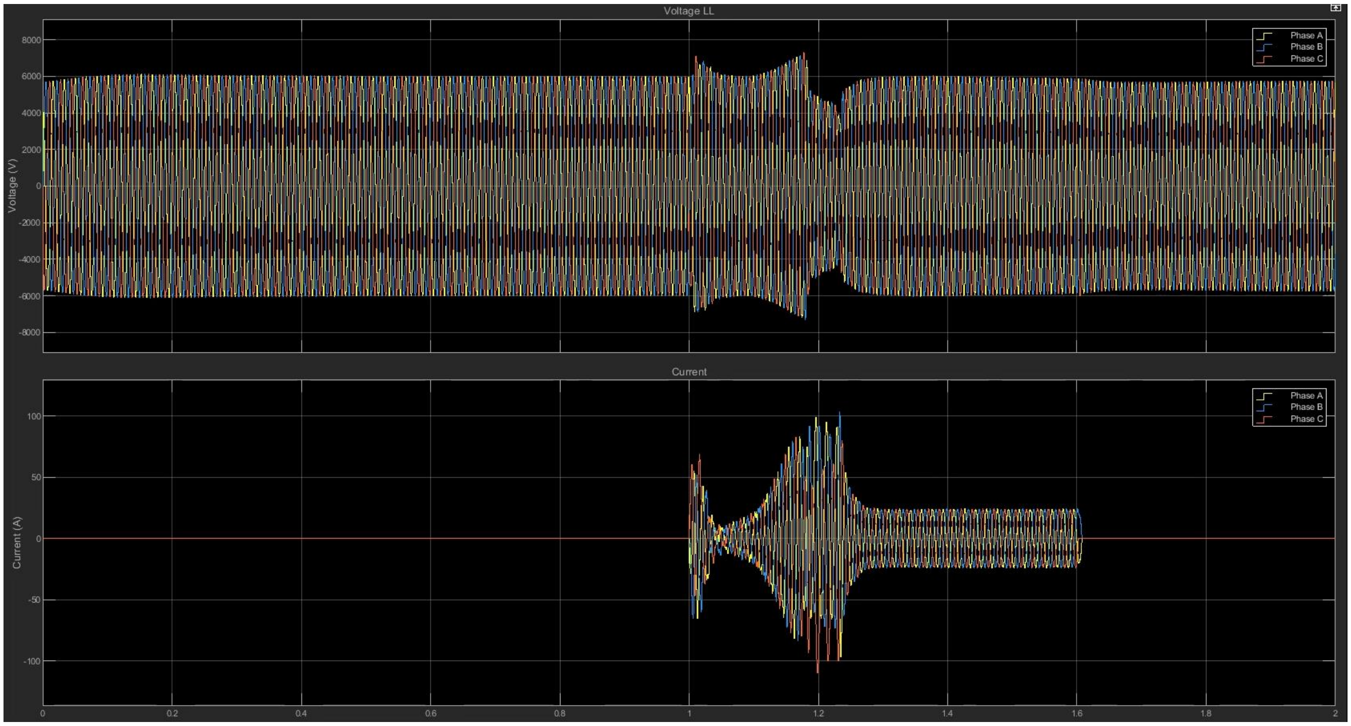


Figure 88: Dynamic Results – Tulita Renewable Sources Variation – 50% – PV

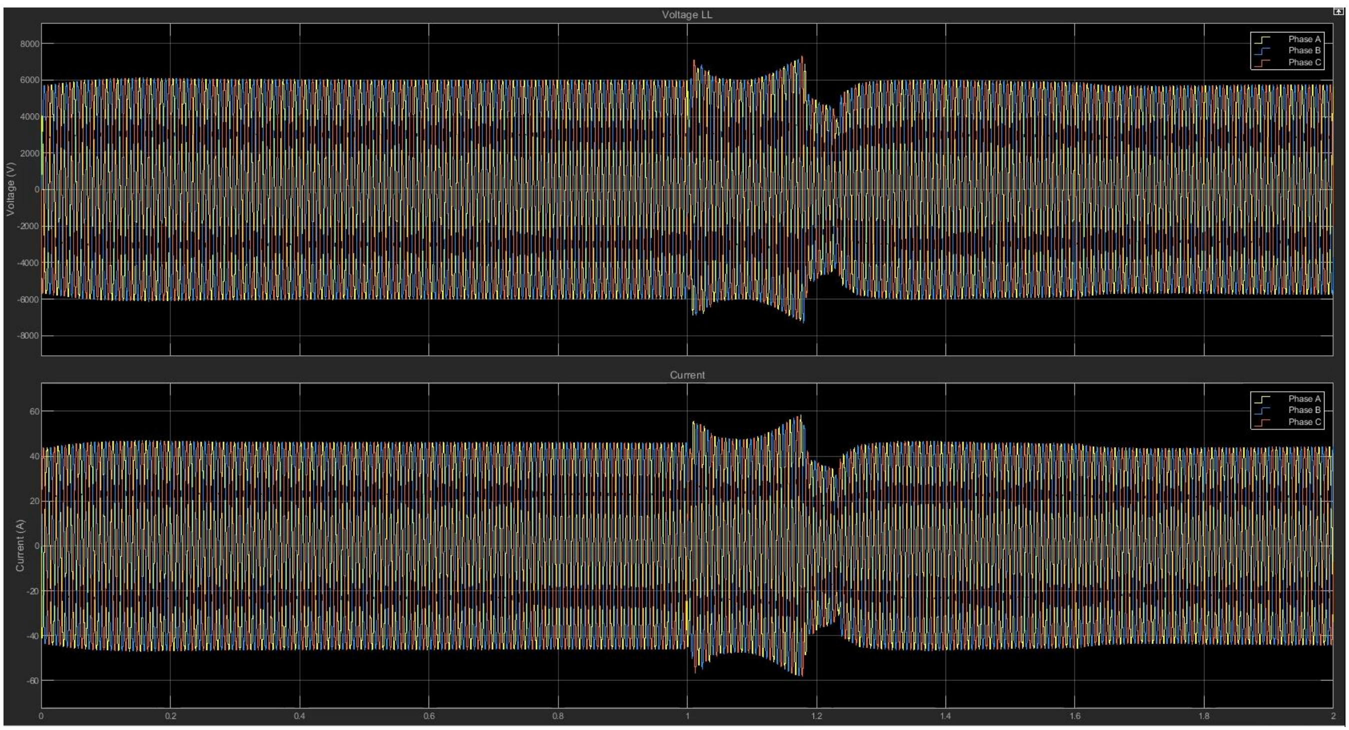


Figure 89: Dynamic Results – Tulita Renewable Sources Variation – 50% – Load

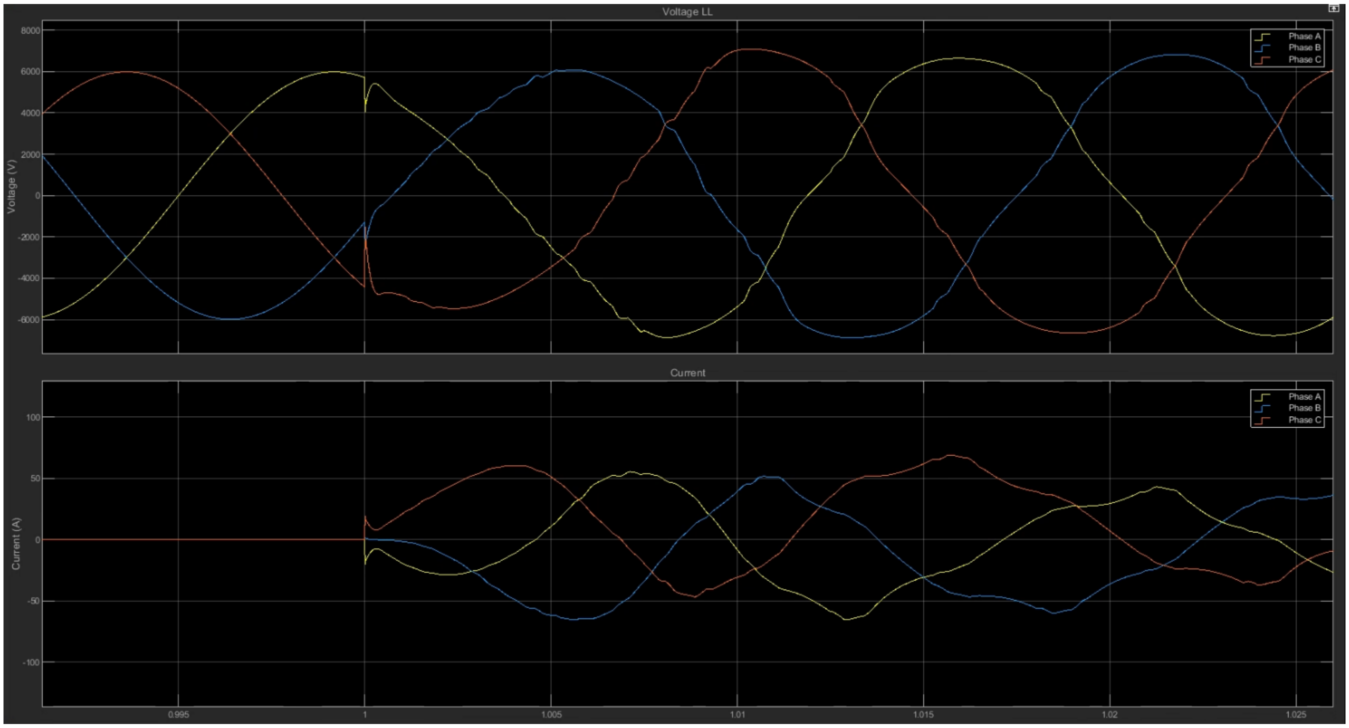


Figure 90: Dynamic Results – Tulita Renewable Sources Connection – 50% – PV

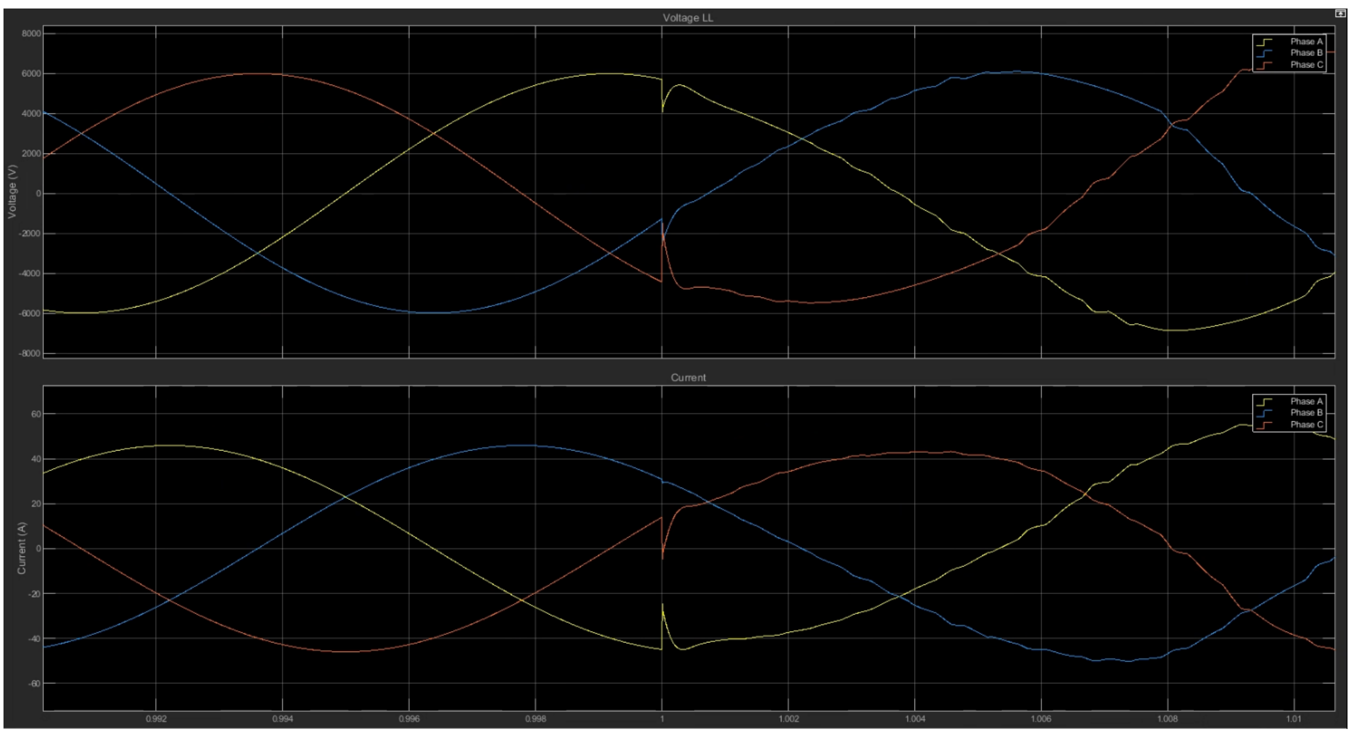


Figure 91: Dynamic Results – Tulita Renewable Sources Connection – 50% – Load

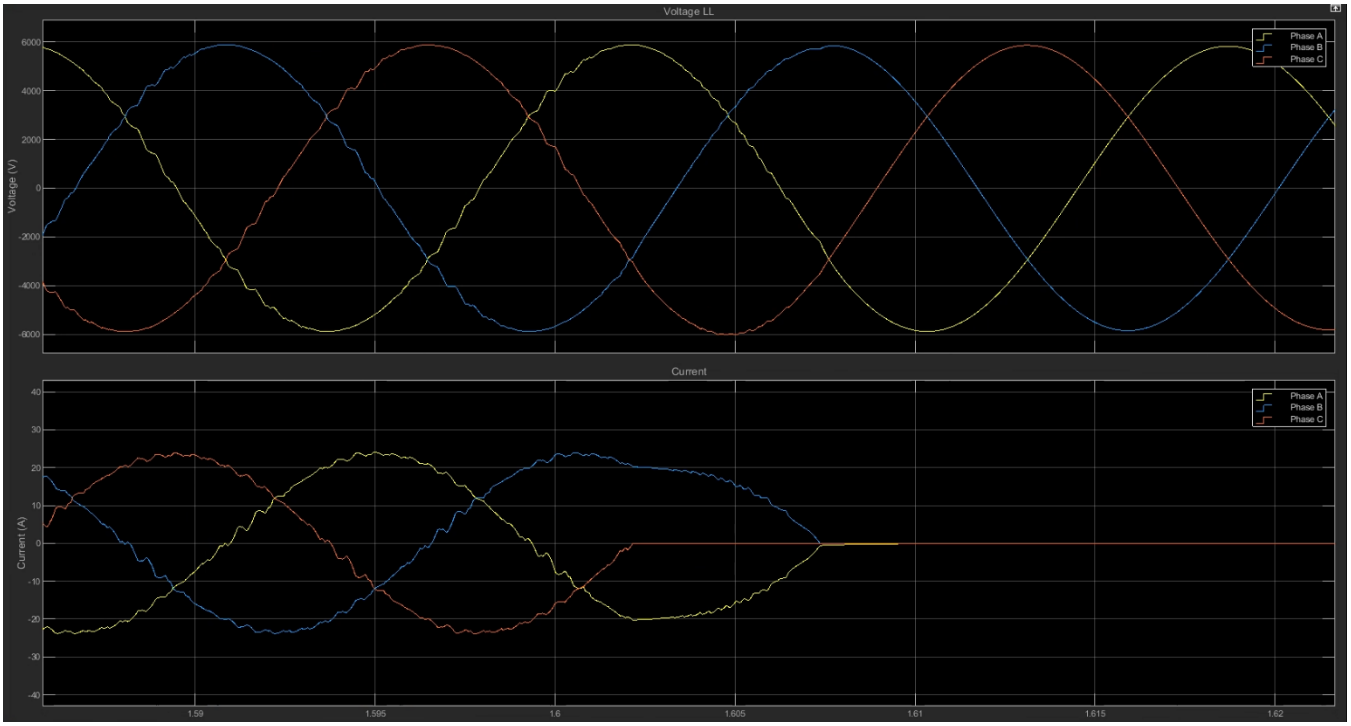


Figure 92: Dynamic Results – Tulita Renewable Sources Disconnection – 50% – PV

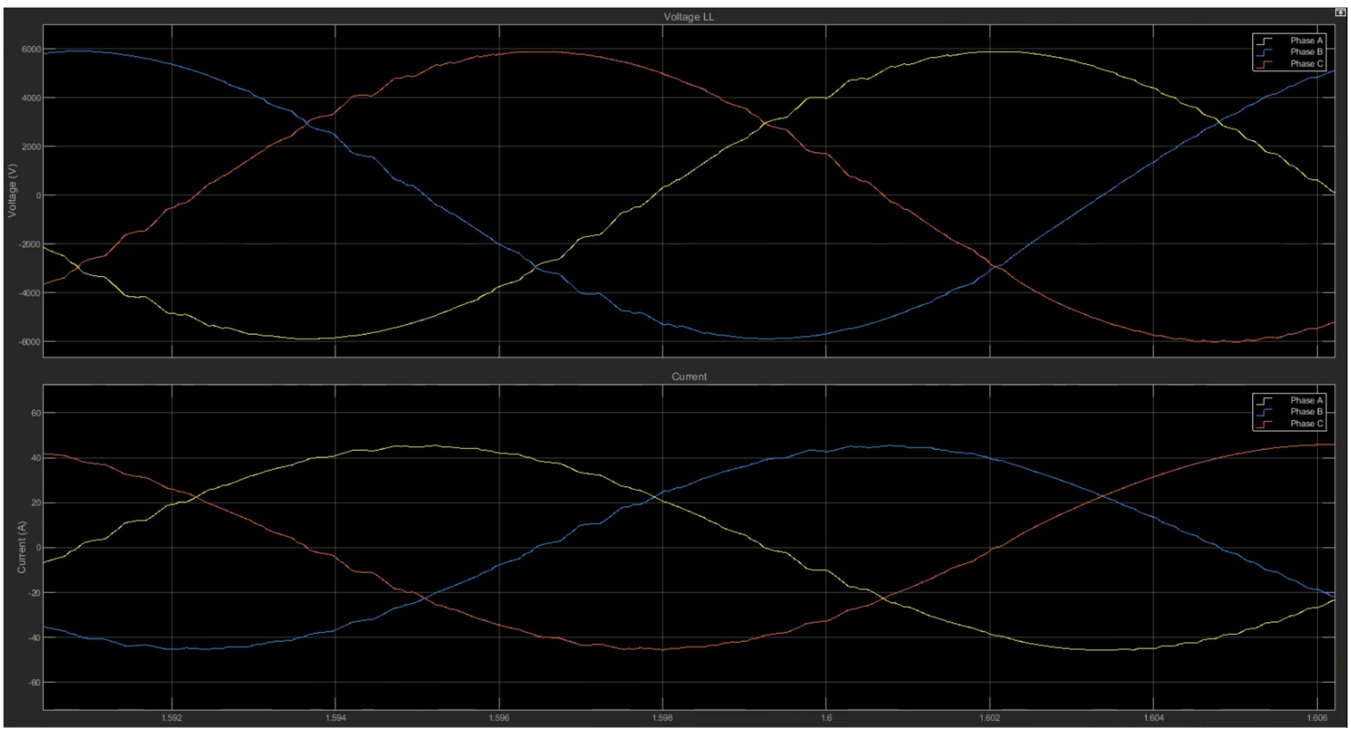


Figure 93: Dynamic Results – Tulita Renewable Sources Disconnection – 50% – Load

E.9. Łutselk'e 20% Renewable Energy Penetration

E.9.1. Load Increase and Decrease

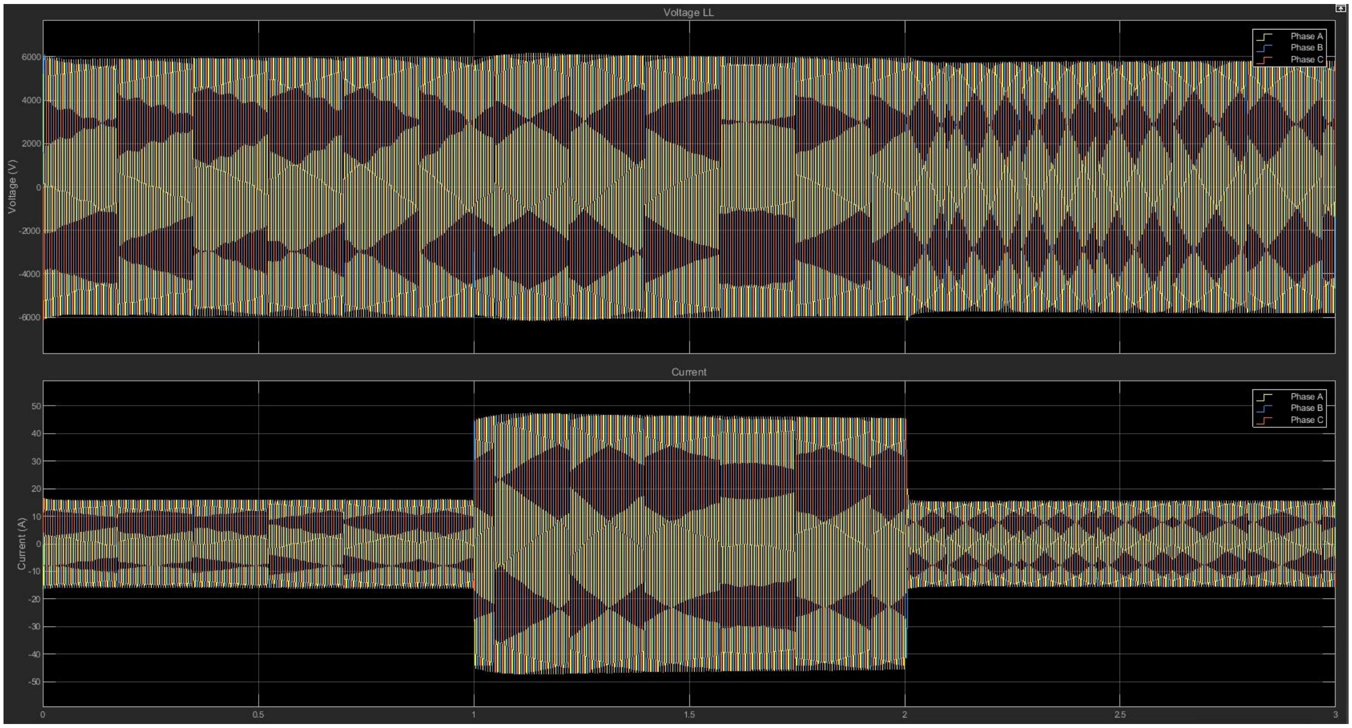


Figure 94: Dynamic Results – Łutselk'e Load Variations – 20%

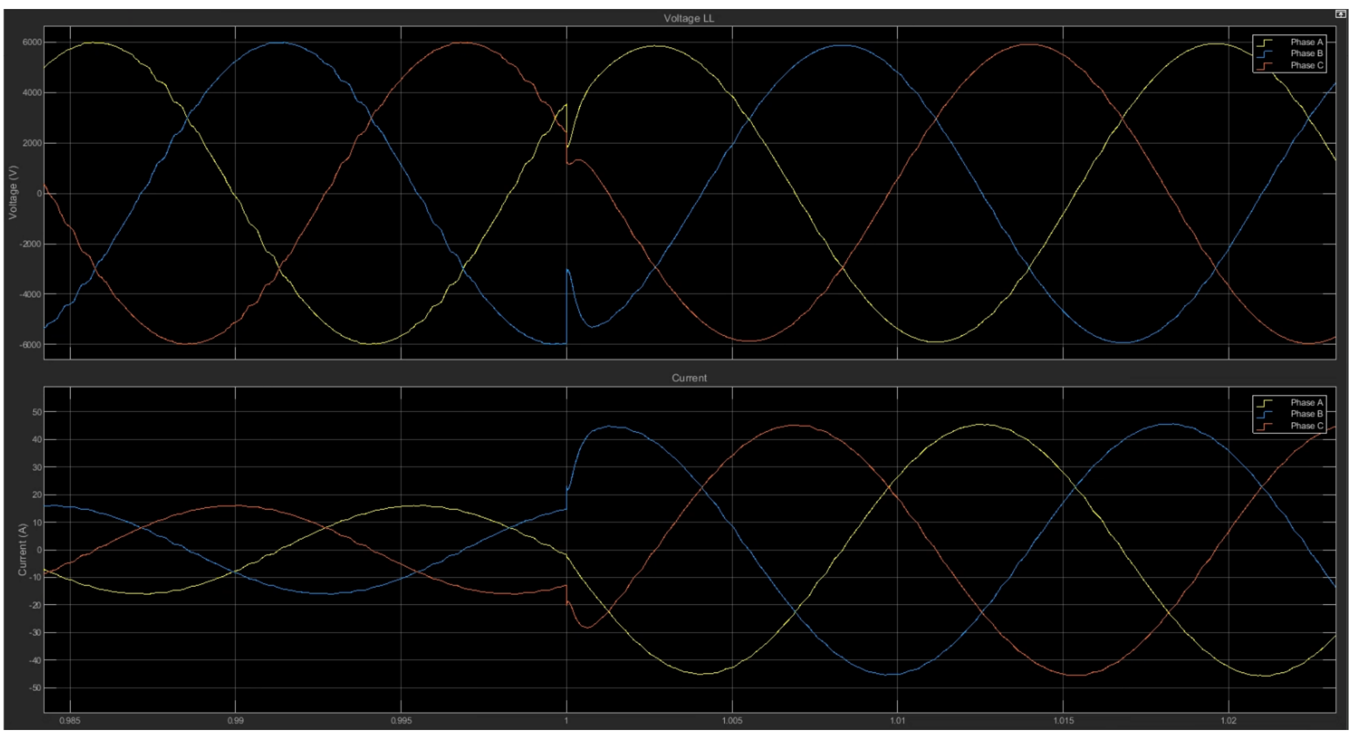


Figure 95: Dynamic Results – Łutselk'e Load Increase – 20%

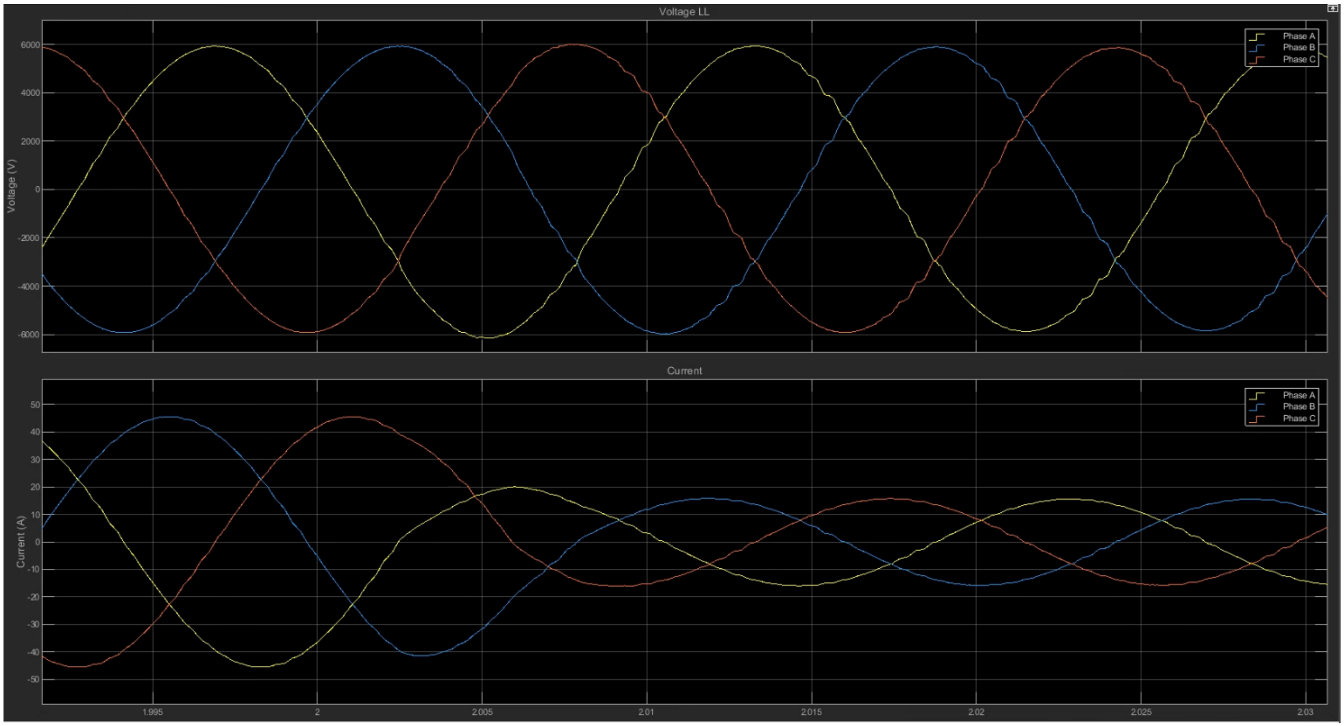


Figure 96: Dynamic Results – Łutselk'e Load Decrease – 20%

E.9.2. Renewable Connection / Disconnection

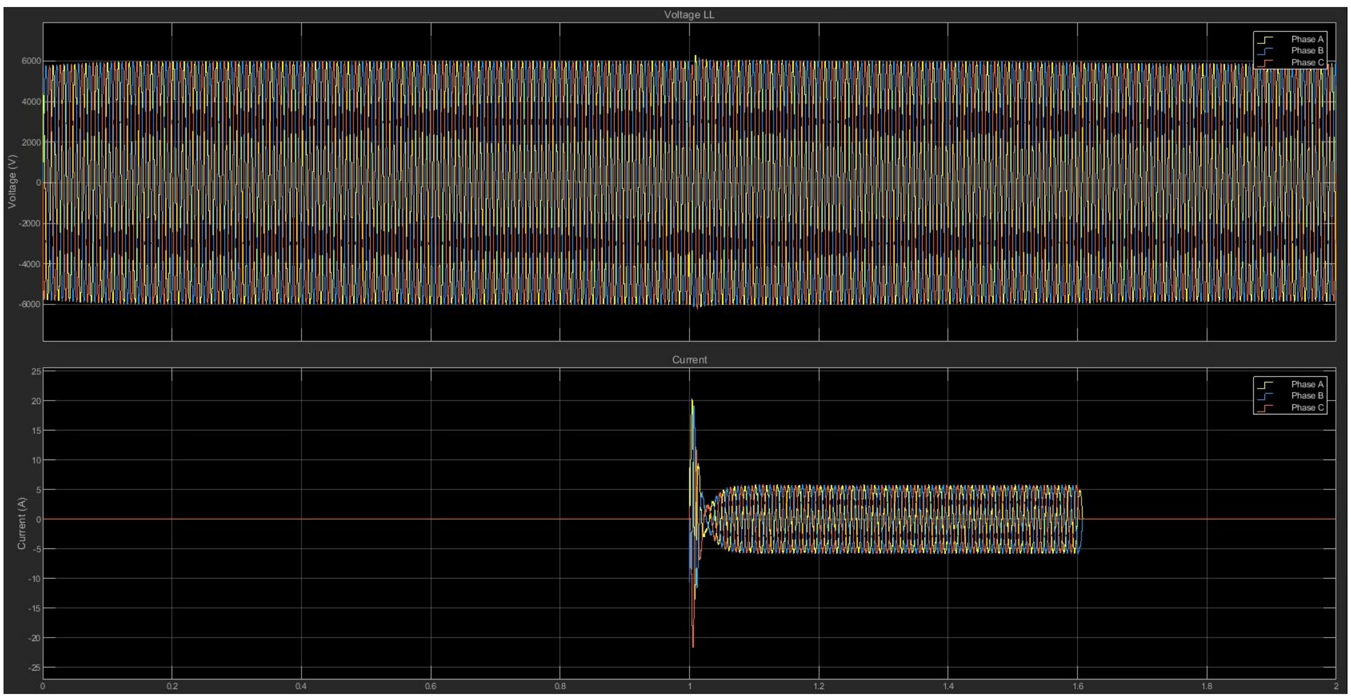


Figure 97: Dynamic Results – Łutselk'e Renewable Sources Variation – 20% – PV

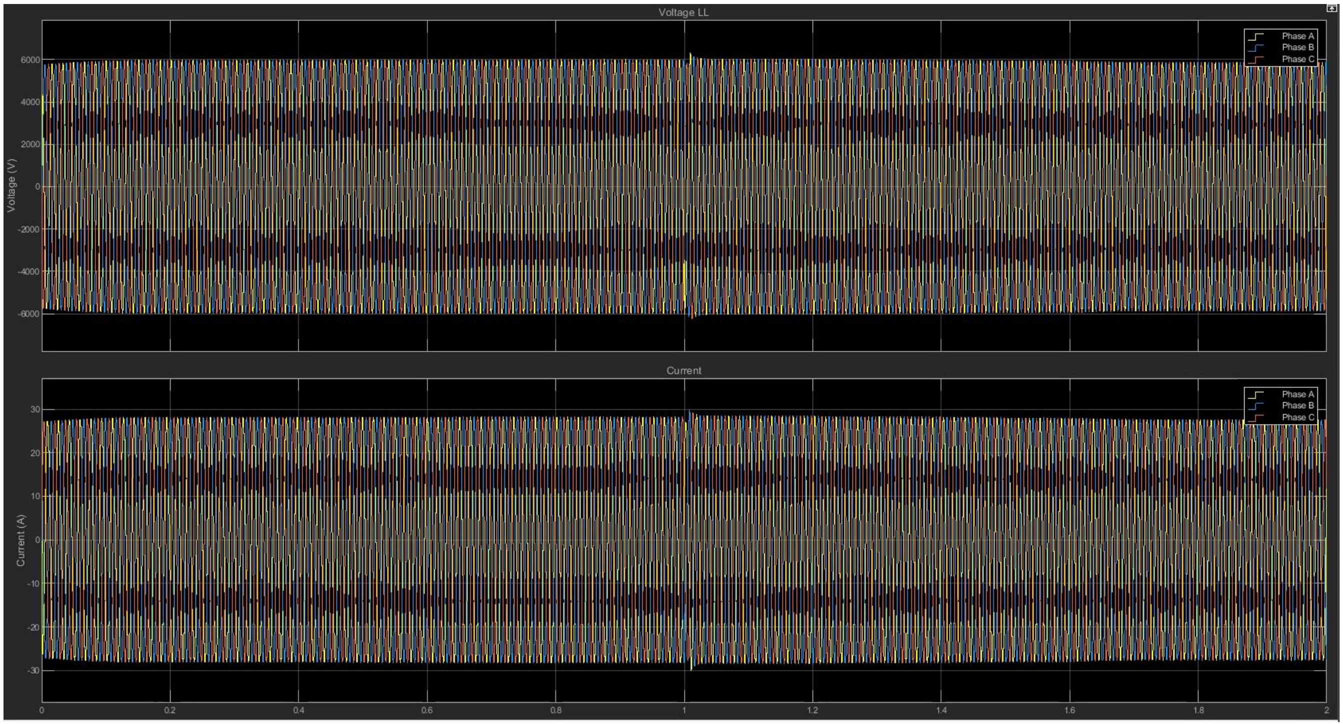


Figure 98: Dynamic Results – Łutselk'e Renewable Sources Variation – 20% – Load

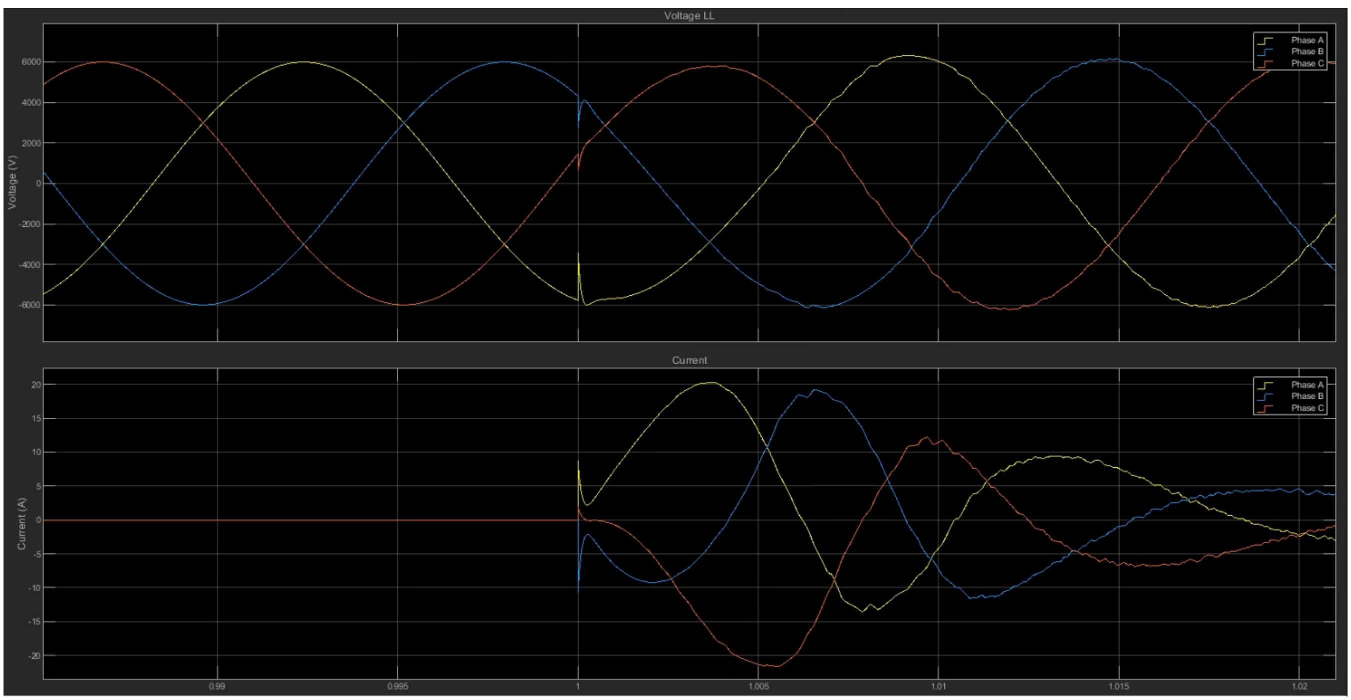


Figure 99: Dynamic Results – Łutselk'e Renewable Sources Connection – 20% – PV

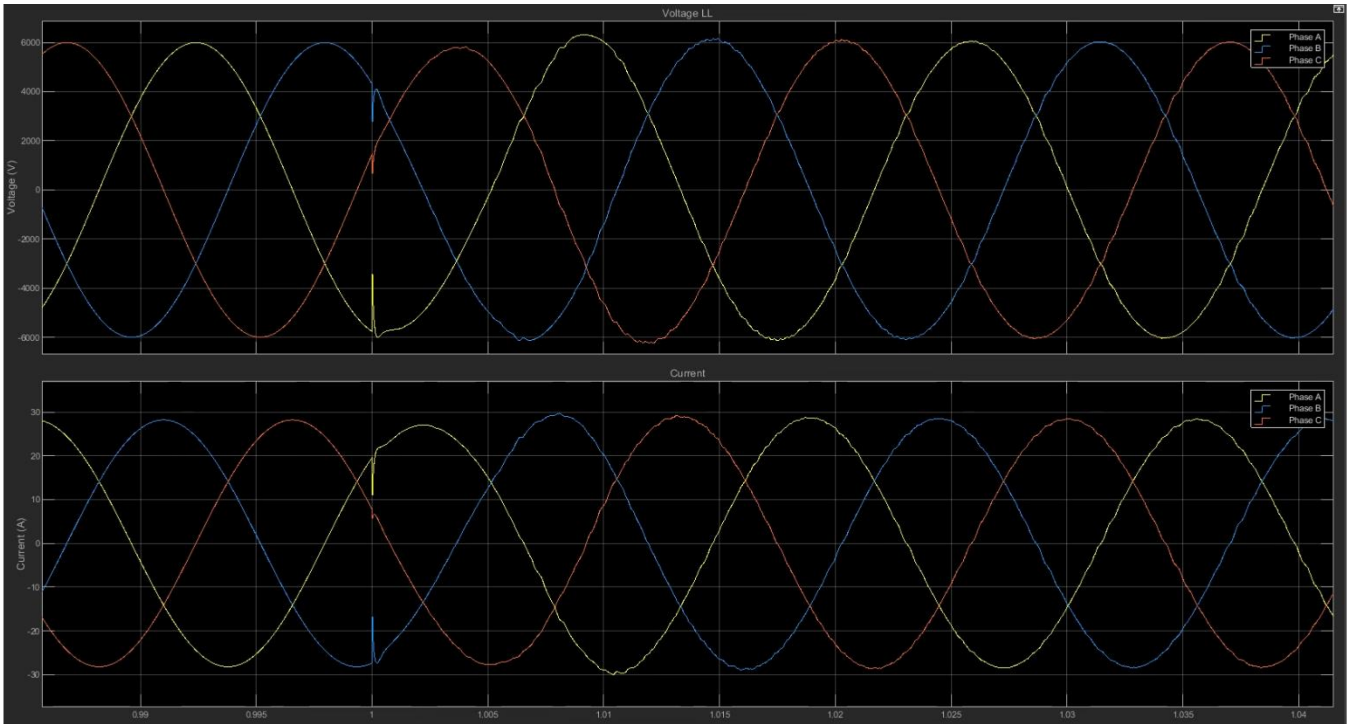


Figure 100: Dynamic Results – Łutselk'e Renewable Sources Connection – 20% – Load

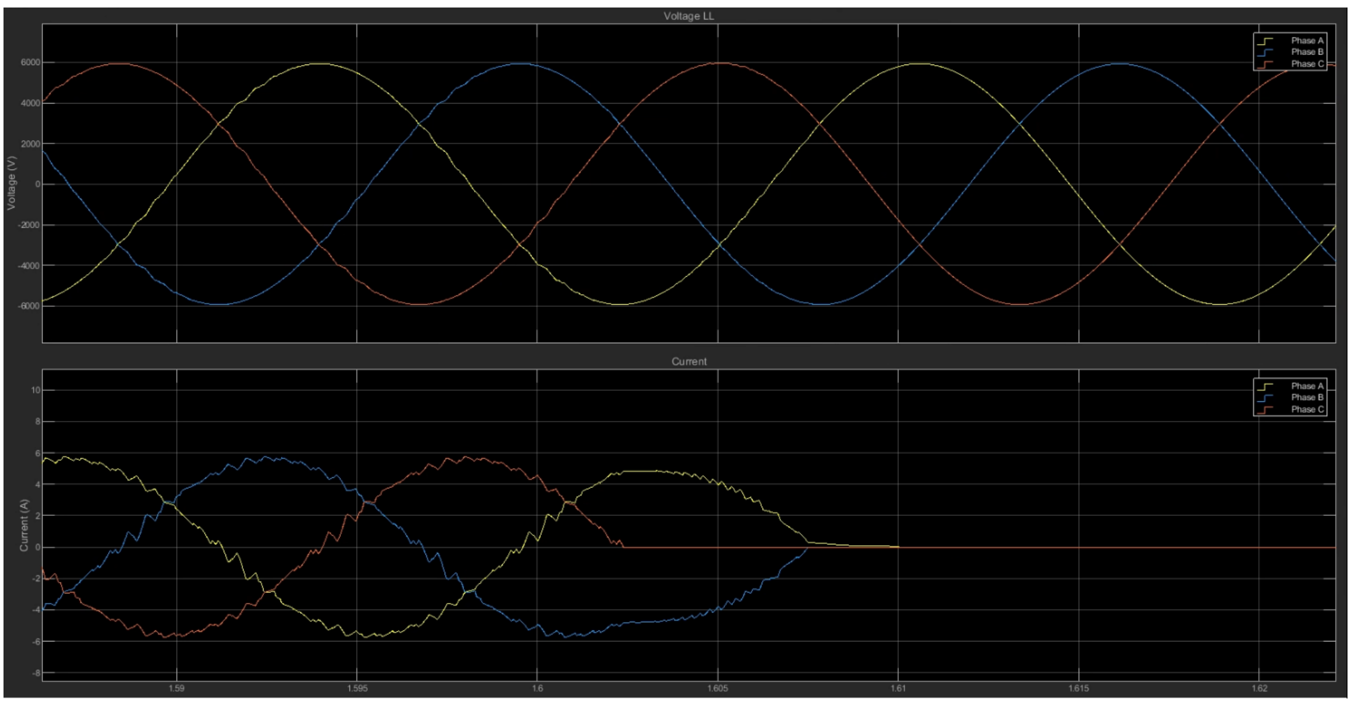


Figure 101: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 20% – PV

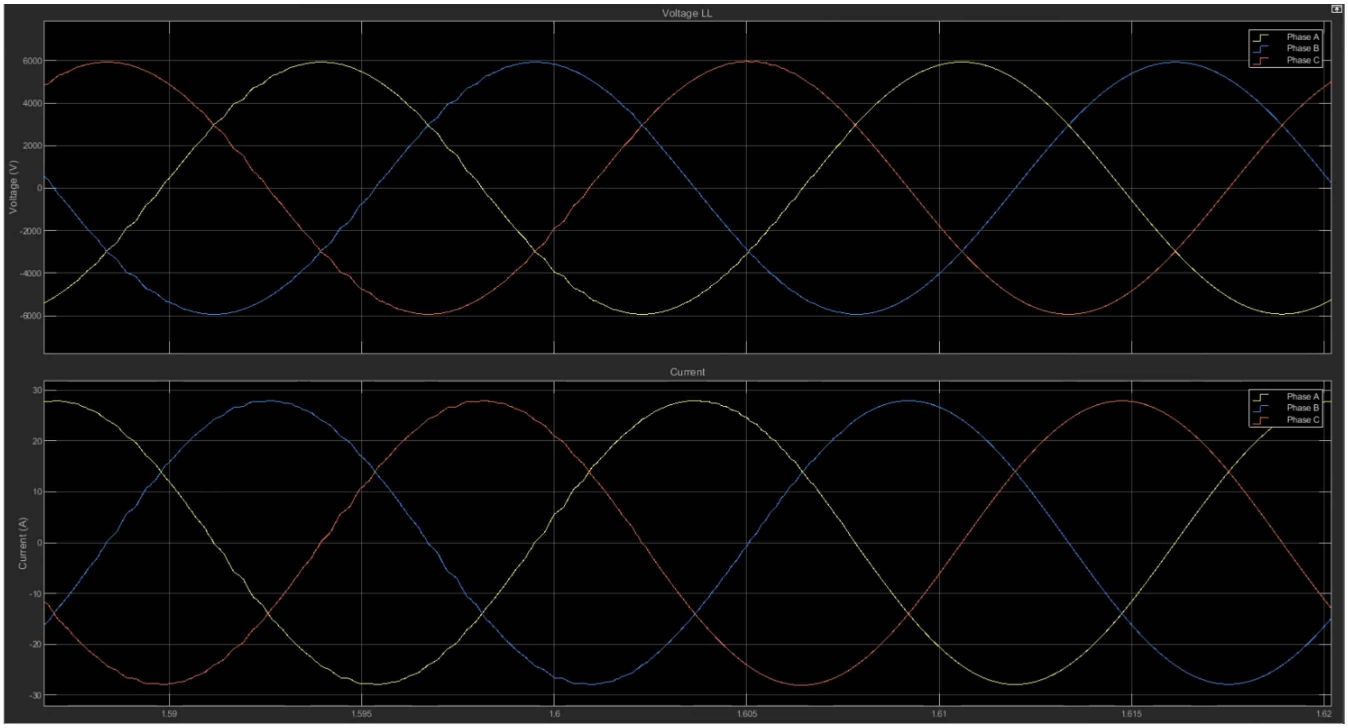


Figure 102: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 20% – Load

E.10. Łutselk'e 25% Renewable Energy Penetration

E.10.1. Load Increase and Decrease

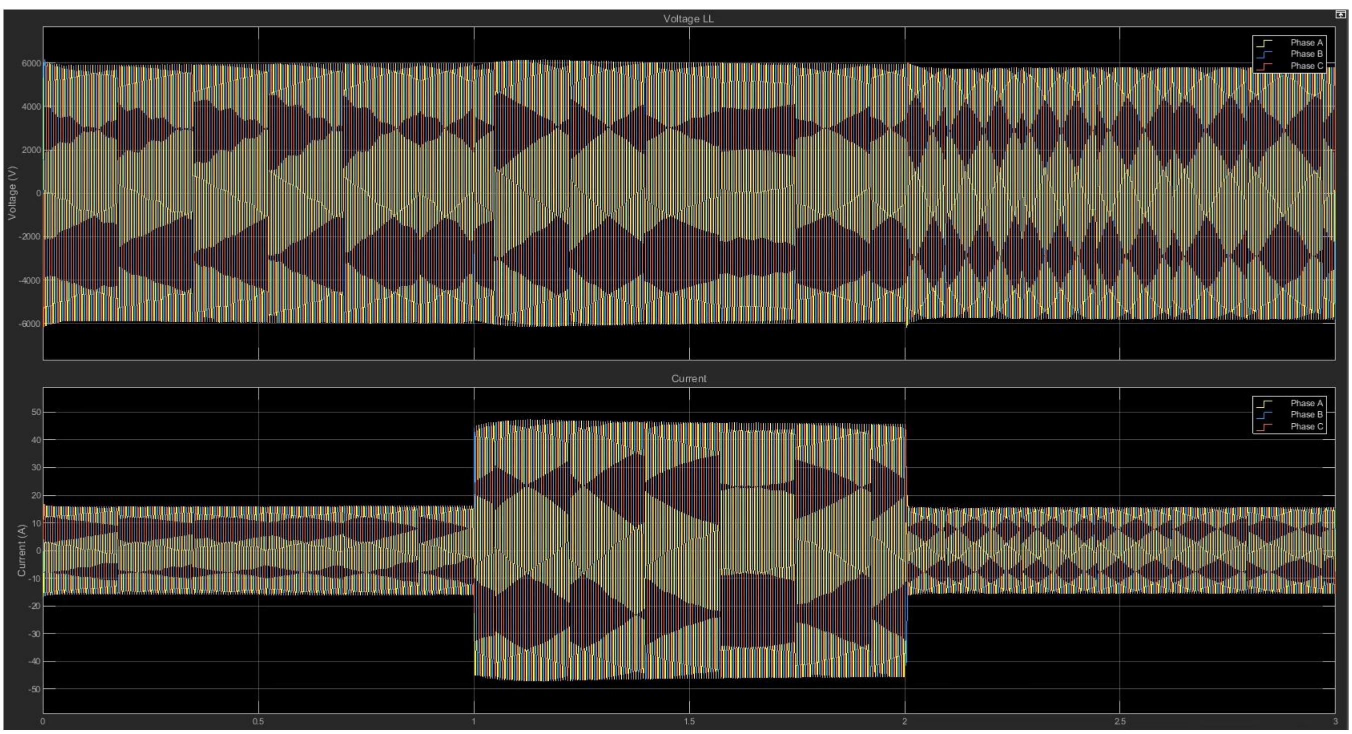


Figure 103: Dynamic Results – Łutselk'e Load Variations – 25%

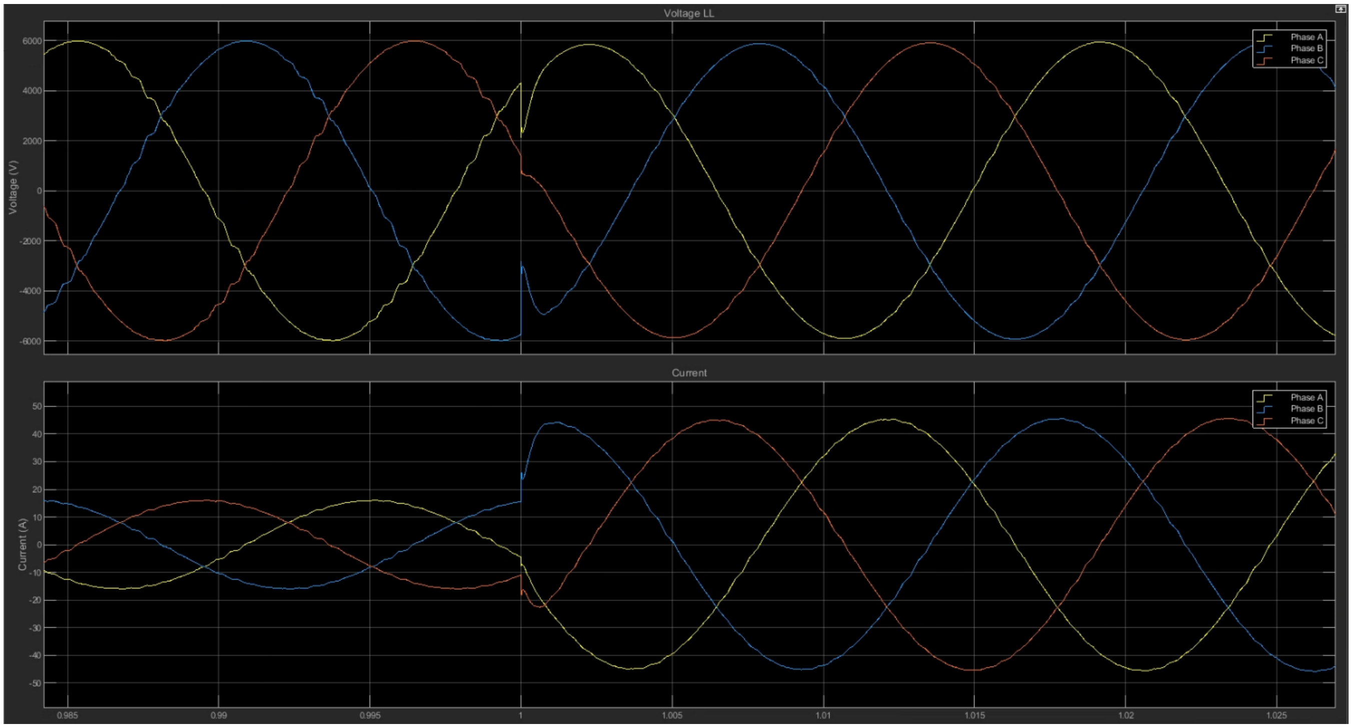


Figure 104: Dynamic Results – Łutselk'e Load Increase – 25%

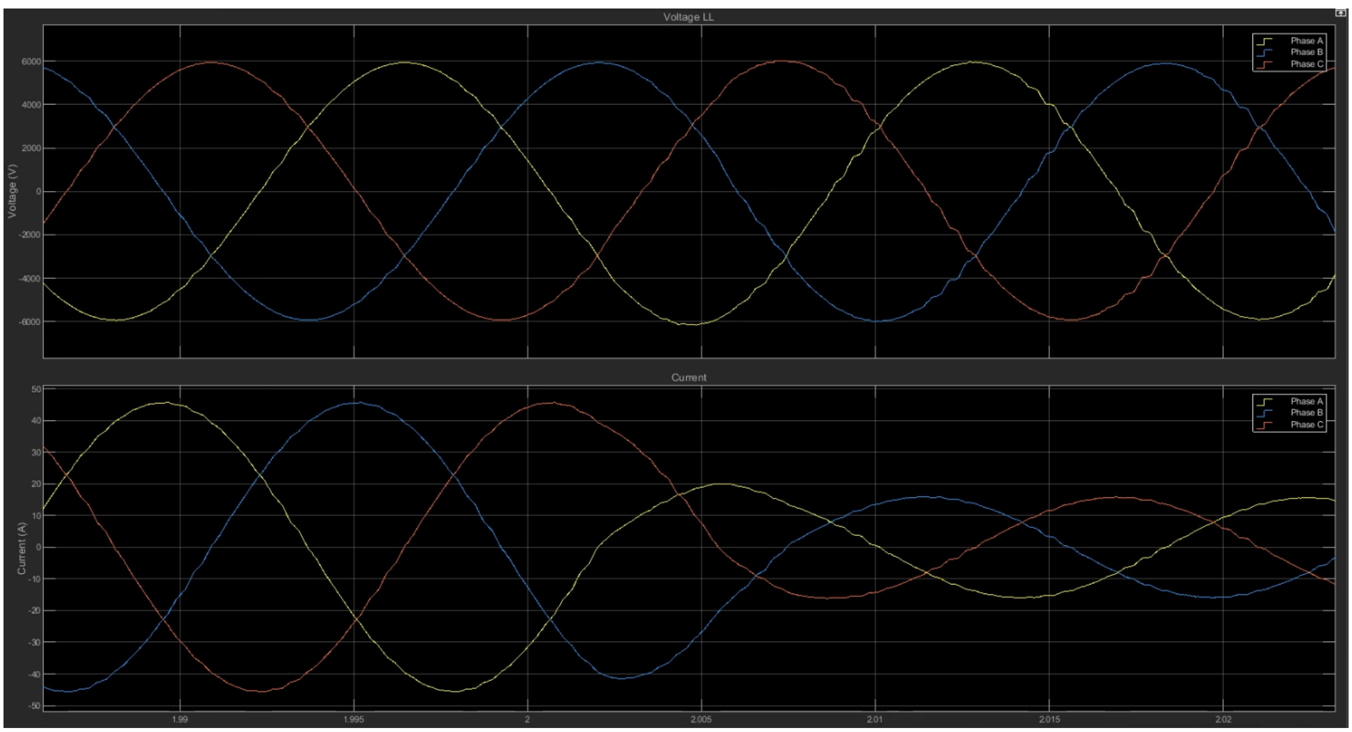


Figure 105: Dynamic Results – Łutselk'e Load Decrease – 25%

E.10.2. Renewable Connection / Disconnection

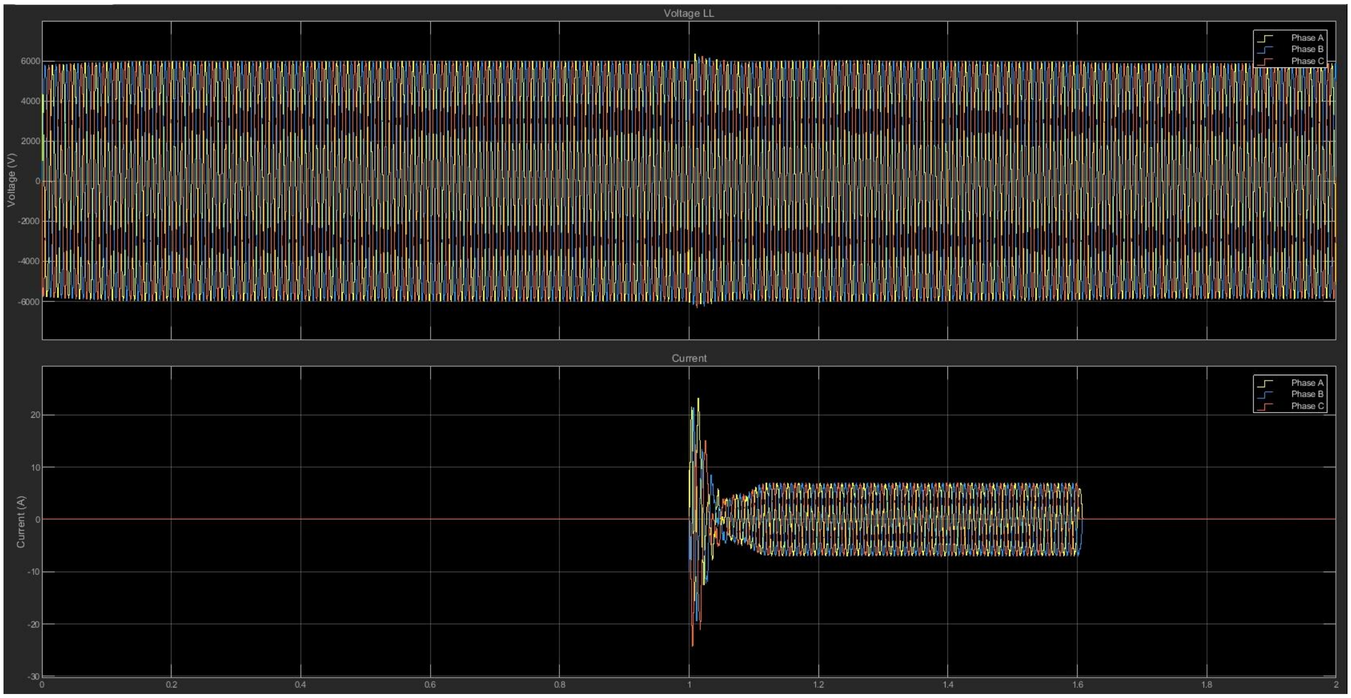


Figure 106: Dynamic Results – Łutselk'e Renewable Sources Variation – 25% – PV

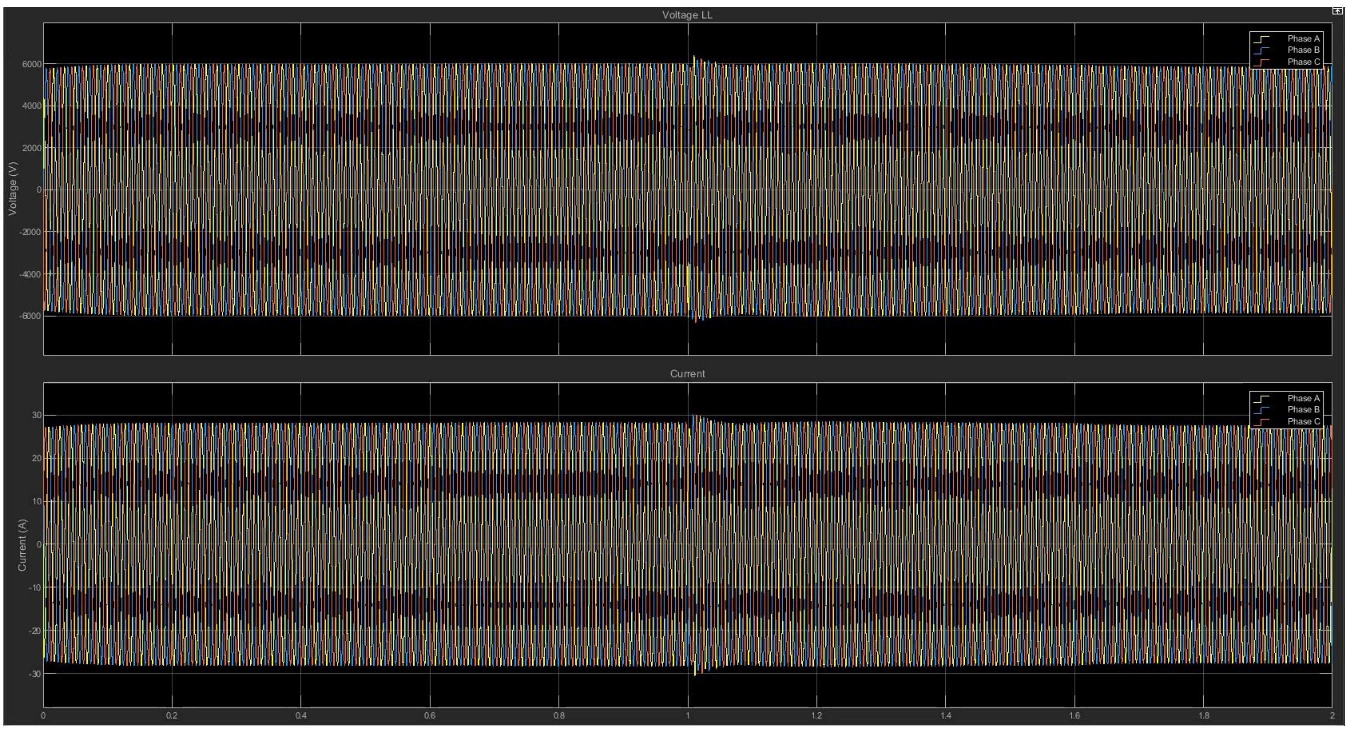


Figure 107: Dynamic Results – Łutselk'e Renewable Sources Variation – 25% – Load

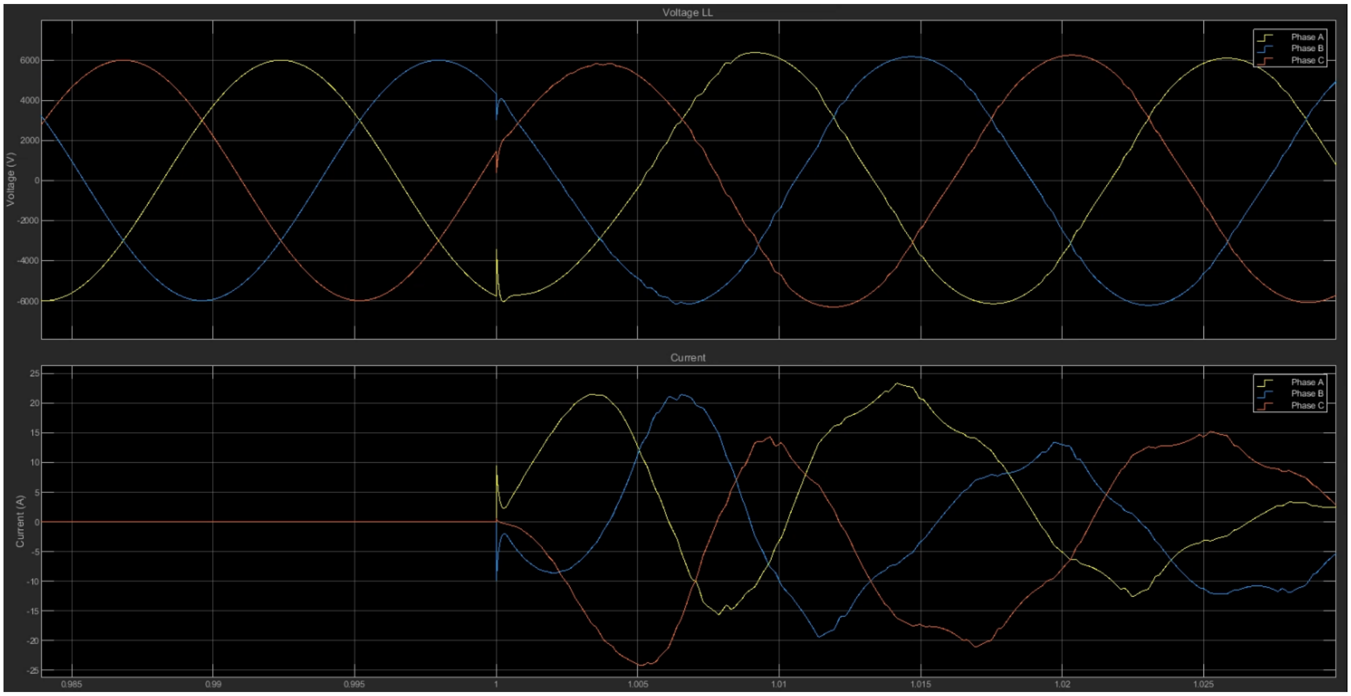


Figure 108: Dynamic Results – Łutselk'e Renewable Sources Connection – 25% – PV

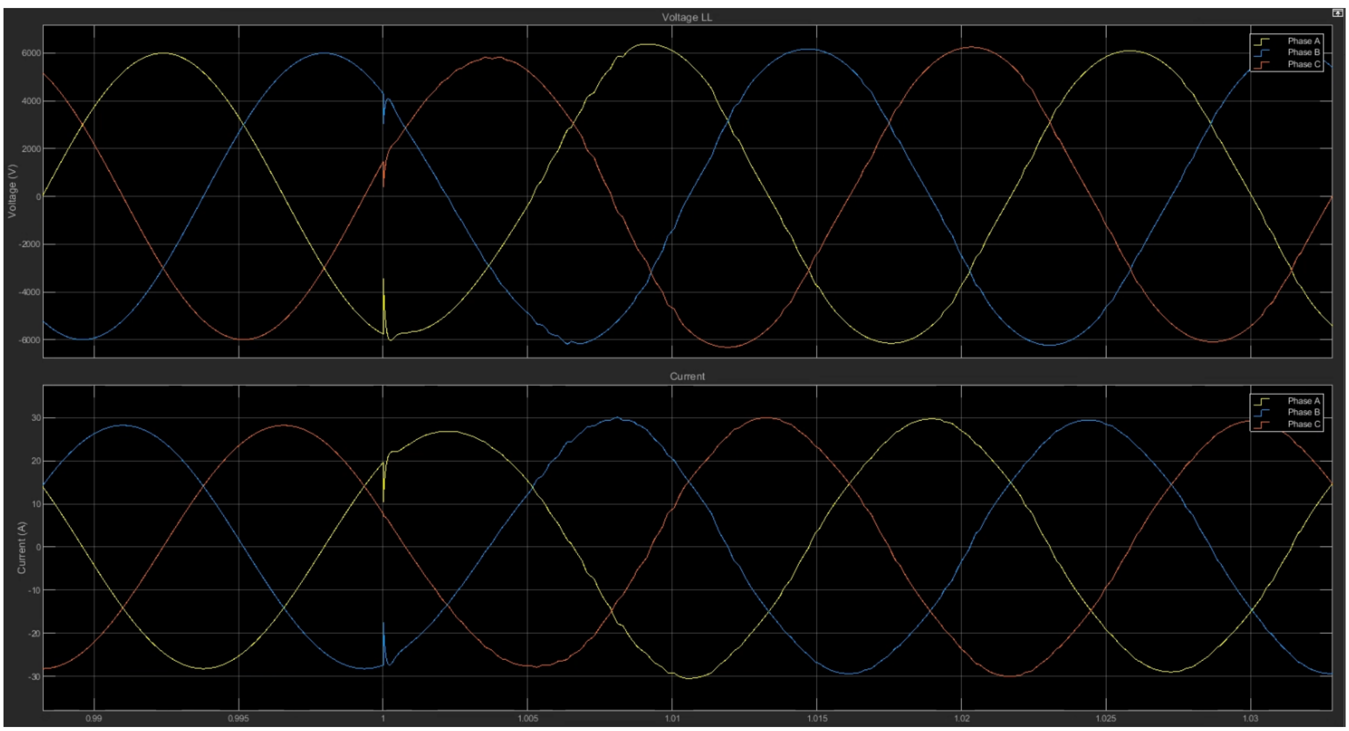


Figure 109: Dynamic Results – Łutselk'e Renewable Sources Connection – 25% – Load

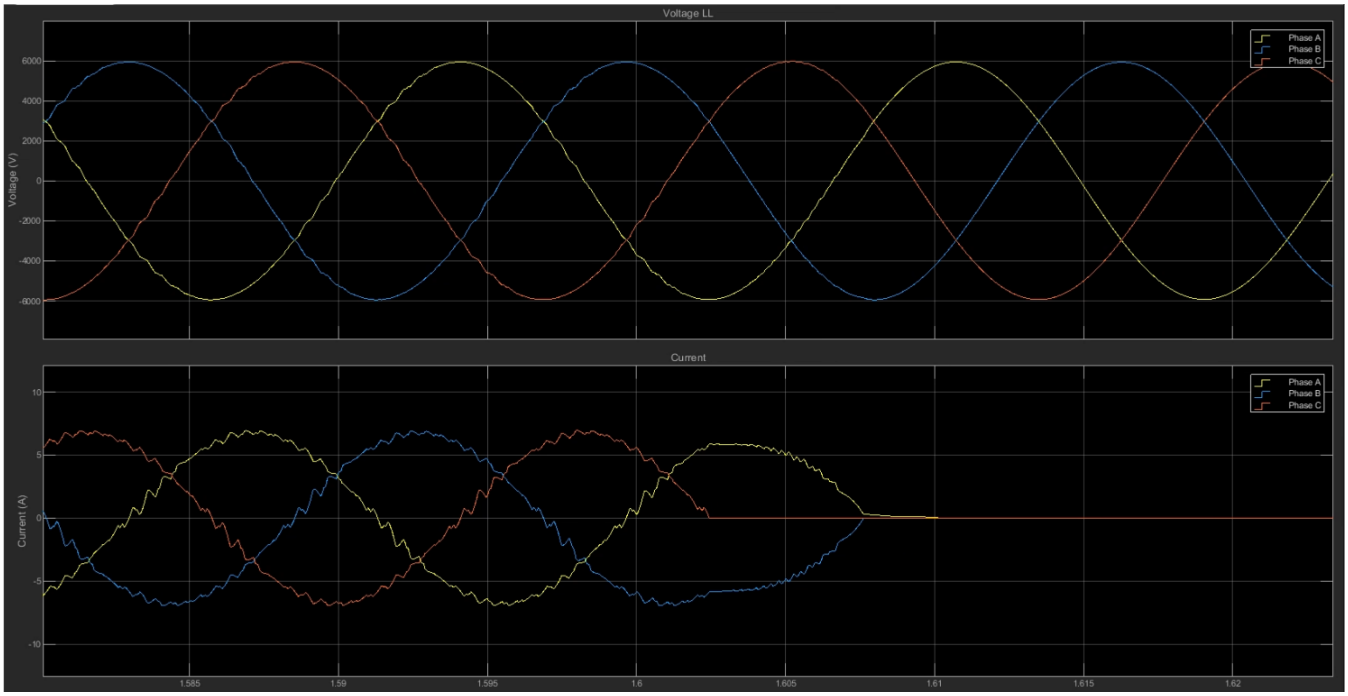


Figure 110: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 25% – PV

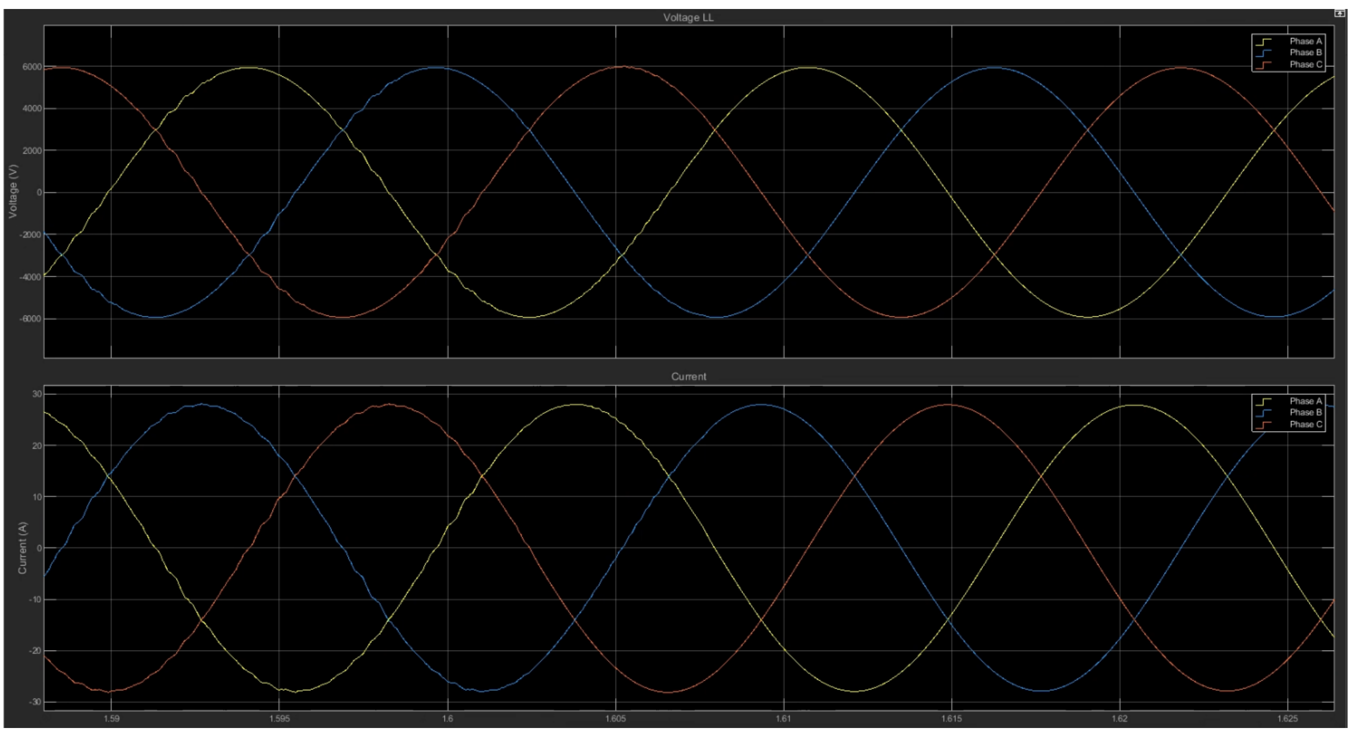


Figure 111: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 25% – Load

E.11. Łutselk'e 30% Renewable Energy Penetration

E.11.1. Load Increase and Decrease

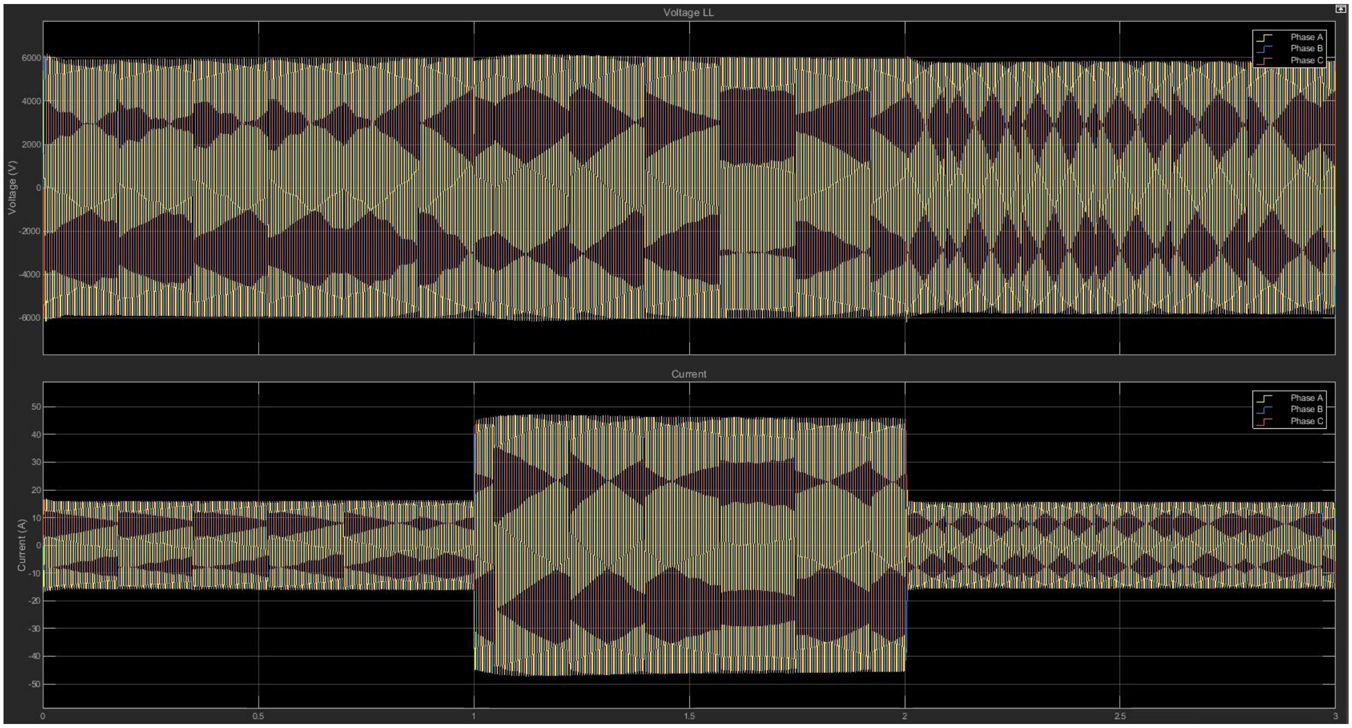


Figure 112: Dynamic Results – Łutselk'e Load Variations – 30%

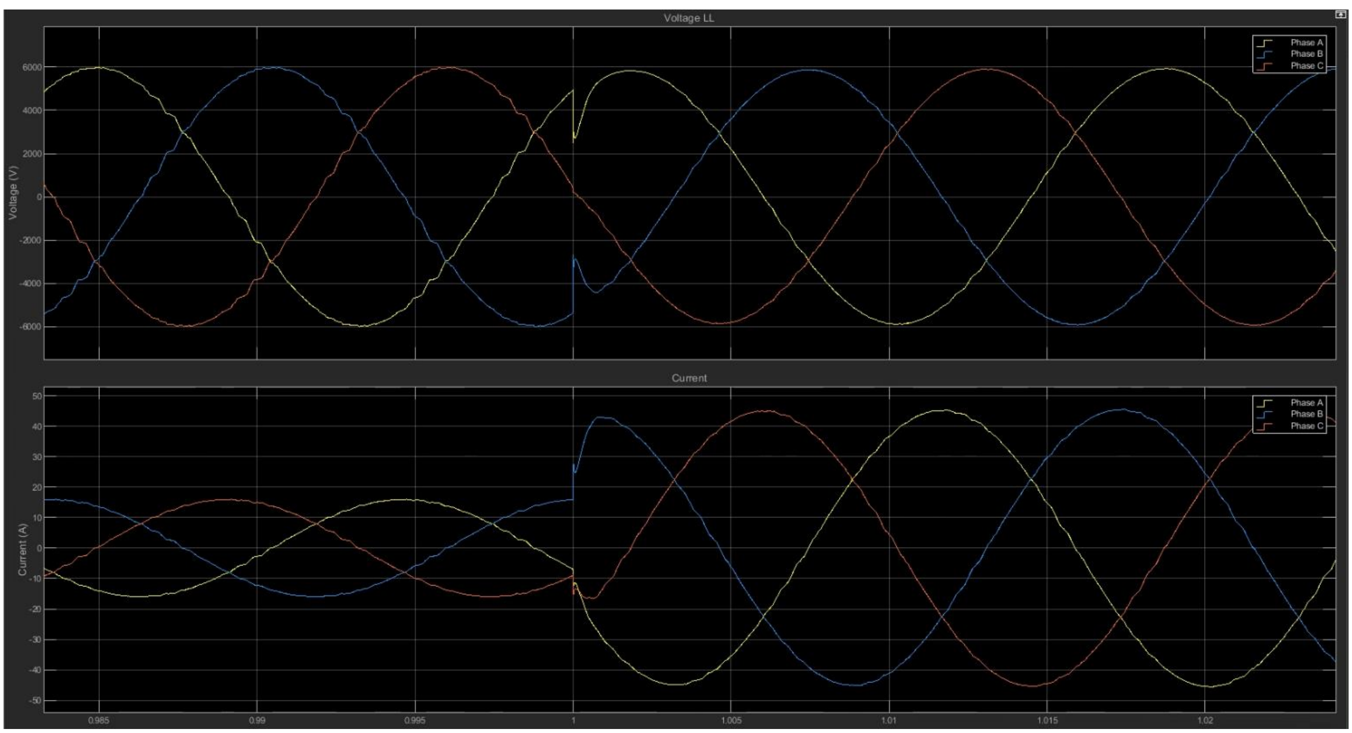


Figure 113: Dynamic Results – Łutselk'e Load Increase – 30%

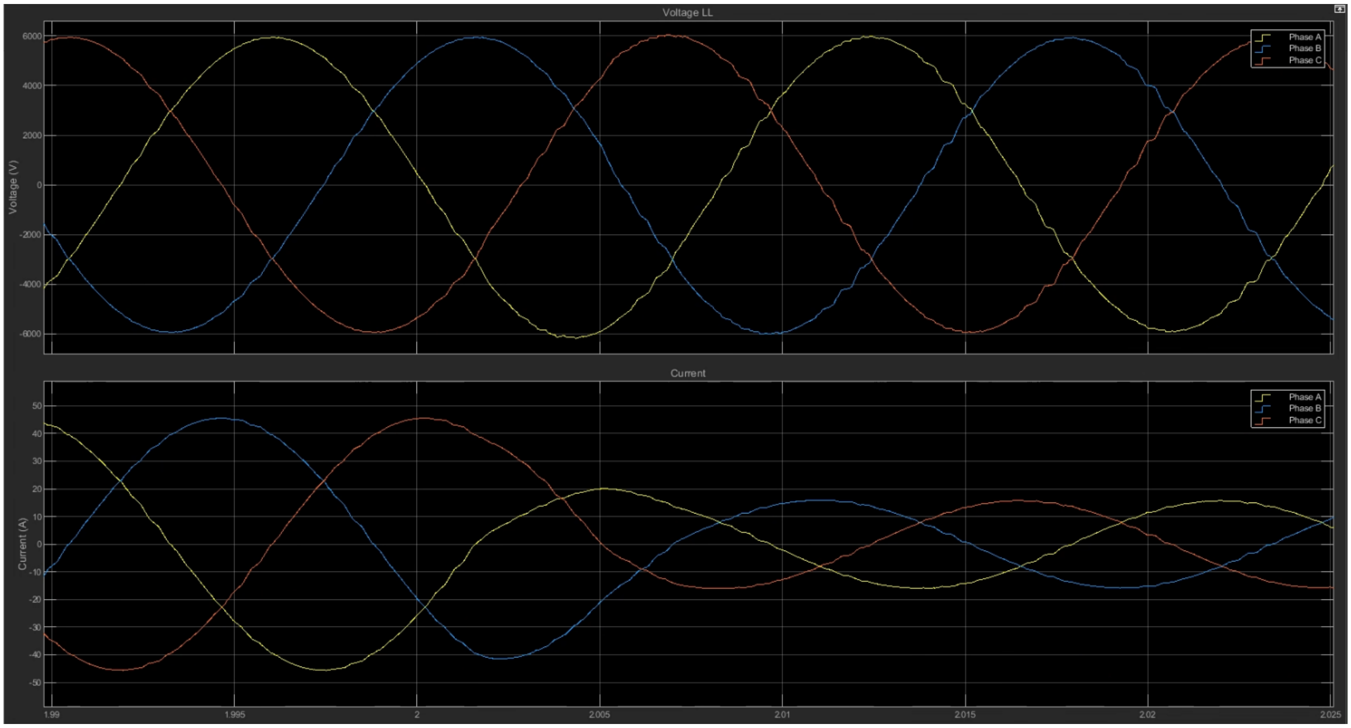


Figure 114: Dynamic Results – Łutselk'e Load Decrease – 30%

E.11.2. Renewable Connection / Disconnection

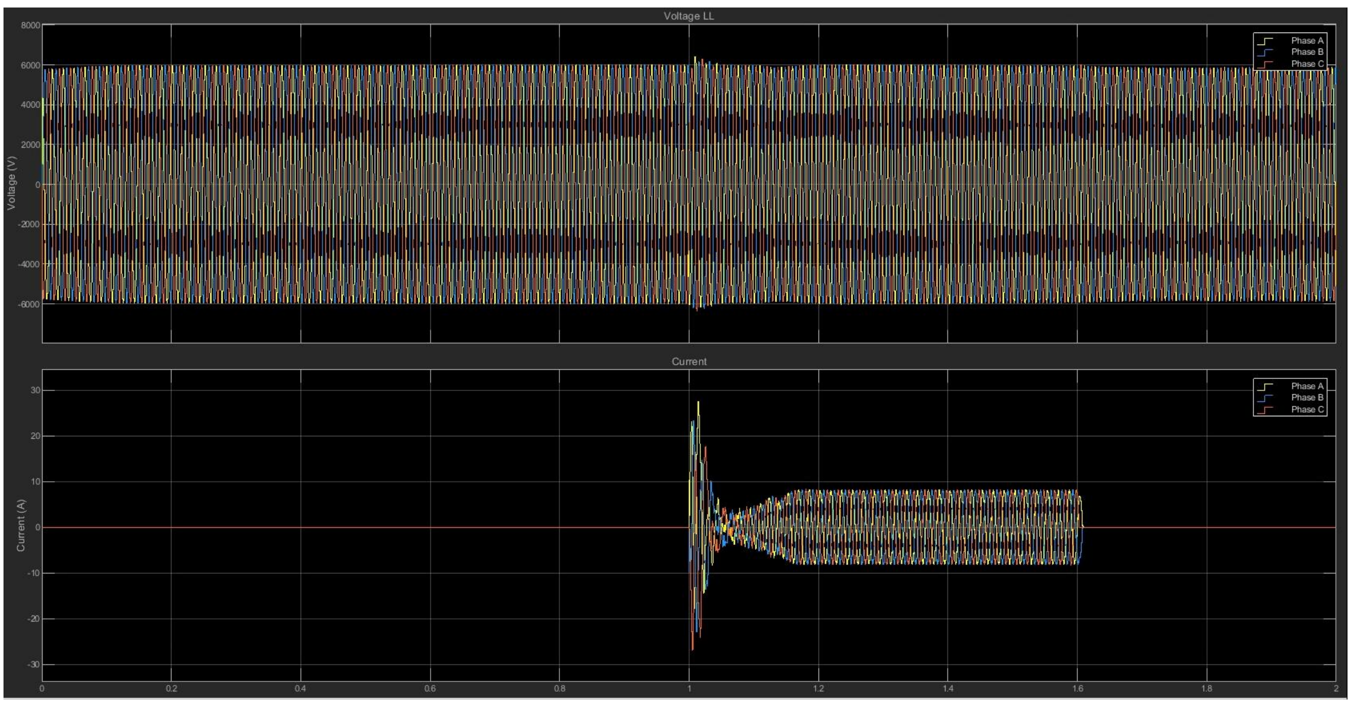


Figure 115: Dynamic Results – Łutselk'e Renewable Sources Variation – 30% – PV

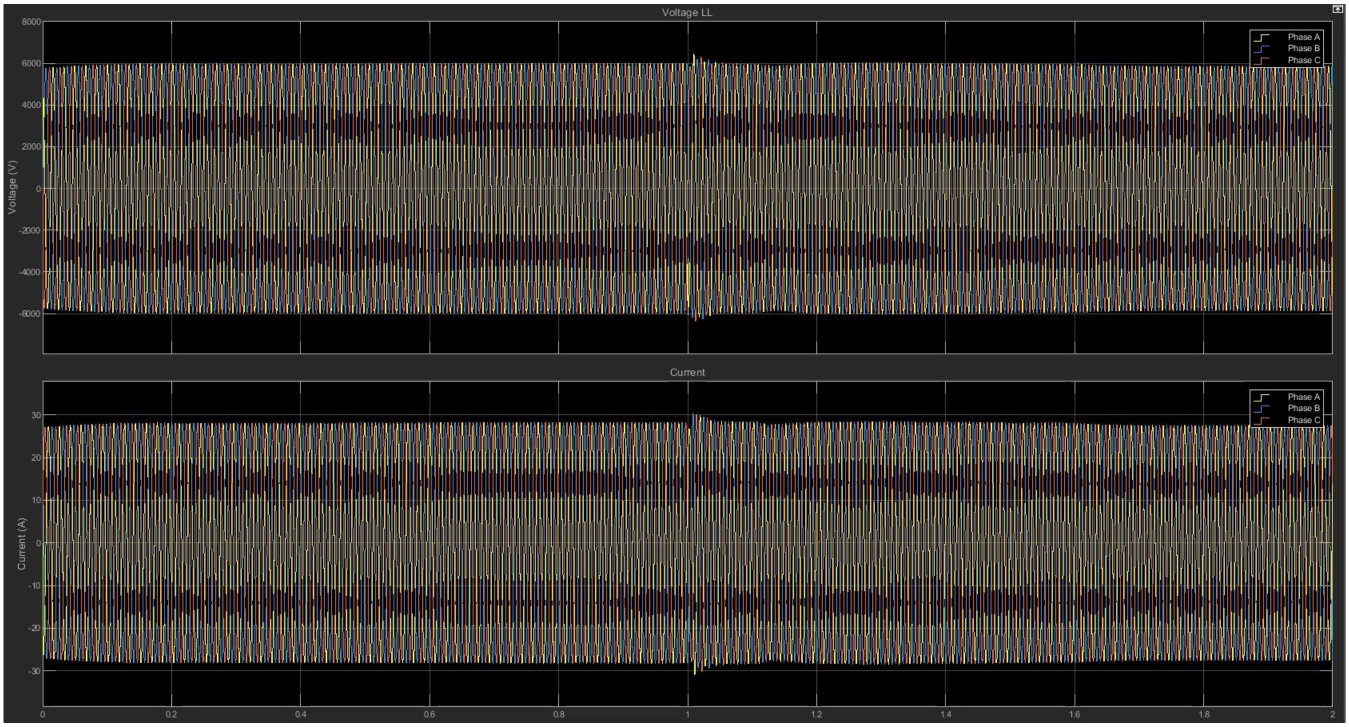


Figure 116: Dynamic Results – Łutselk'e Renewable Sources Variation – 30% – Load

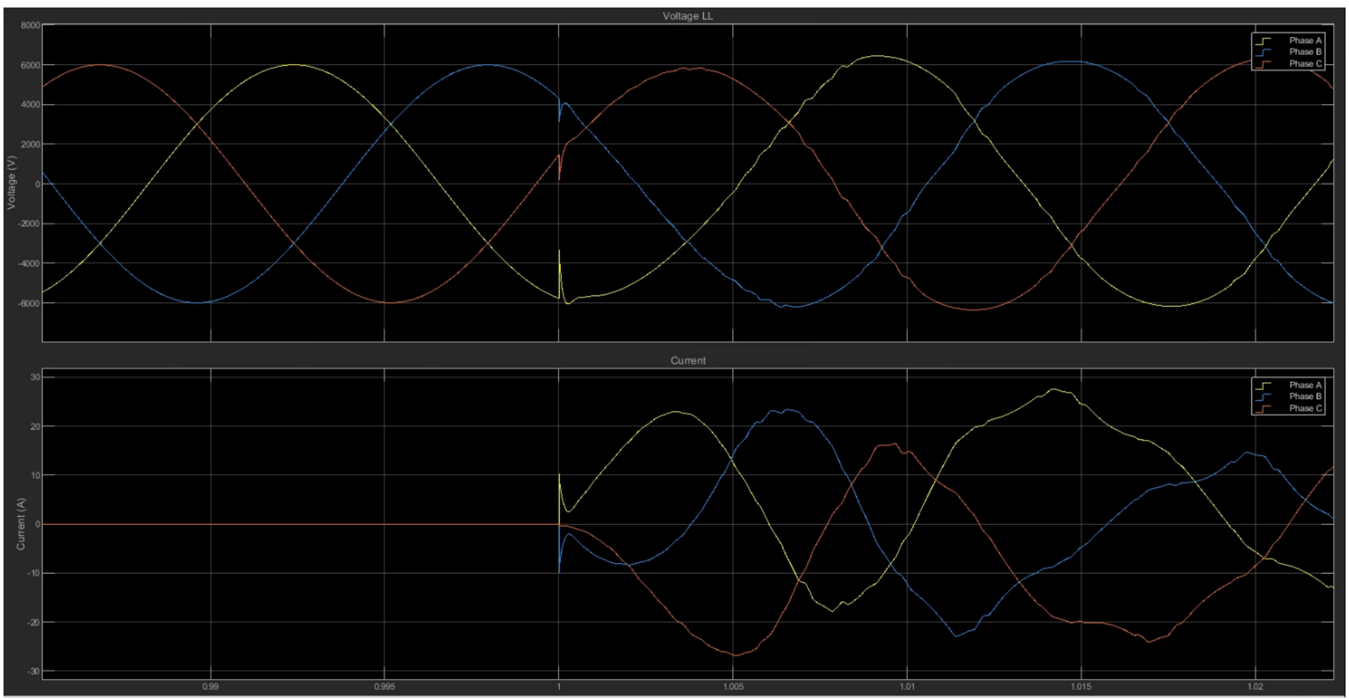


Figure 117: Dynamic Results – Łutselk'e Renewable Sources Connection – 30% – PV

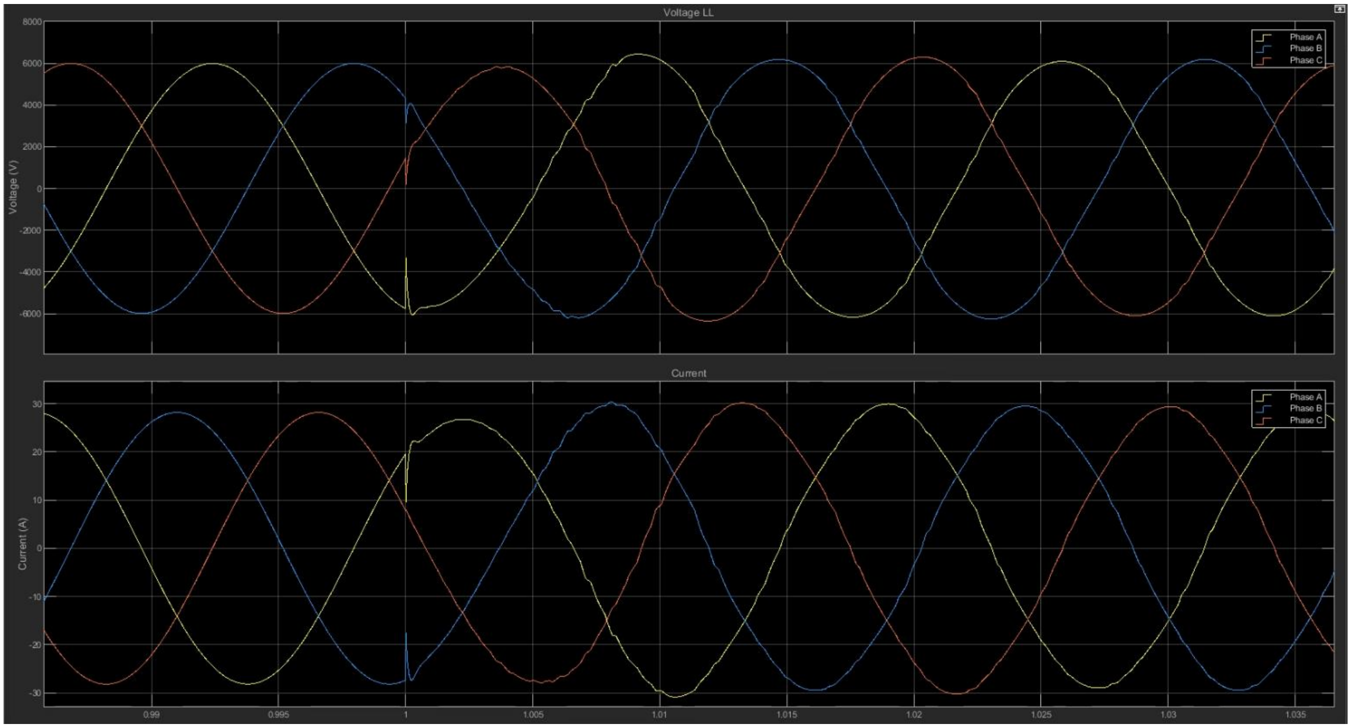


Figure 118: Dynamic Results – Łutselk'e Renewable Sources Connection – 30% – Load

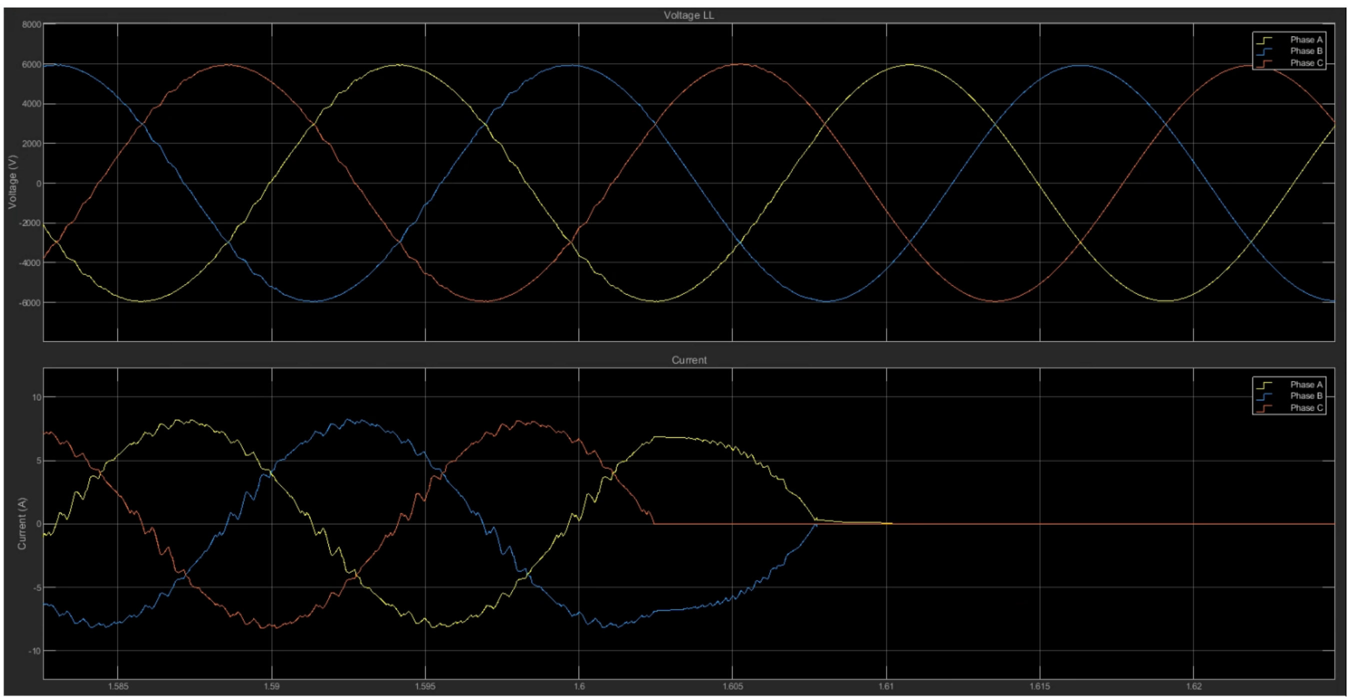


Figure 119: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 30% – PV

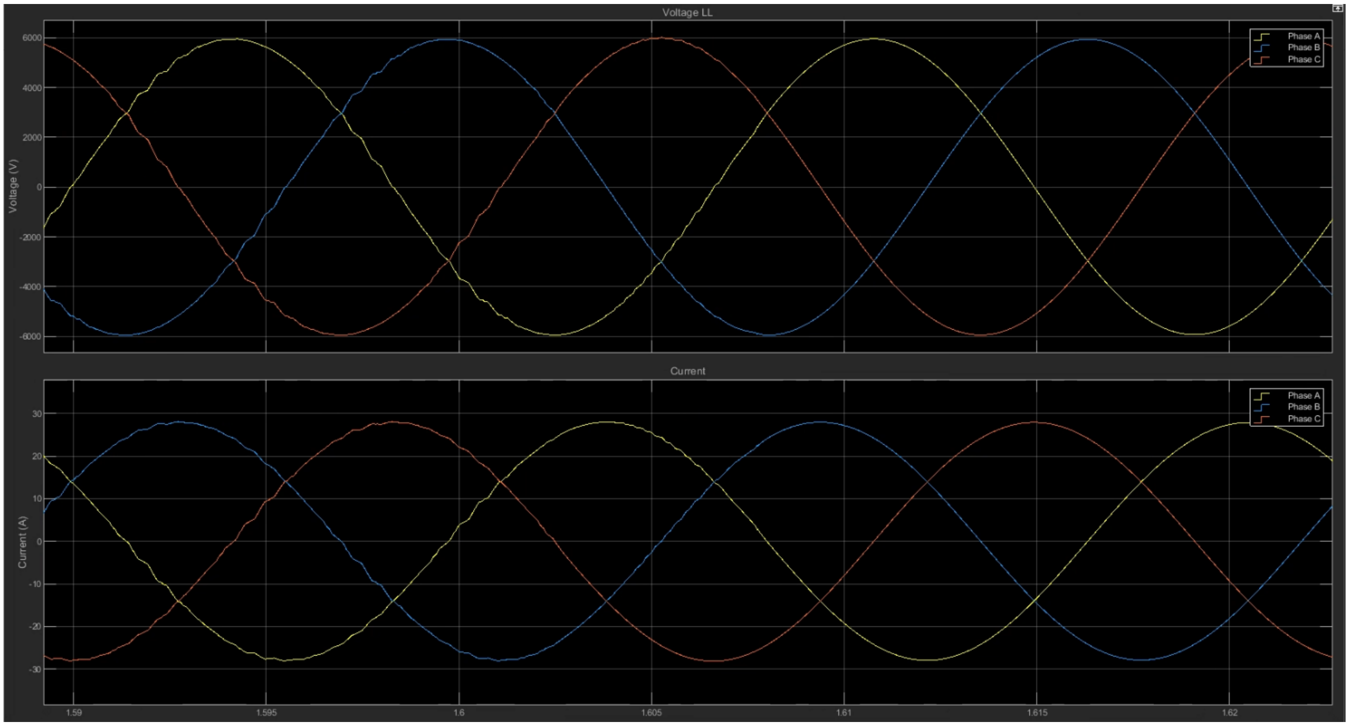


Figure 120: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 30% – Load

E.12. Łutselk'e 50% Renewable Energy Penetration

E.12.1. Load Increase and Decrease

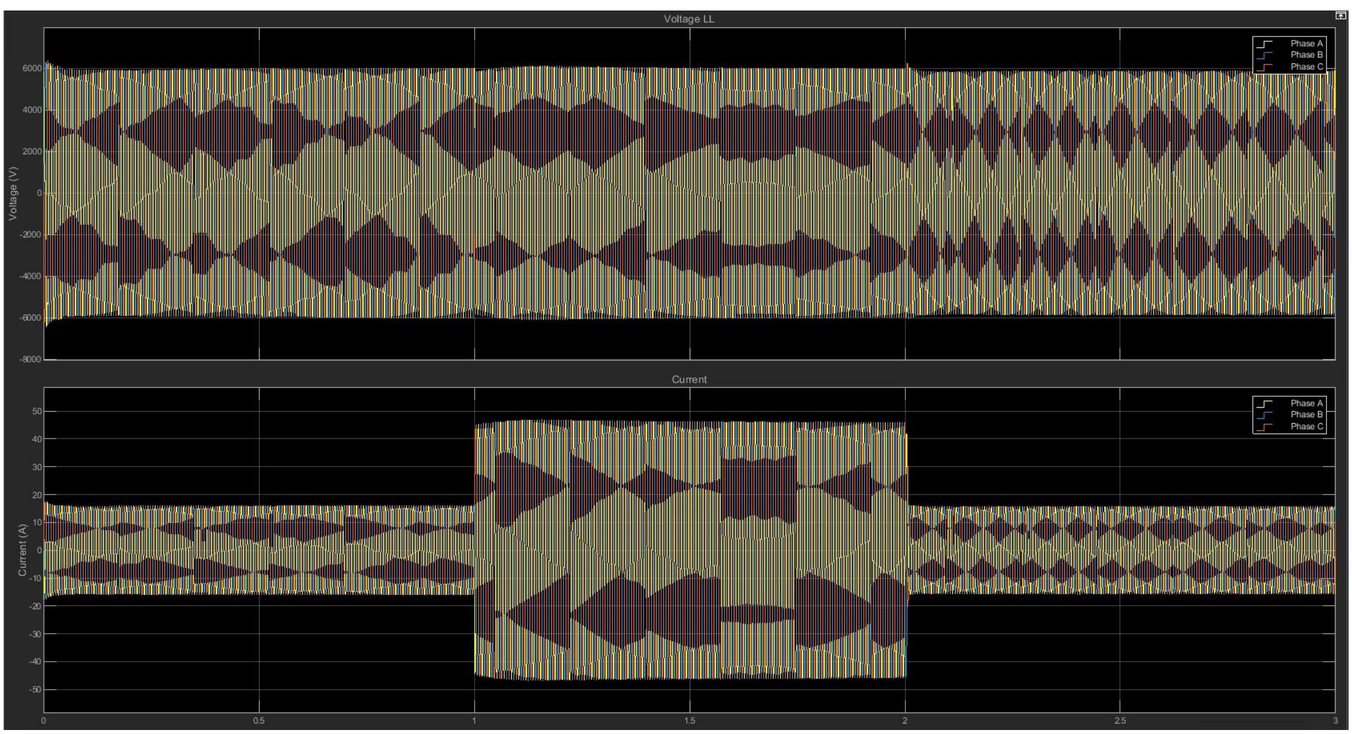


Figure 121: Dynamic Results – Łutselk'e Load Variations – 50%

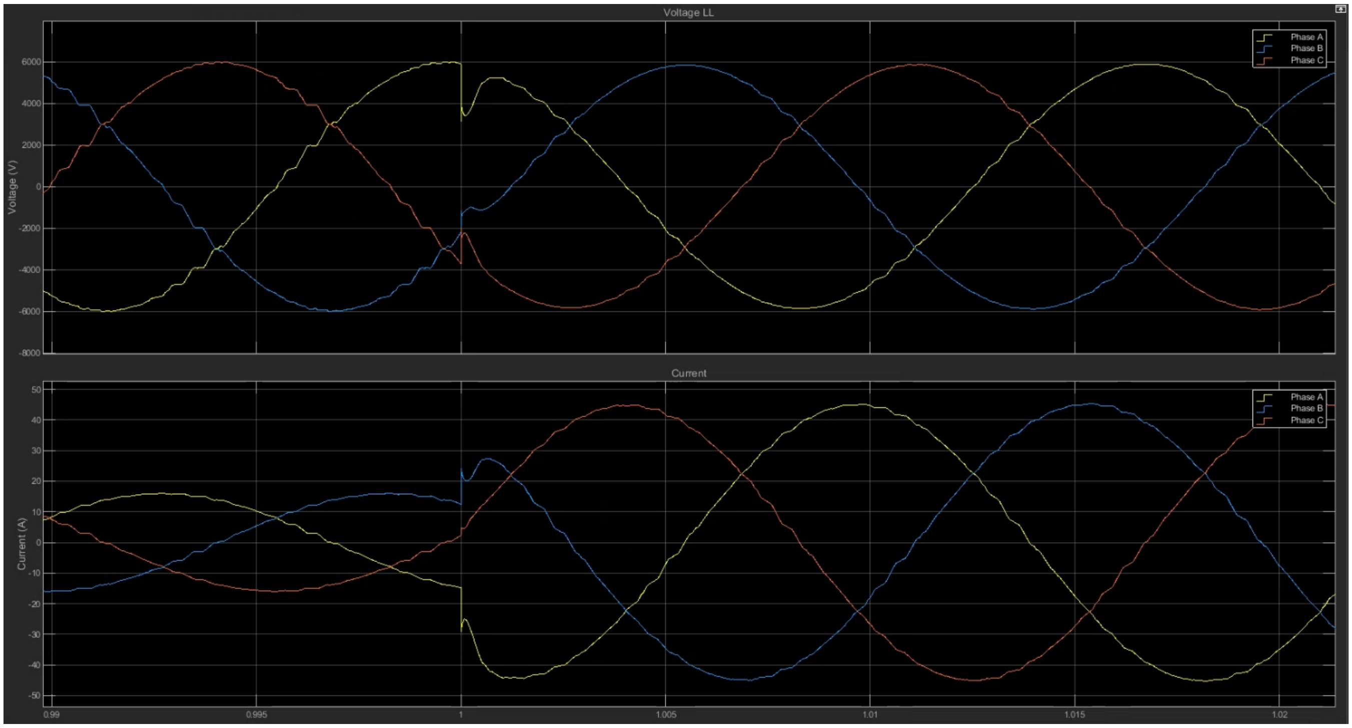


Figure 122: Dynamic Results – Łutselk'e Load Increase – 50%

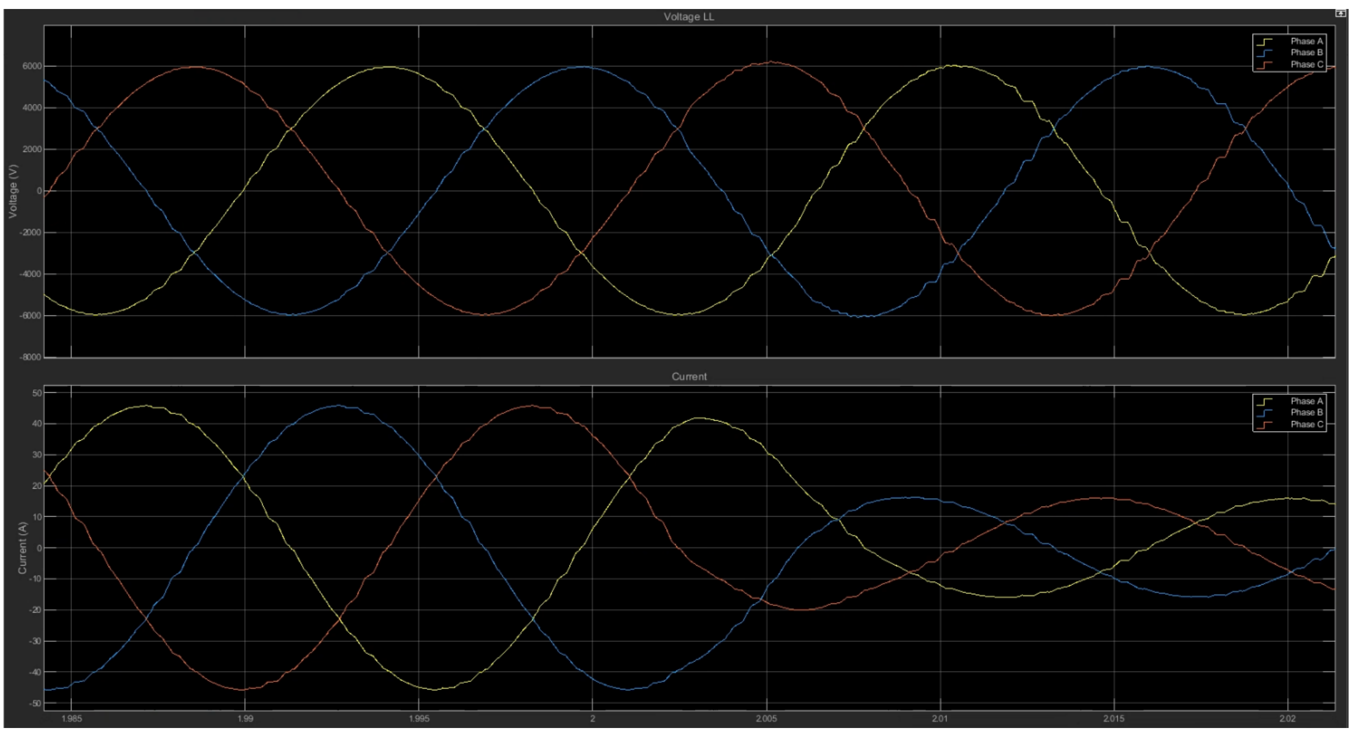


Figure 123: Dynamic Results – Łutselk'e Load Decrease – 50%

E.12.2. Renewable Connection / Disconnection

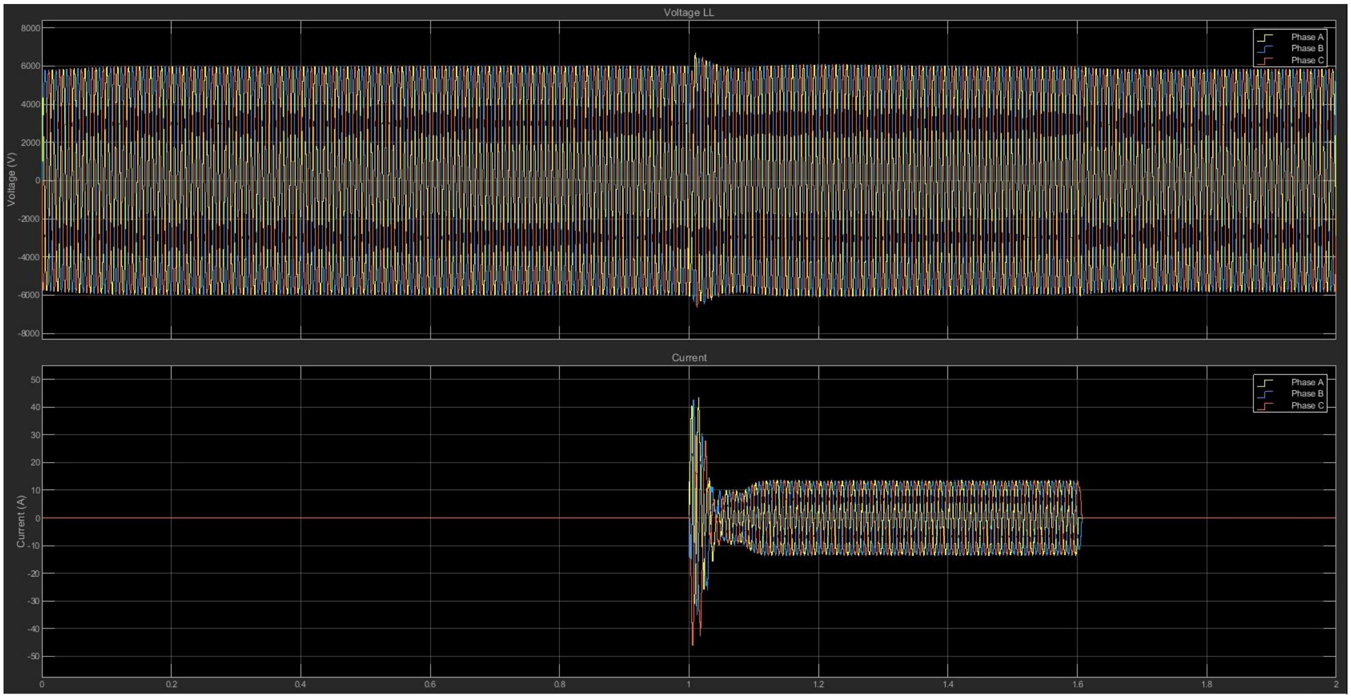


Figure 124: Dynamic Results – Łutselk'e Renewable Sources Variation – 50% – PV

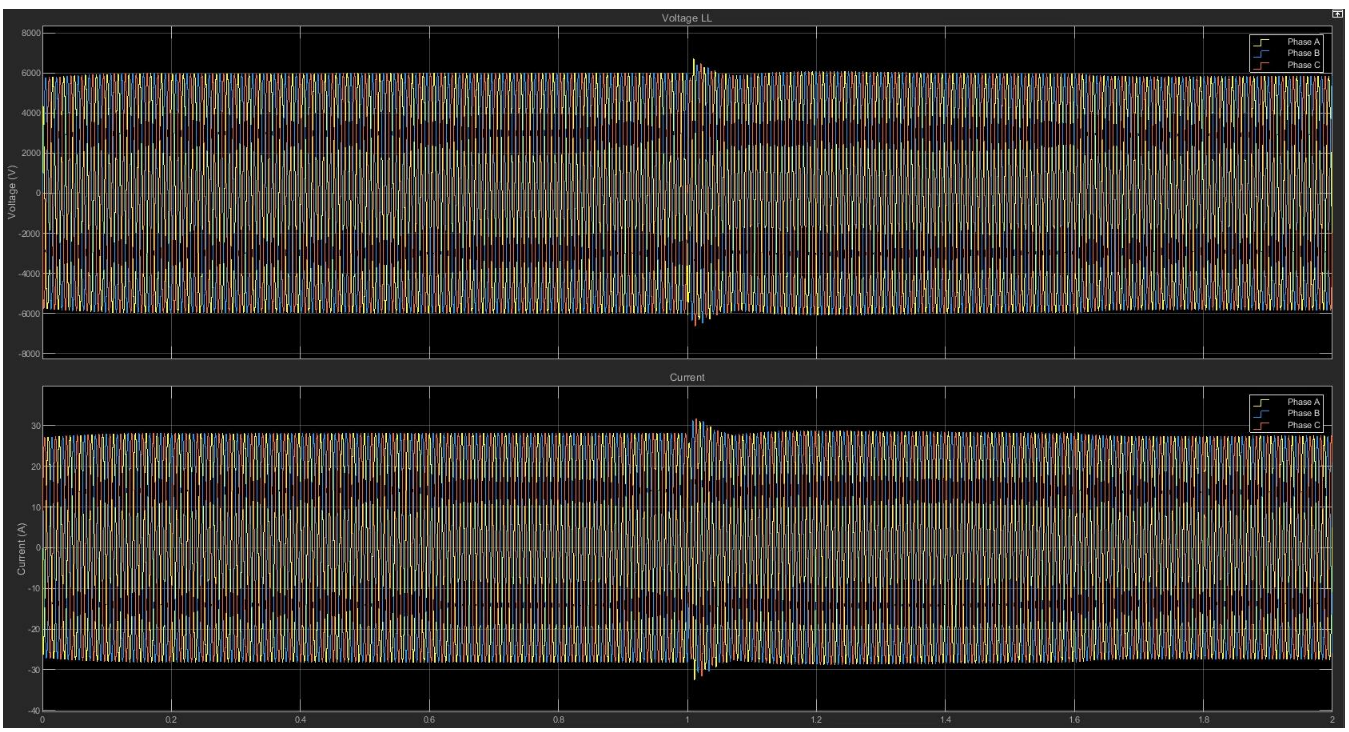


Figure 125: Dynamic Results – Łutselk'e Renewable Sources Variation – 50% – Load

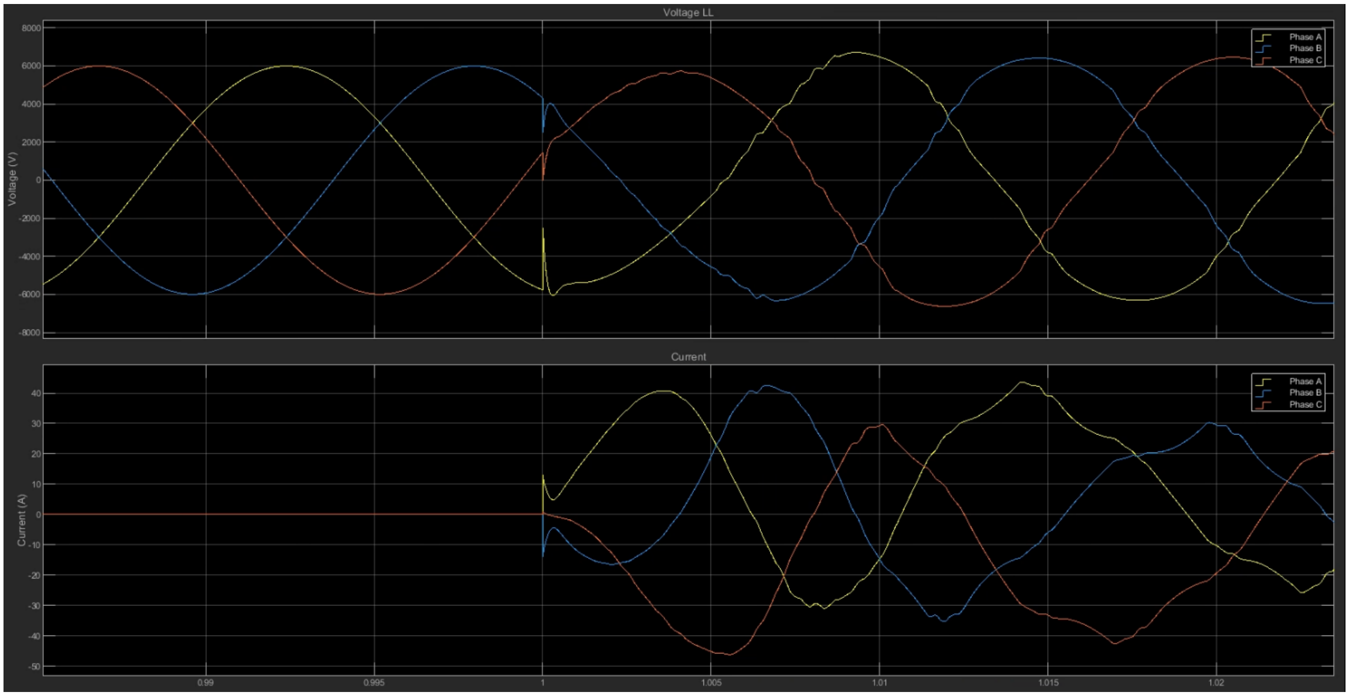


Figure 126: Dynamic Results – Łutselk'e Renewable Sources Connection – 50% – PV

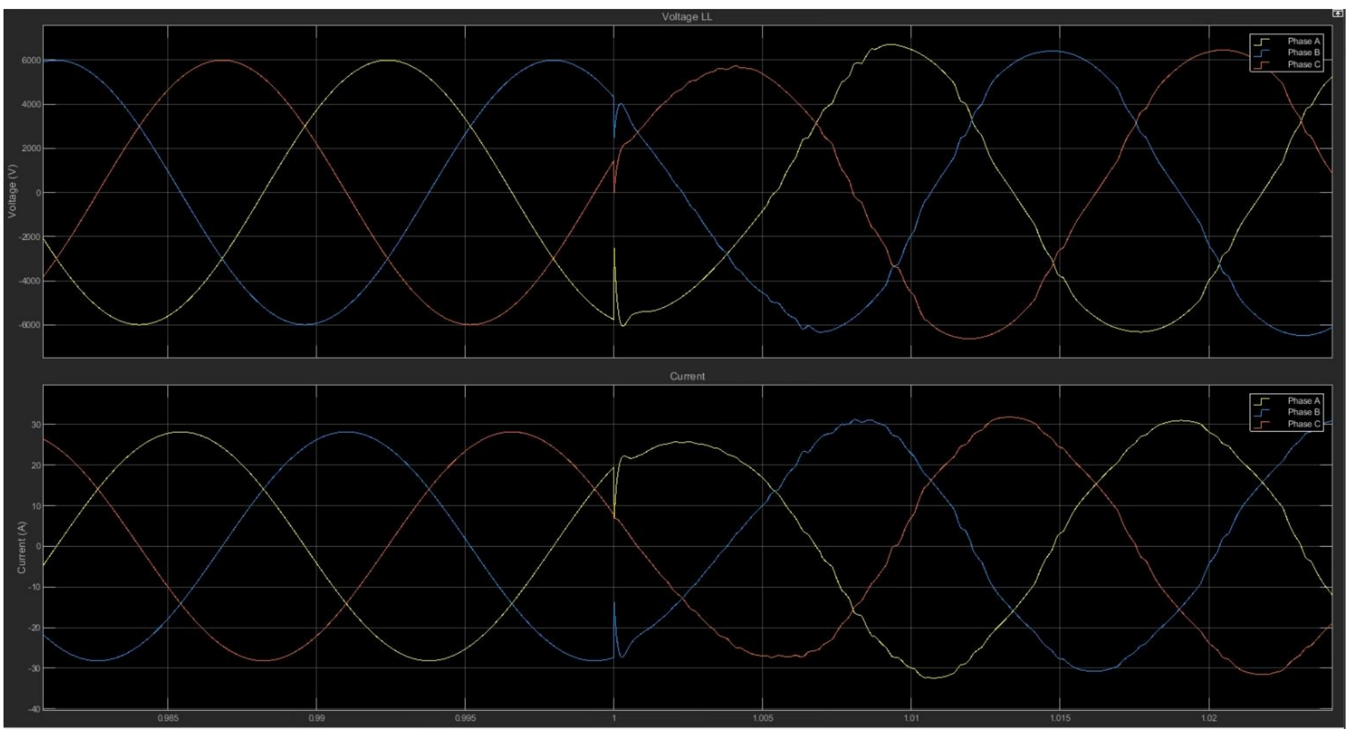


Figure 127: Dynamic Results – Łutselk'e Renewable Sources Connection – 50% – Load

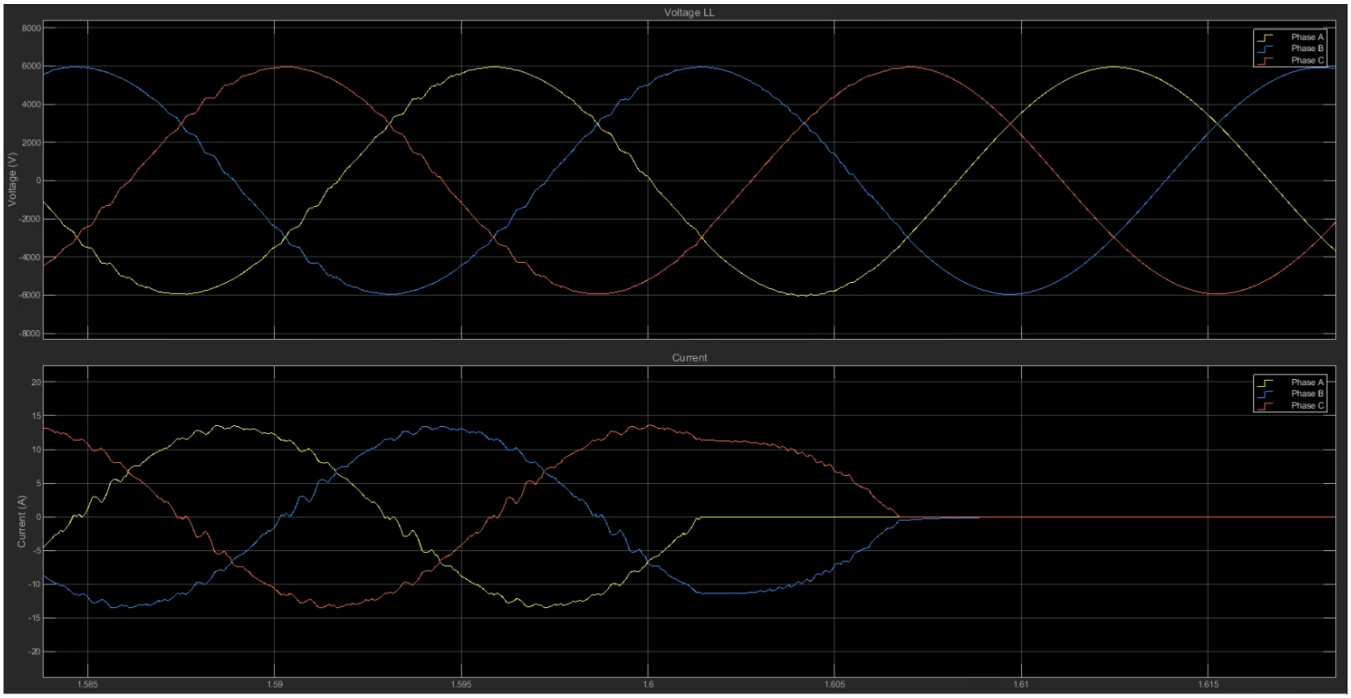


Figure 128: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 50% – PV

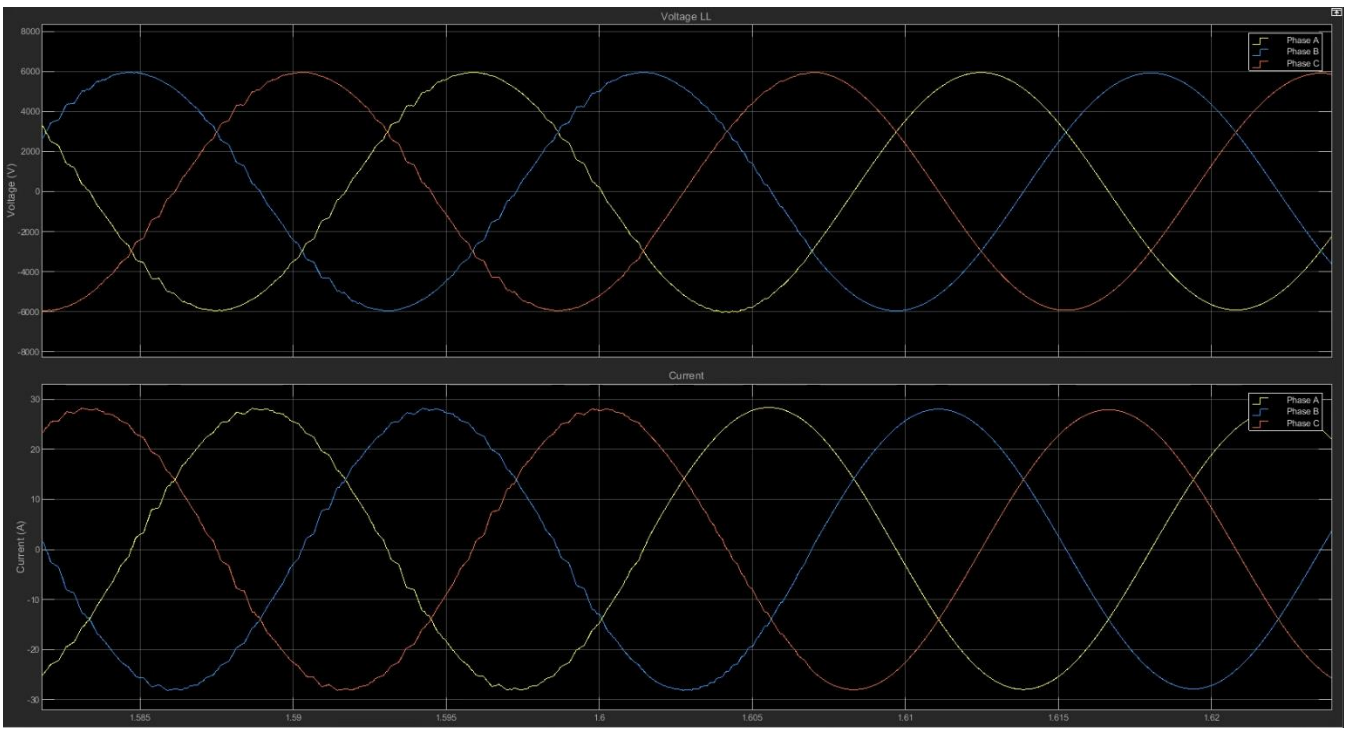


Figure 129: Dynamic Results – Łutselk'e Renewable Sources Disconnection – 50% – Load

E.13. Fort Simpson 20% Renewable Energy Penetration

E.13.1. Load Increase and Decrease

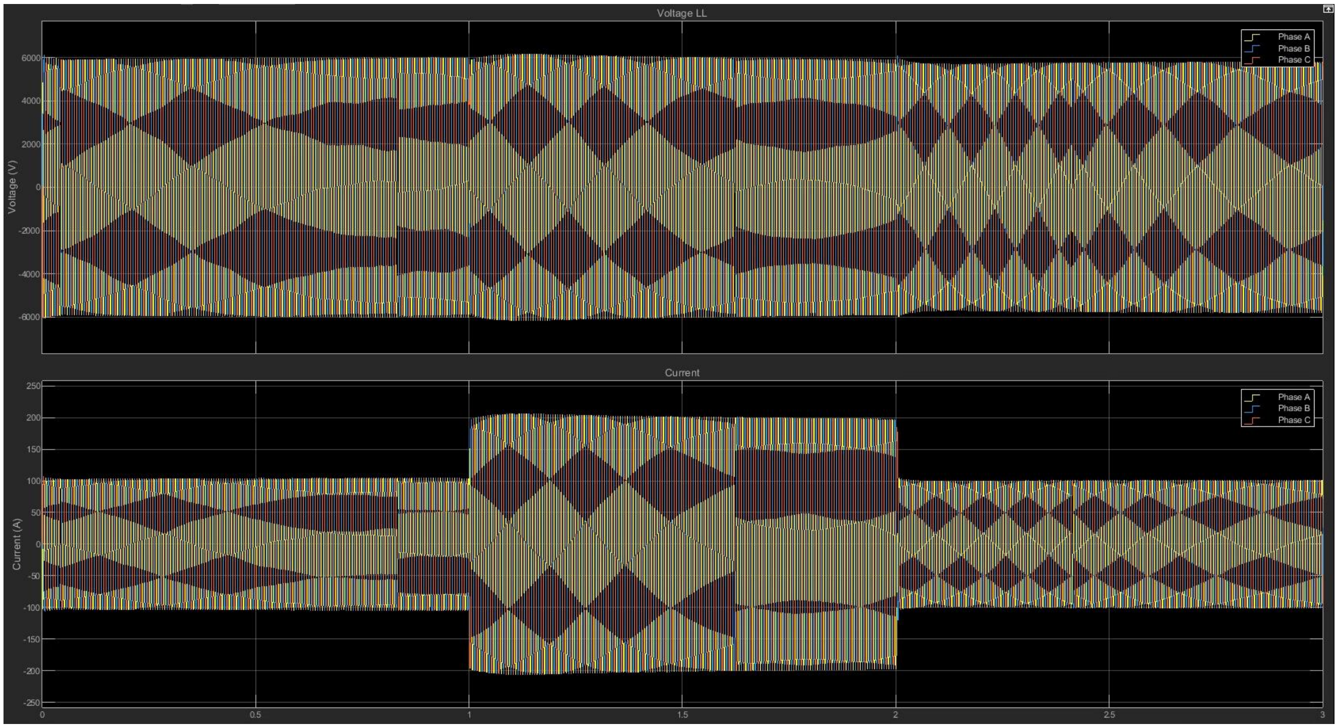


Figure 130: Dynamic Results – Fort Simpson Load Variations – 20%

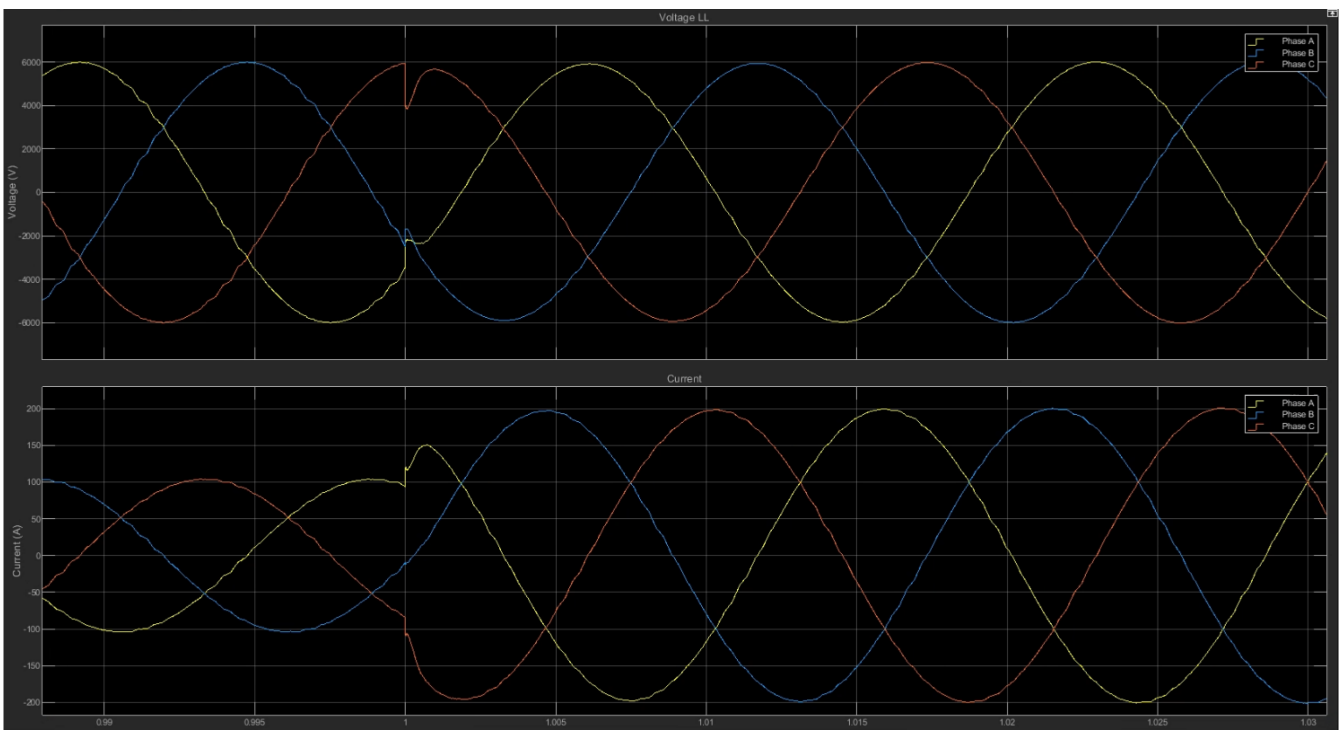


Figure 131: Dynamic Results – Fort Simpson Load Increase – 20%

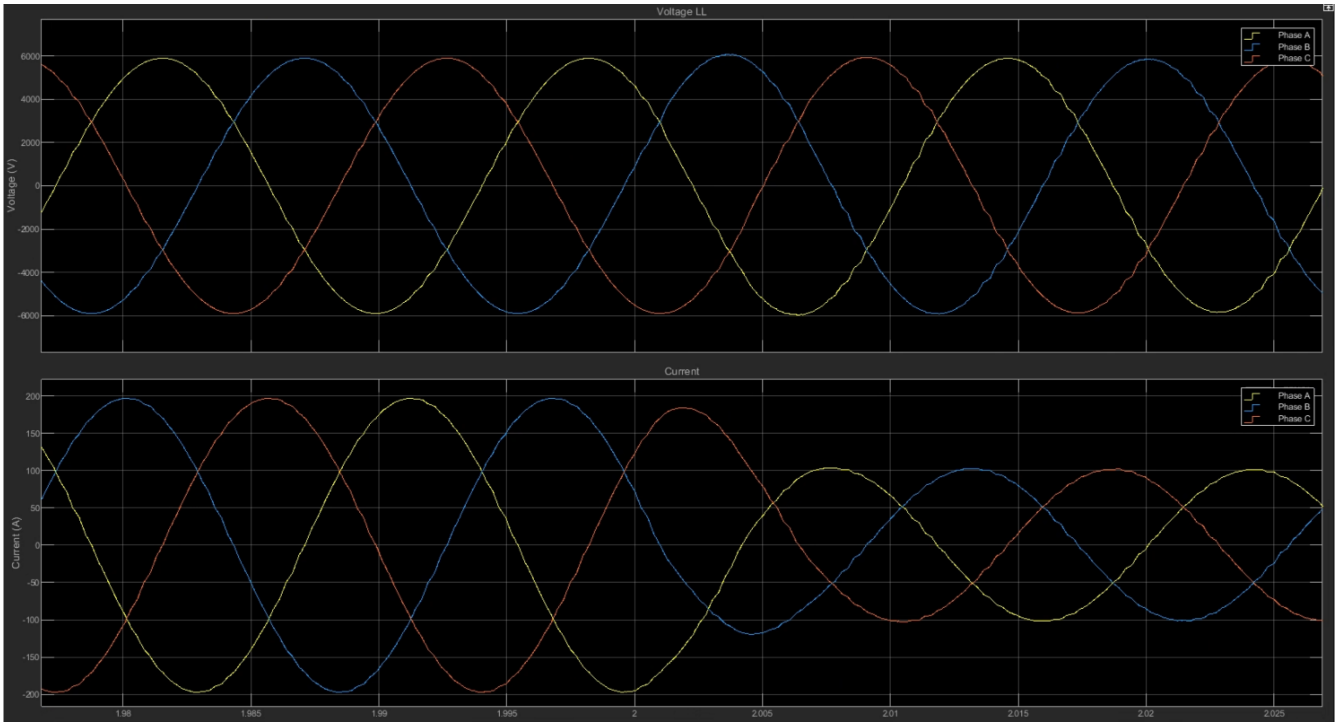


Figure 132: Dynamic Results – Fort Simpson Load Decrease – 20%

E.13.2. Renewable Connection / Disconnection

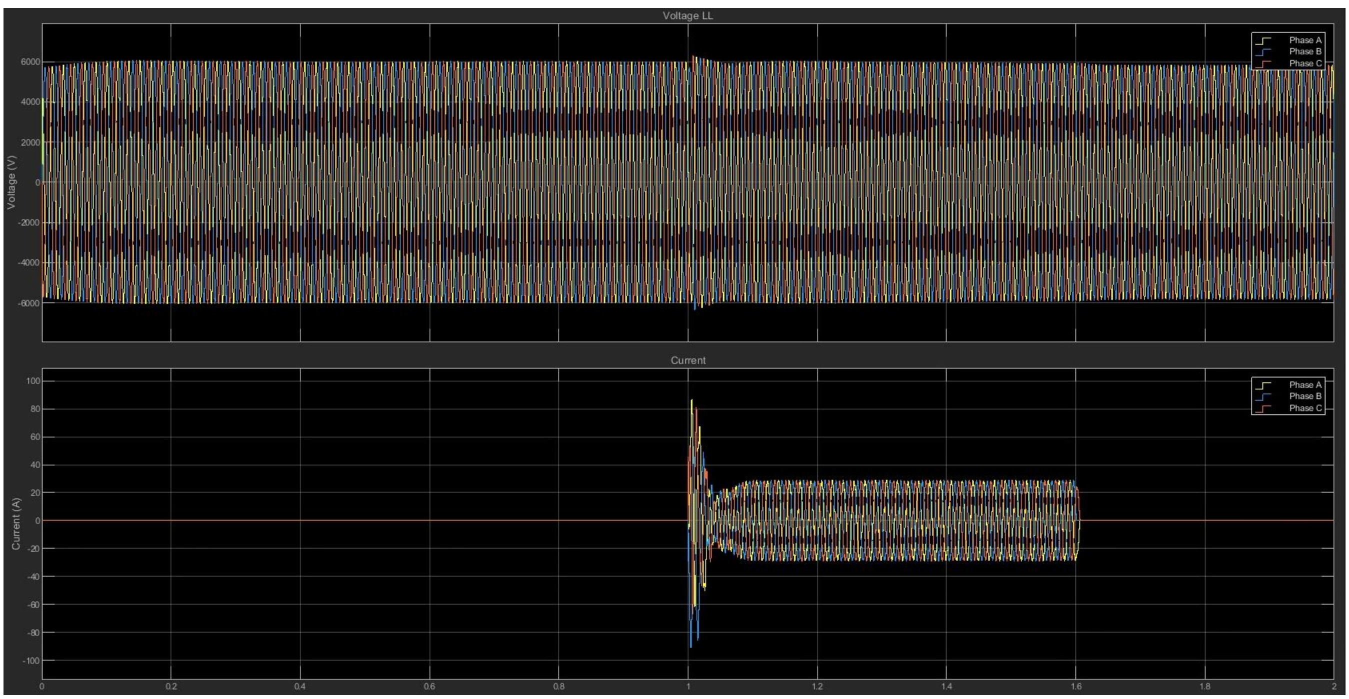


Figure 133: Dynamic Results – Fort Simpson Renewable Sources Variation – 20% – PV

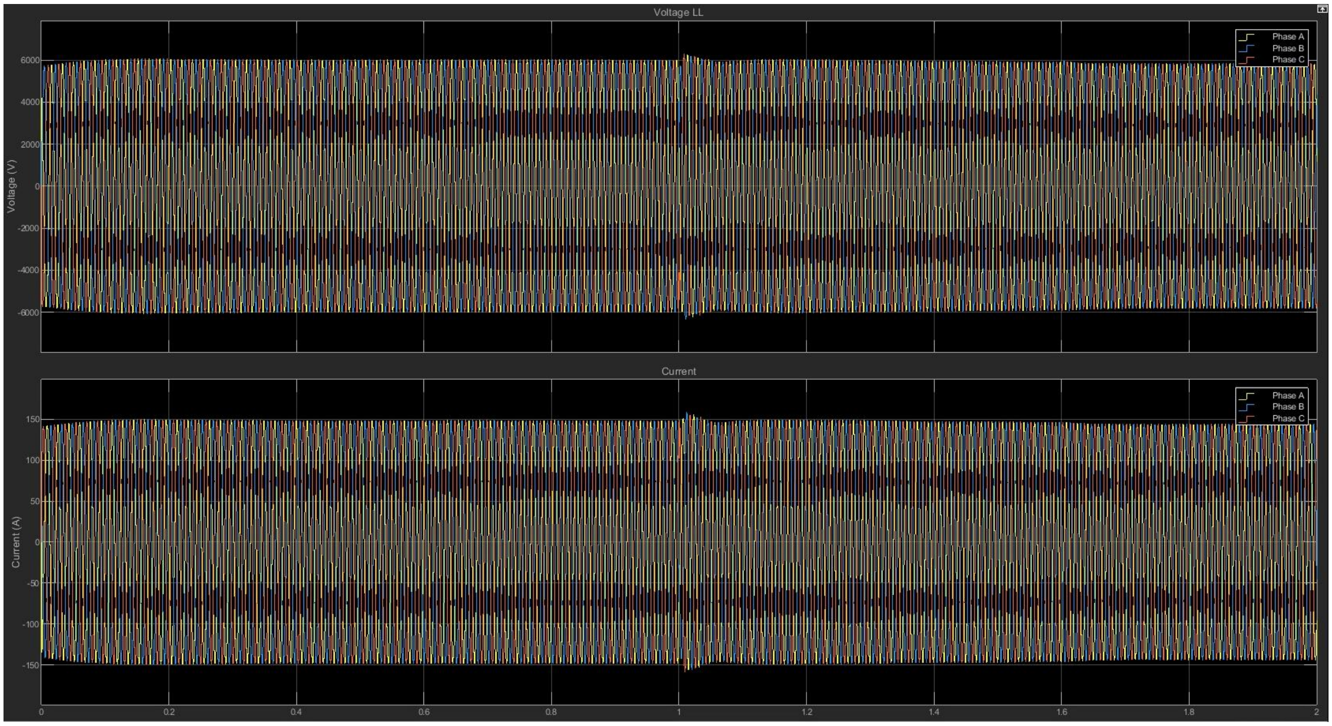


Figure 134: Dynamic Results – Fort Simpson Renewable Sources Variation – 20% – Load

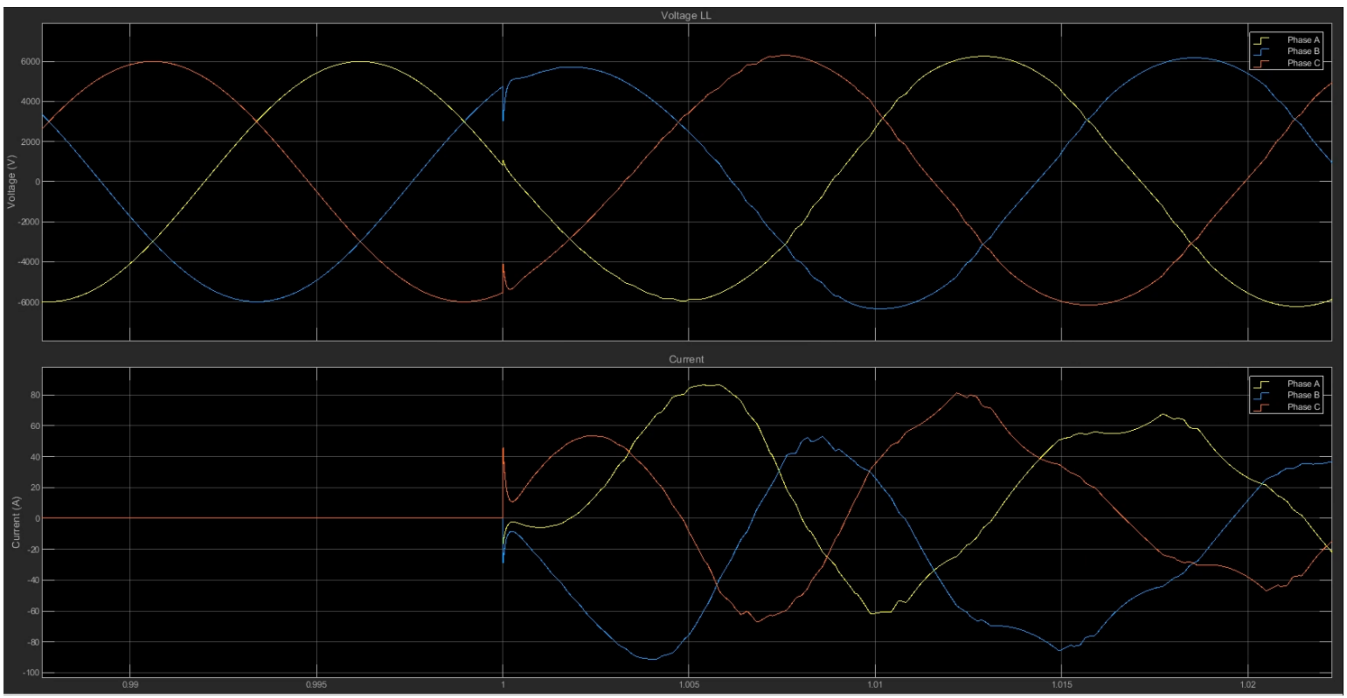


Figure 135: Dynamic Results – Fort Simpson Renewable Sources Connection – 20% – PV

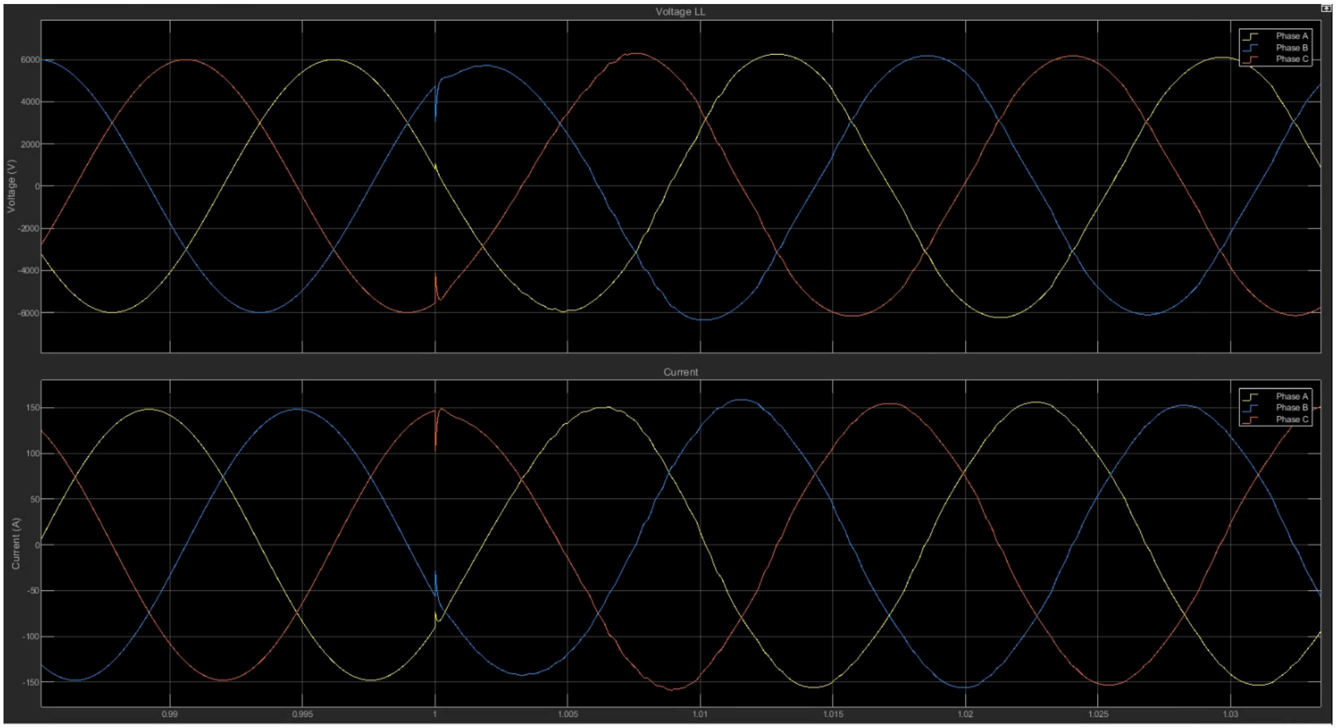


Figure 136: Dynamic Results – Fort Simpson Renewable Sources Connection – 20% – Load

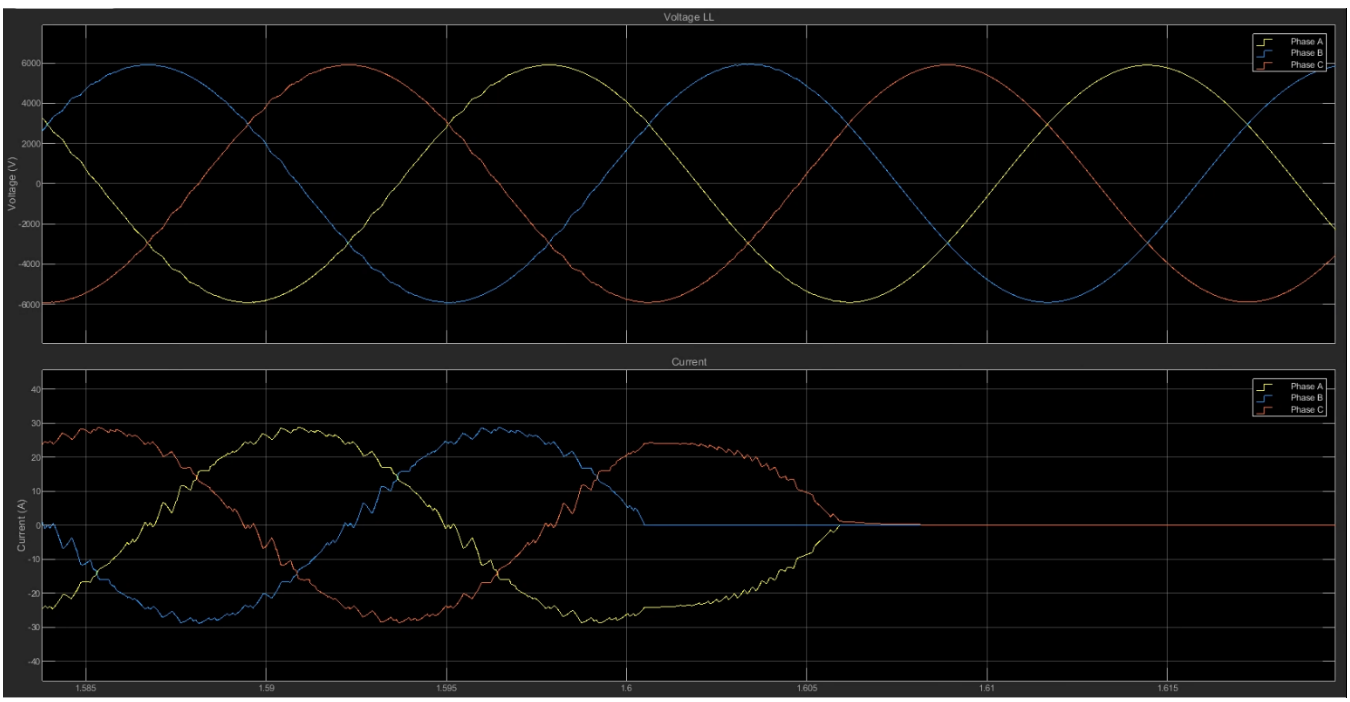


Figure 137: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 20% – PV

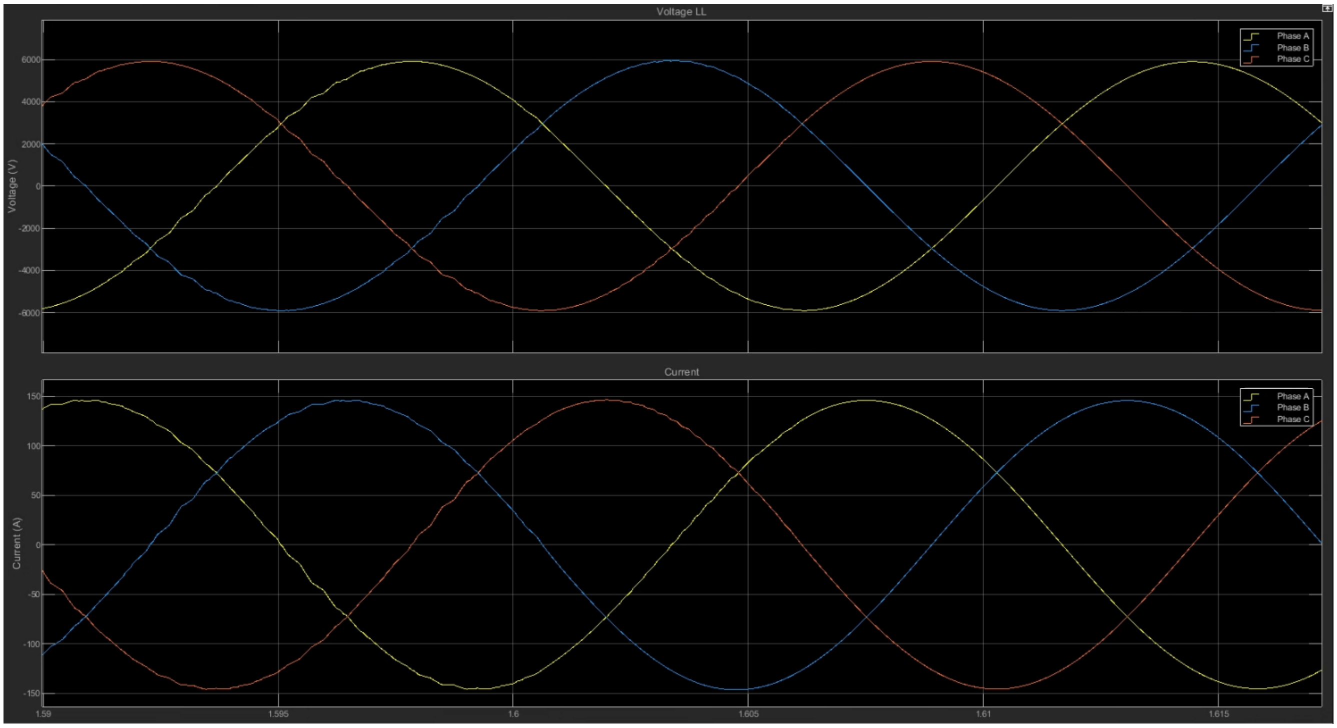


Figure 138: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 20% – Load

E.14. Fort Simpson 25% Renewable Energy Penetration

E.14.1. Load Increase and Decrease

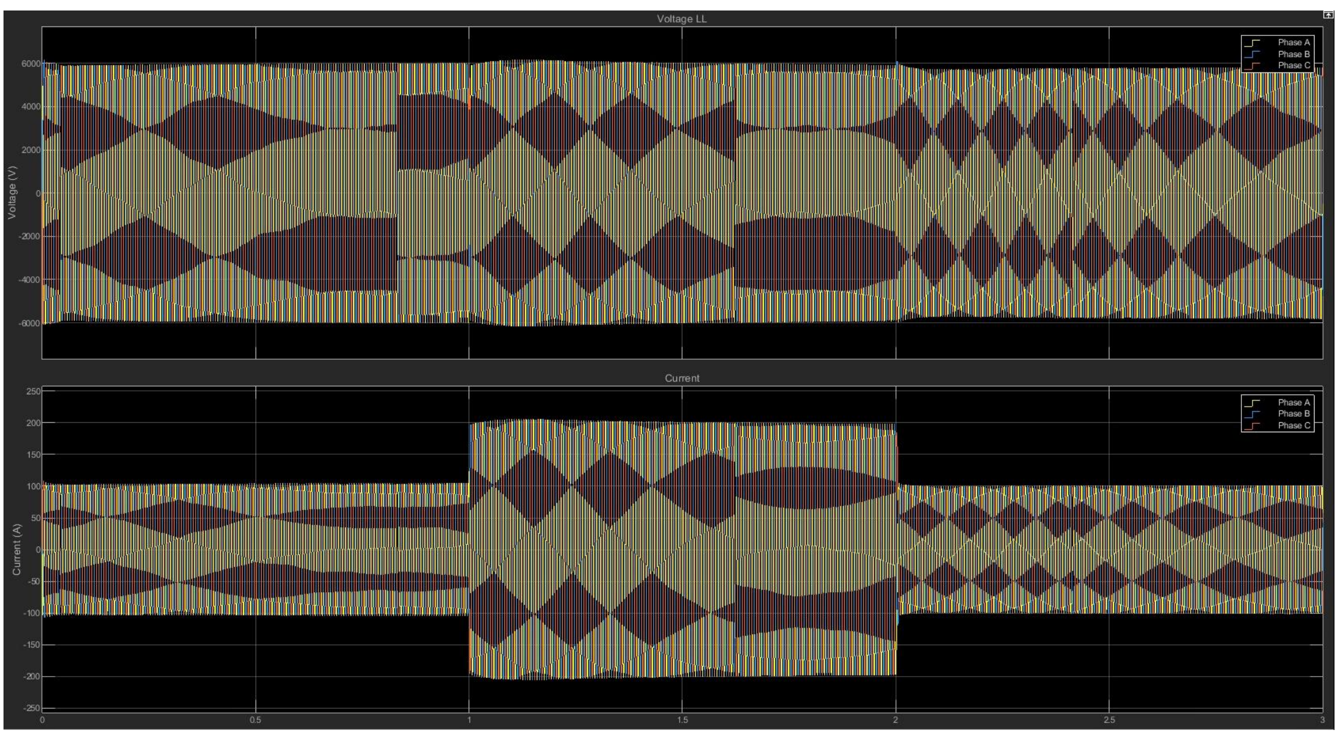


Figure 139: Dynamic Results – Fort Simpson Load Variations – 25%

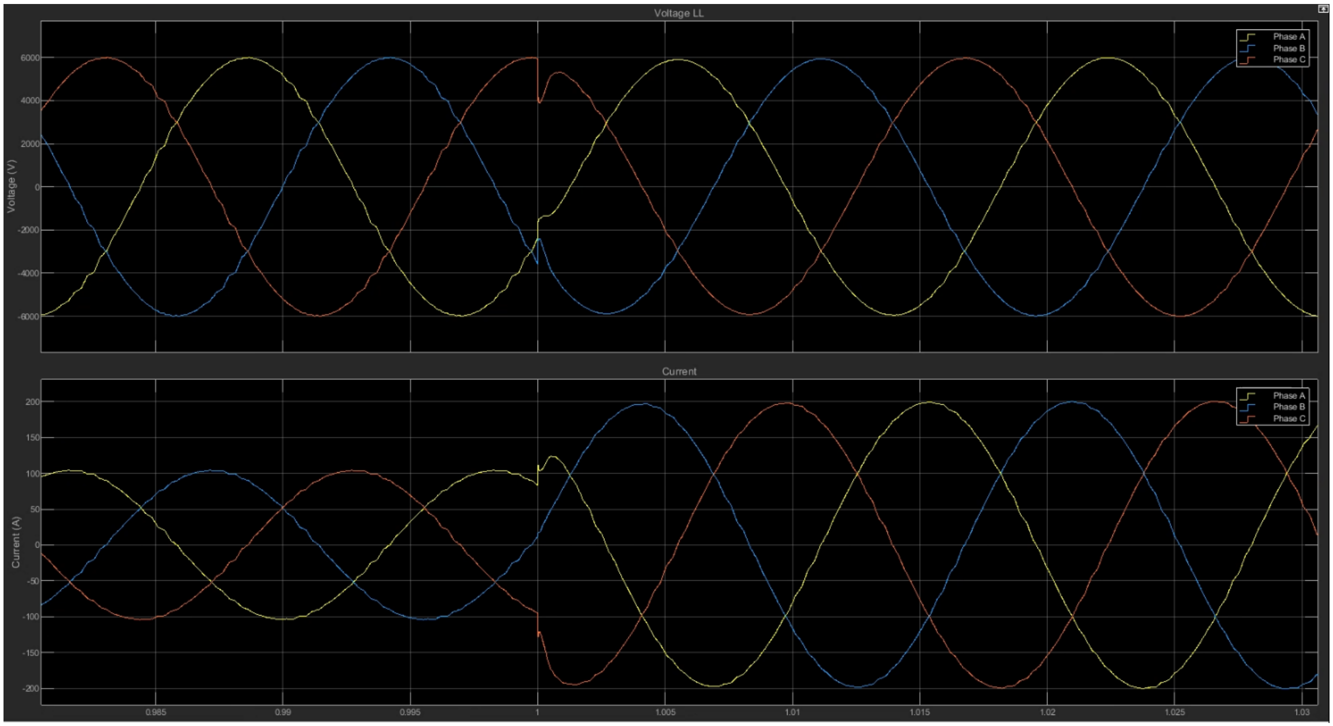


Figure 140: Dynamic Results – Fort Simpson Load Increase – 25%

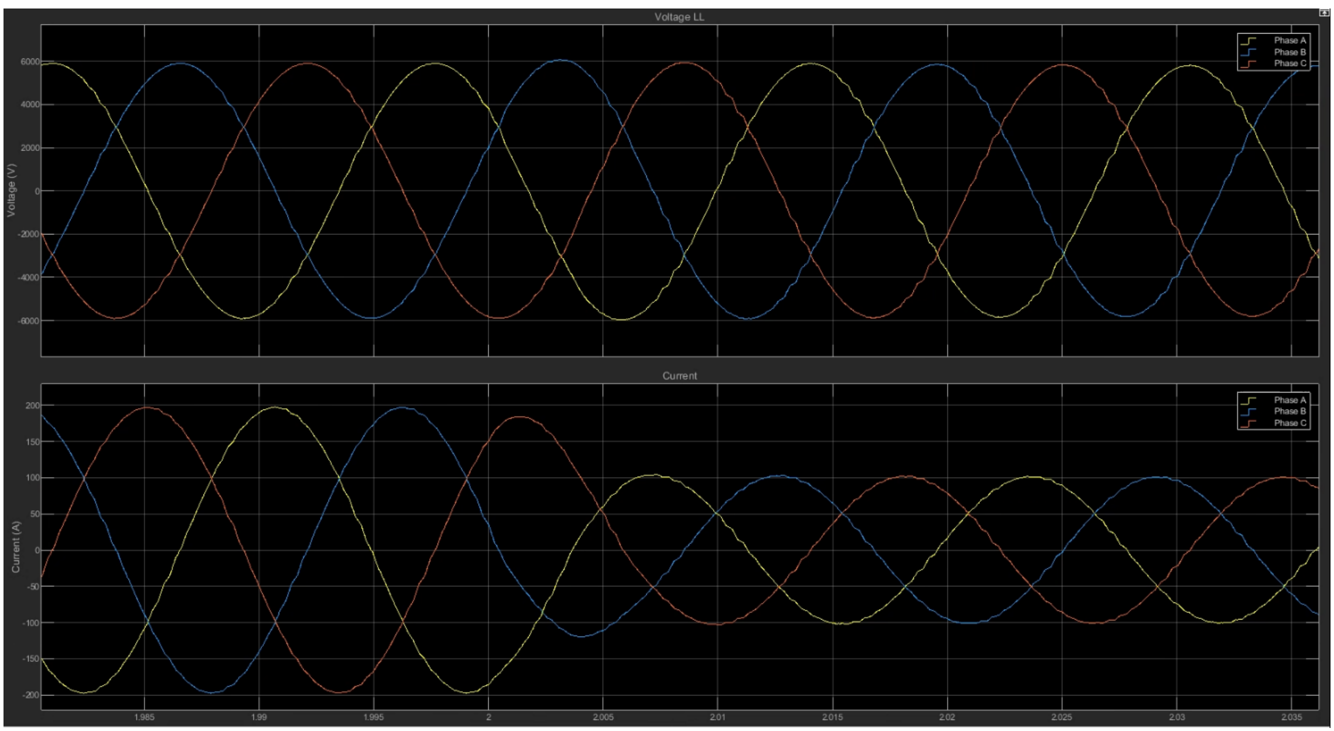


Figure 141: Dynamic Results – Fort Simpson Load Decrease – 25%

E.14.2. Renewable Connection / Disconnection

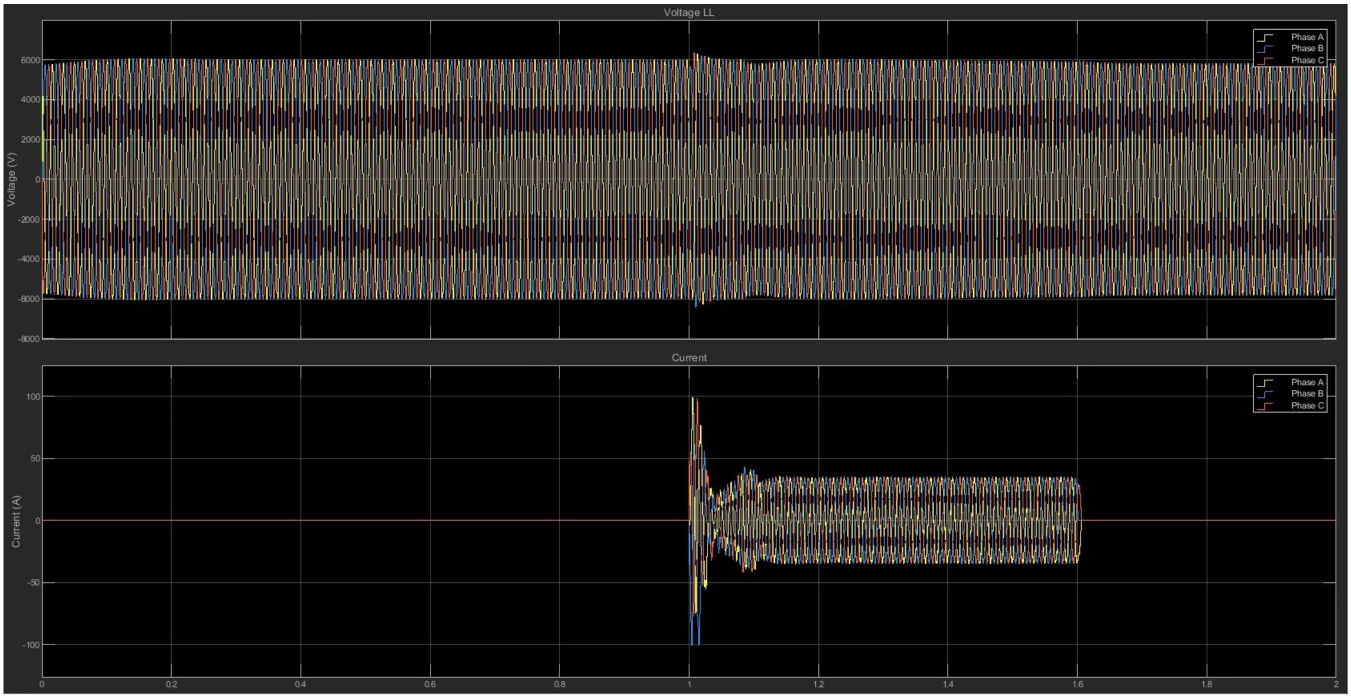


Figure 142: Dynamic Results – Fort Simpson Renewable Sources Variation – 25% – PV

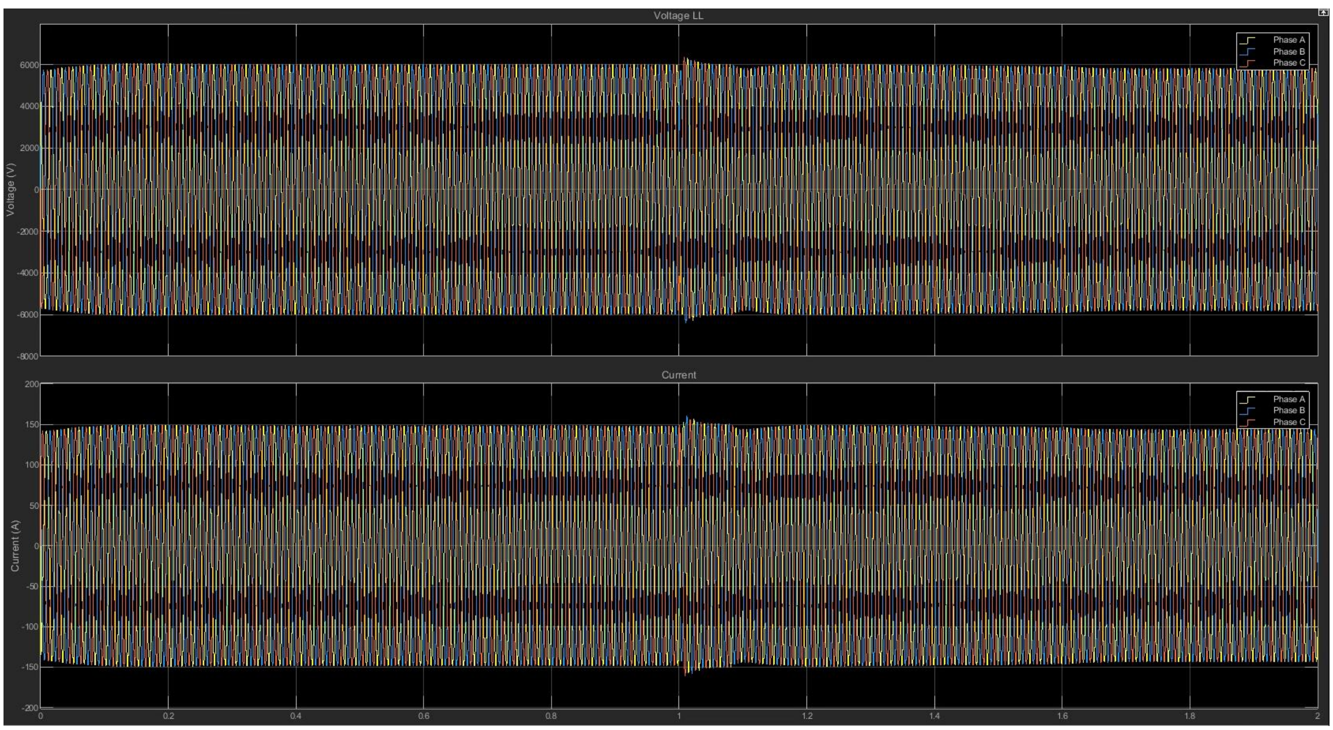


Figure 143: Dynamic Results – Fort Simpson Renewable Sources Variation – 25% – Load

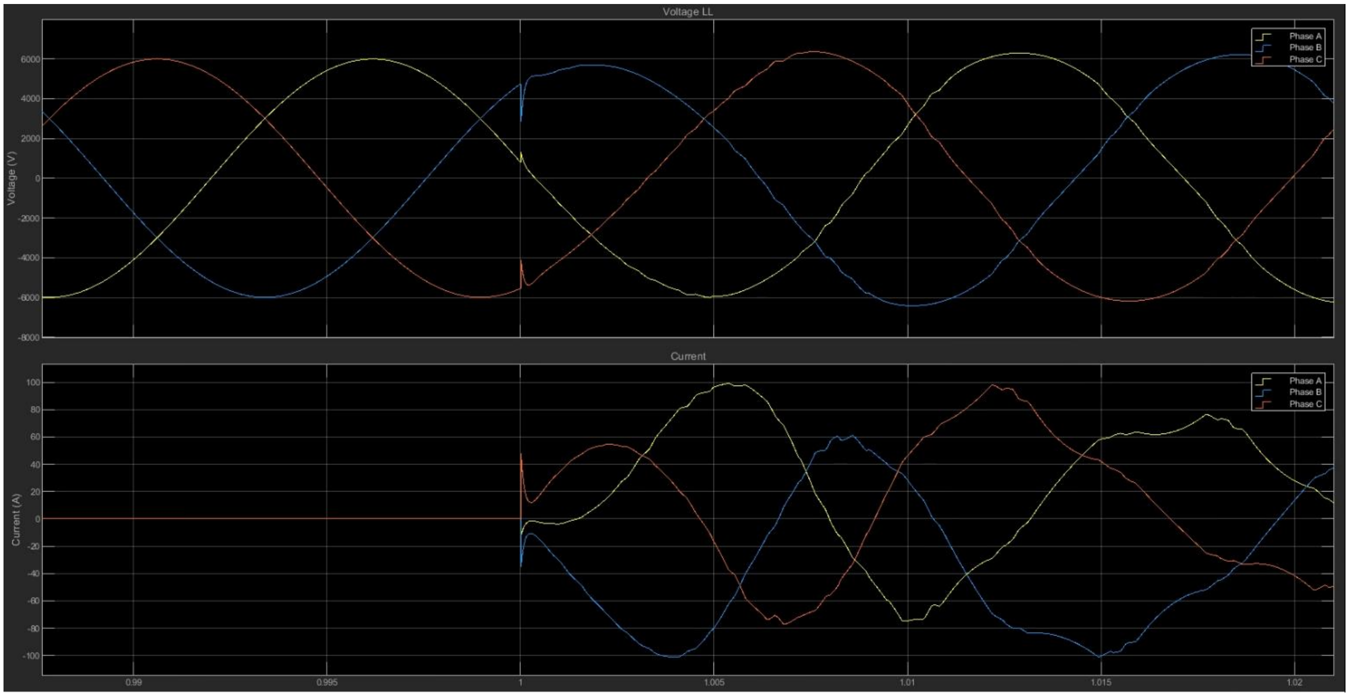


Figure 144: Dynamic Results – Fort Simpson Renewable Sources Connection – 25% – PV

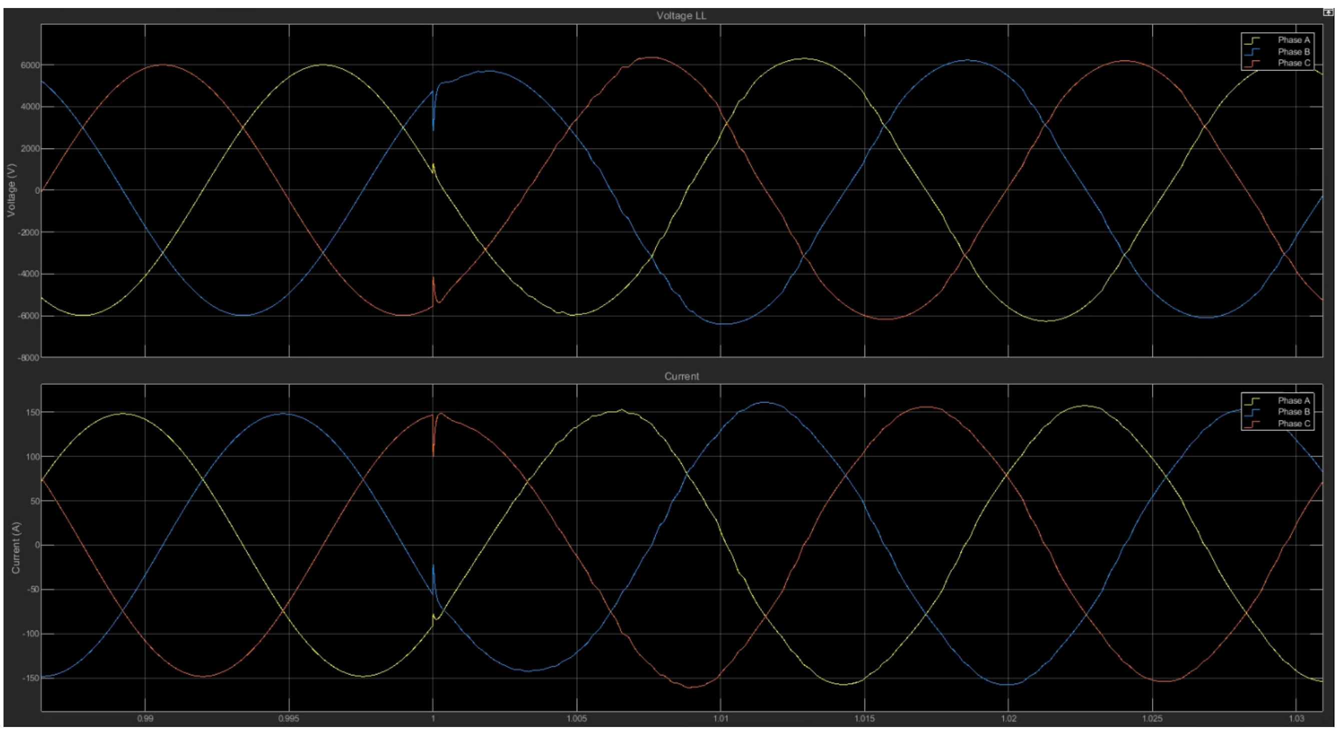


Figure 145: Dynamic Results – Fort Simpson Renewable Sources Connection – 25% – Load

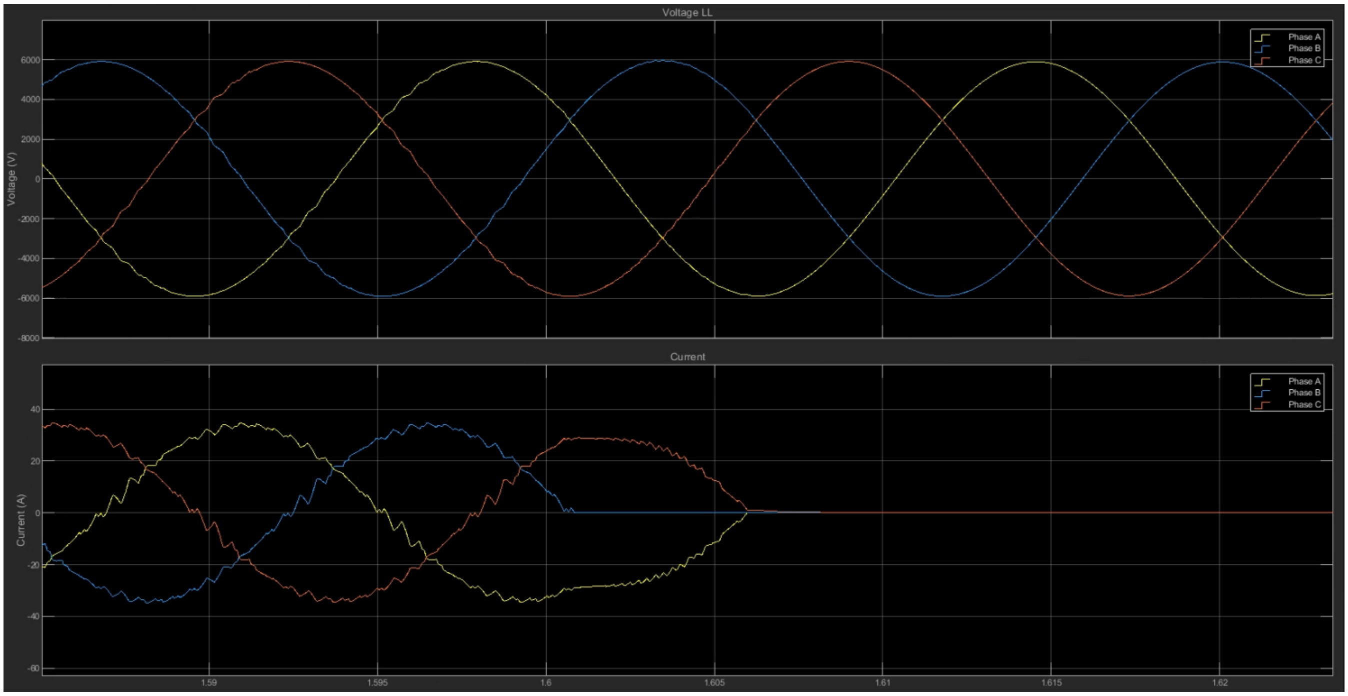


Figure 146: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 25% – PV

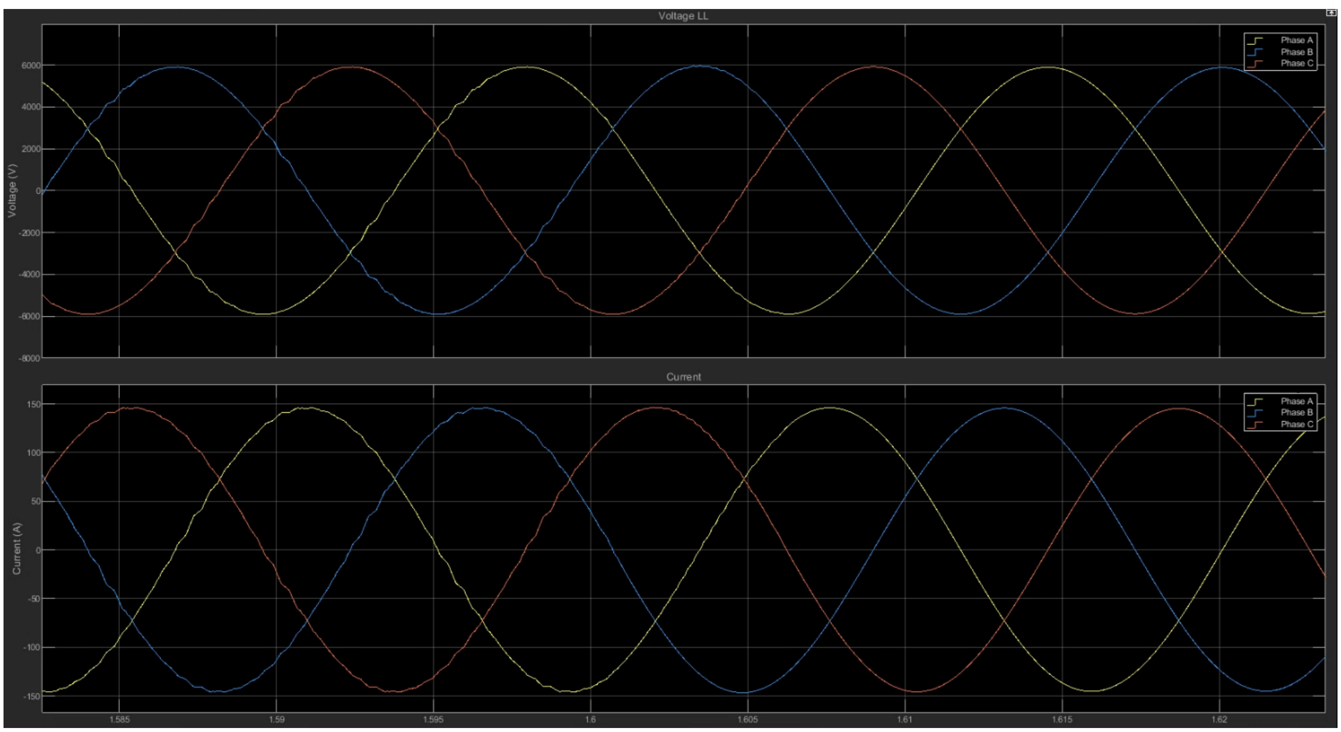


Figure 147: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 25% – Load

E.15. Fort Simpson 30% Renewable Energy Penetration

E.15.1. Load Increase and Decrease

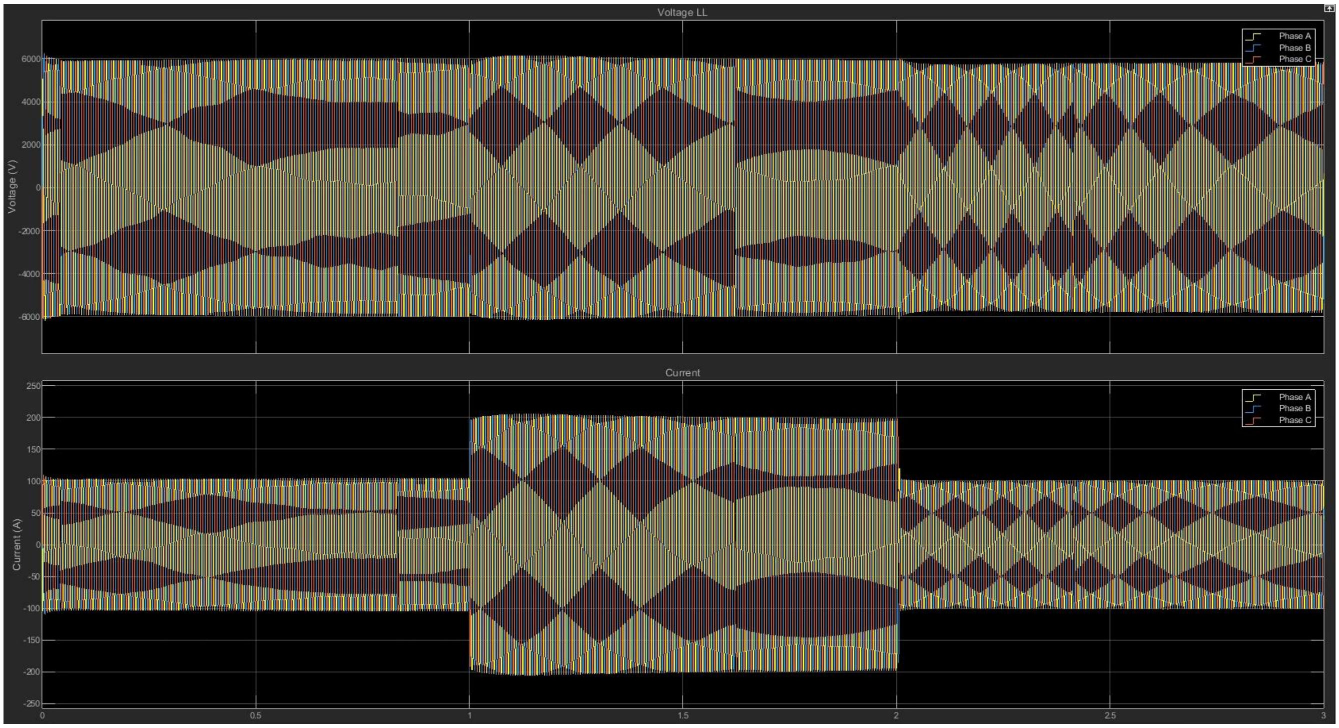


Figure 148: Dynamic Results – Fort Simpson Load Variations – 30%

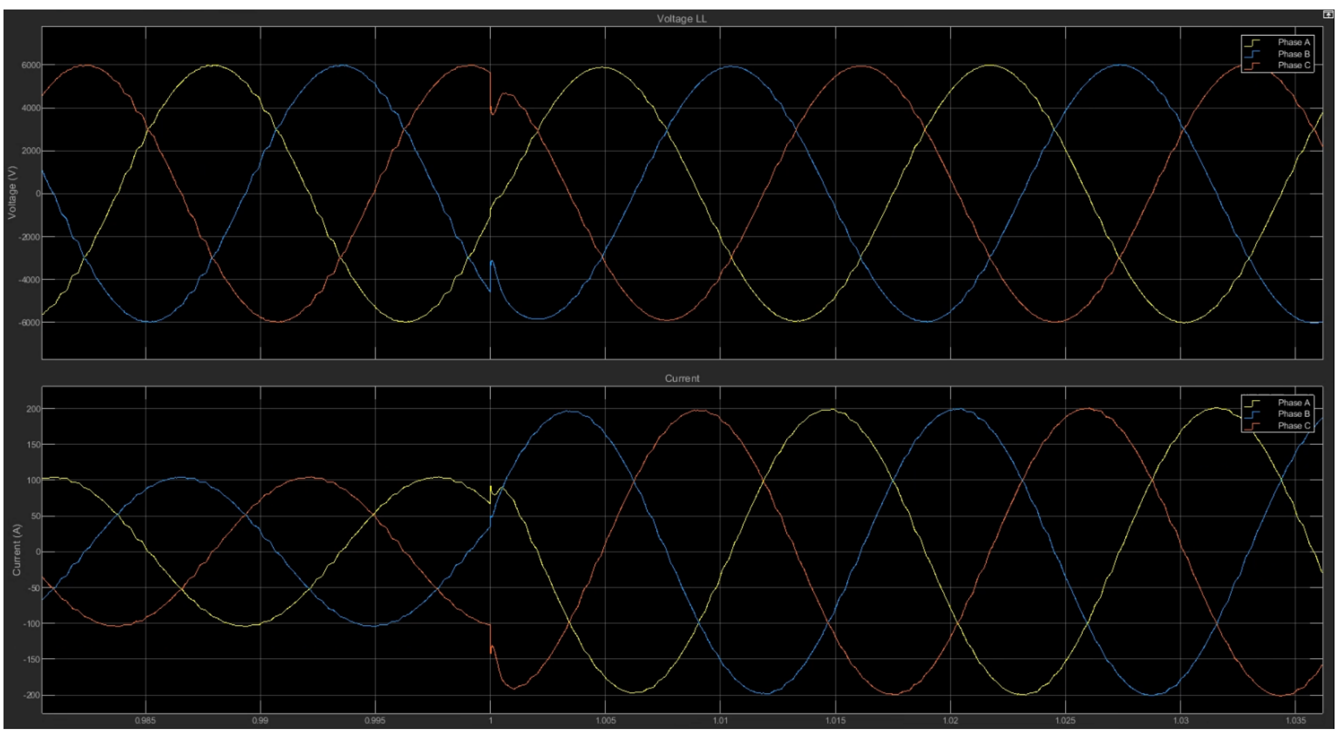


Figure 149: Dynamic Results – Fort Simpson Load Increase – 30%

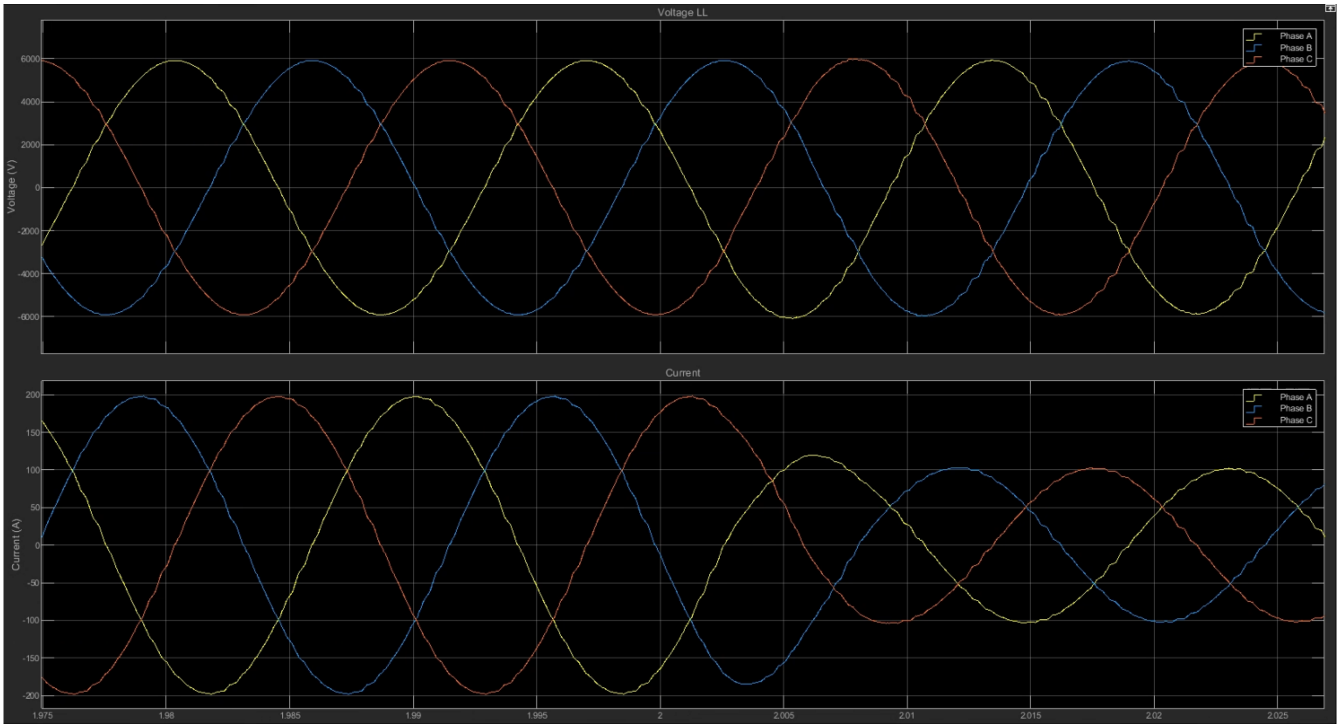


Figure 150: Dynamic Results – Fort Simpson Load Decrease – 30%

E.15.2. Renewable Connection / Disconnection

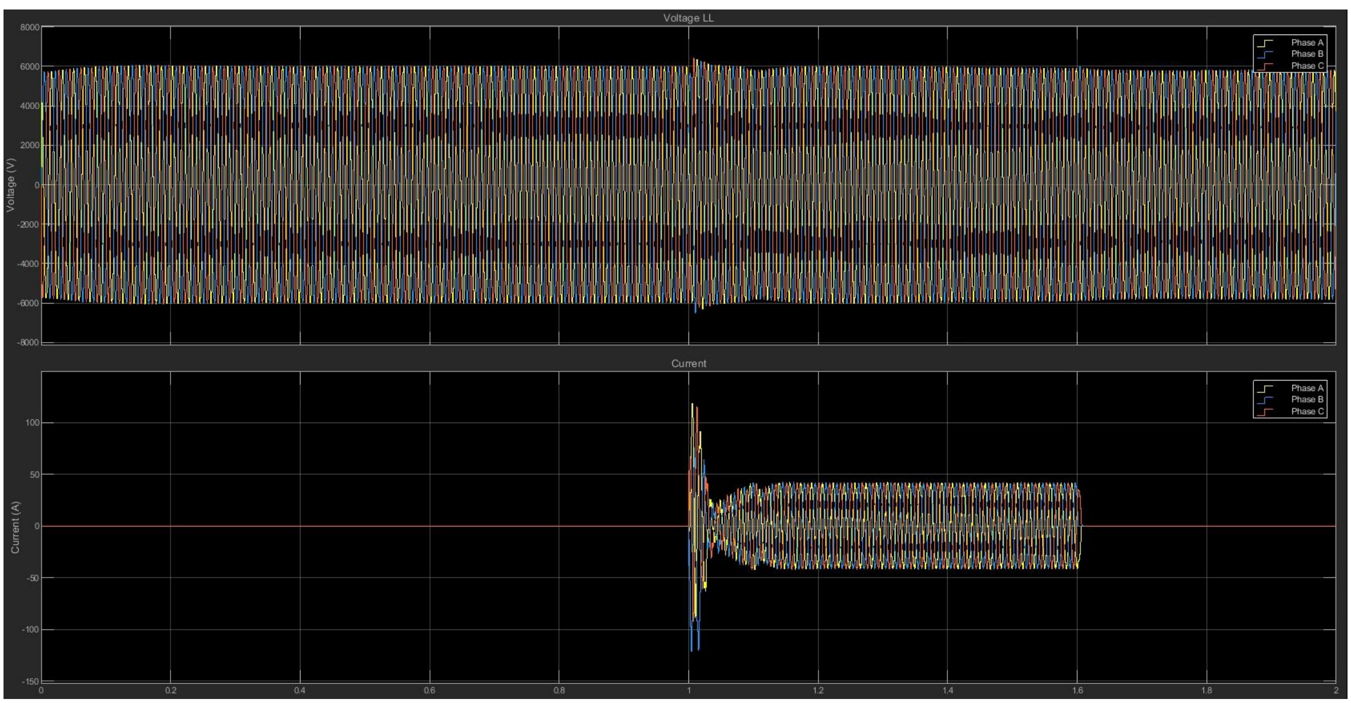


Figure 151: Dynamic Results – Fort Simpson Renewable Sources Variation – 30% – PV

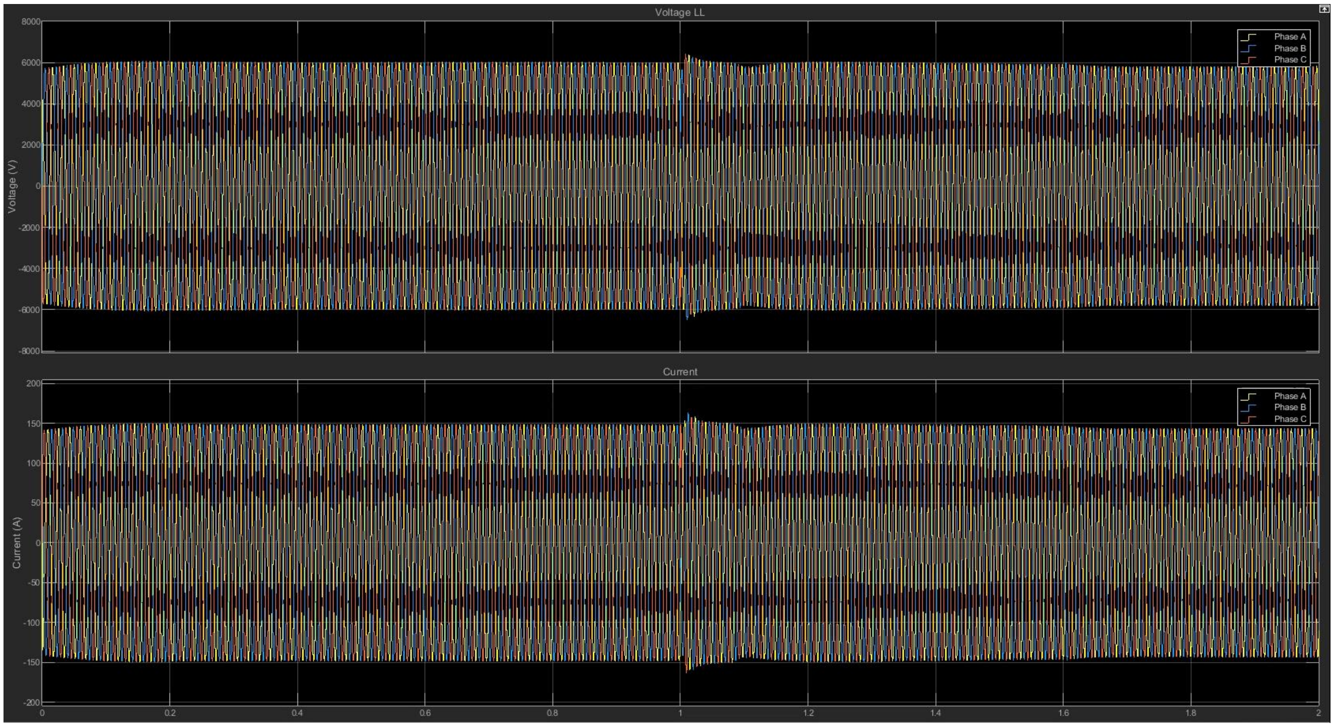


Figure 152: Dynamic Results – Fort Simpson Renewable Sources Variation – 30% – Load

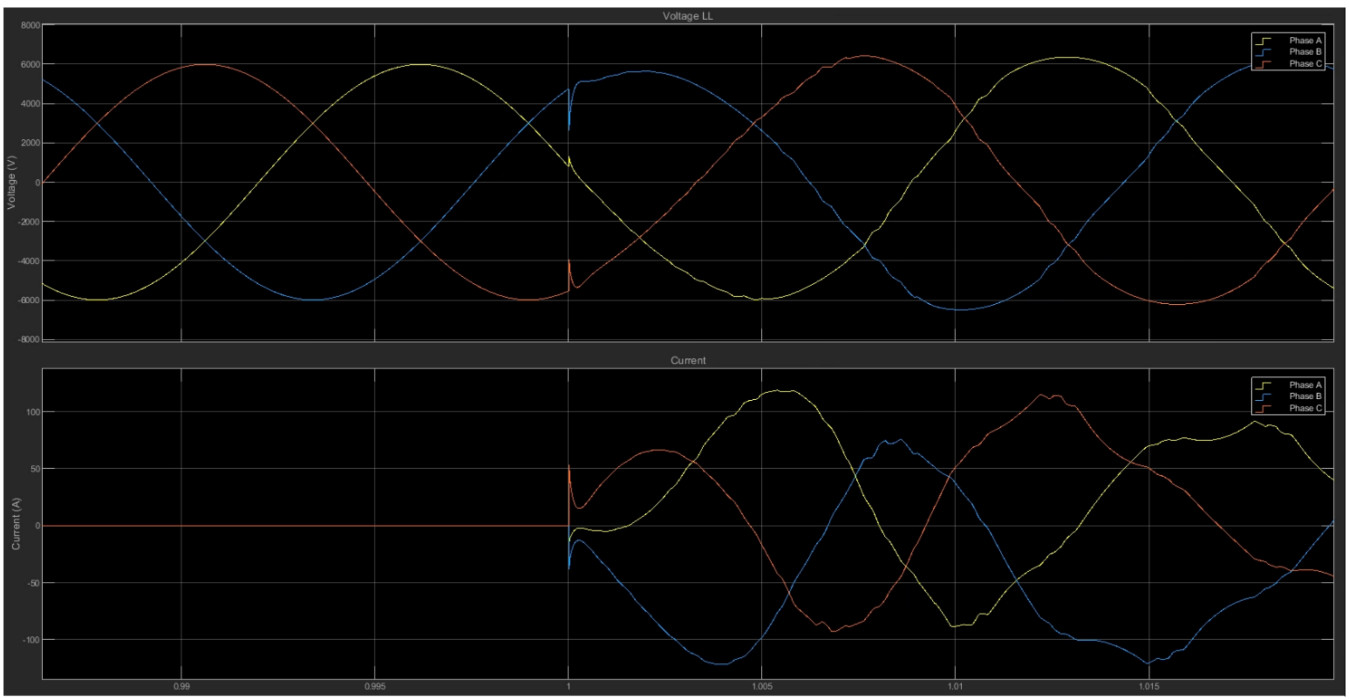


Figure 153: Dynamic Results – Fort Simpson Renewable Sources Connection – 30% – PV

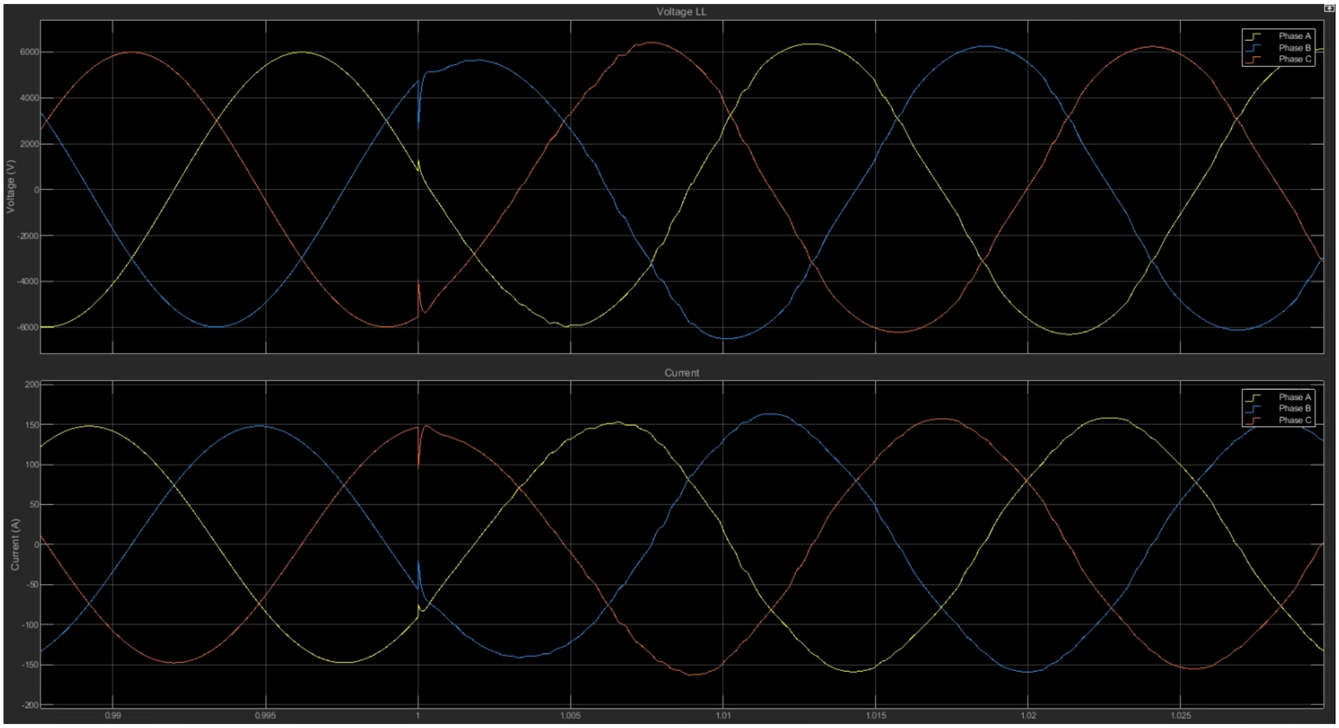


Figure 154: Dynamic Results – Fort Simpson Renewable Sources Connection – 30% – Load

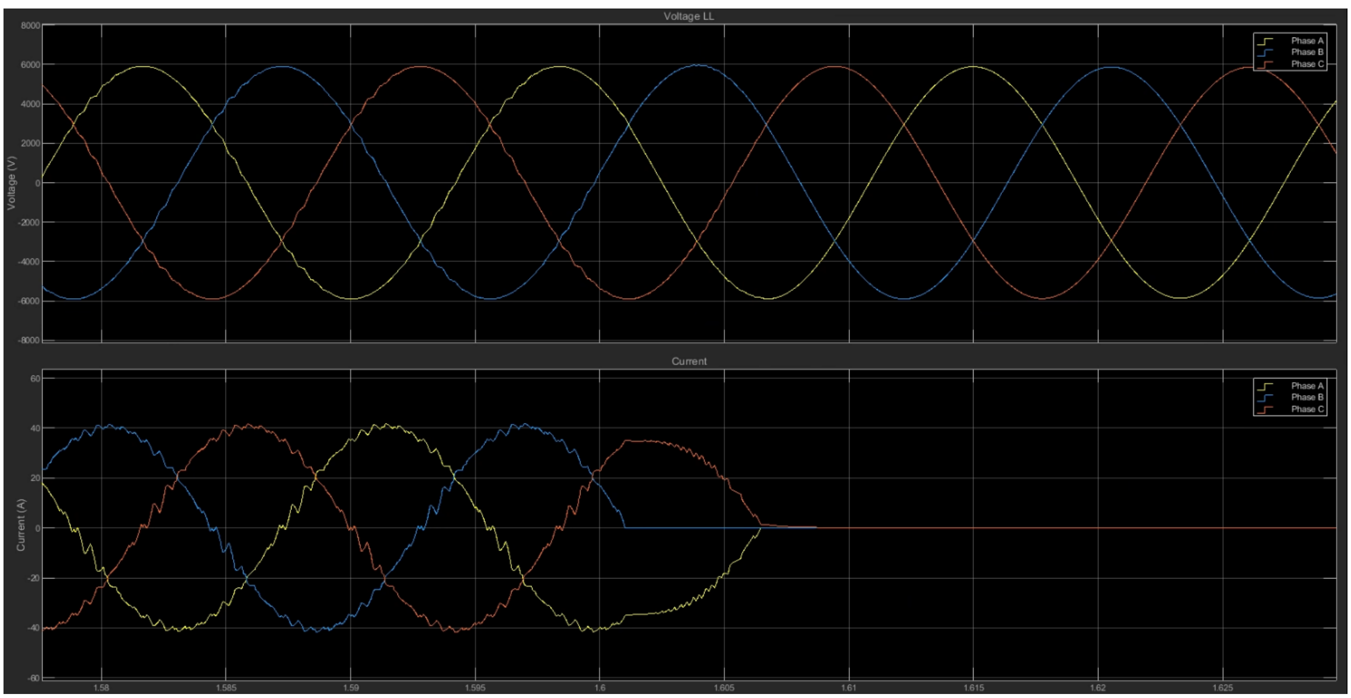


Figure 155: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 30% – PV

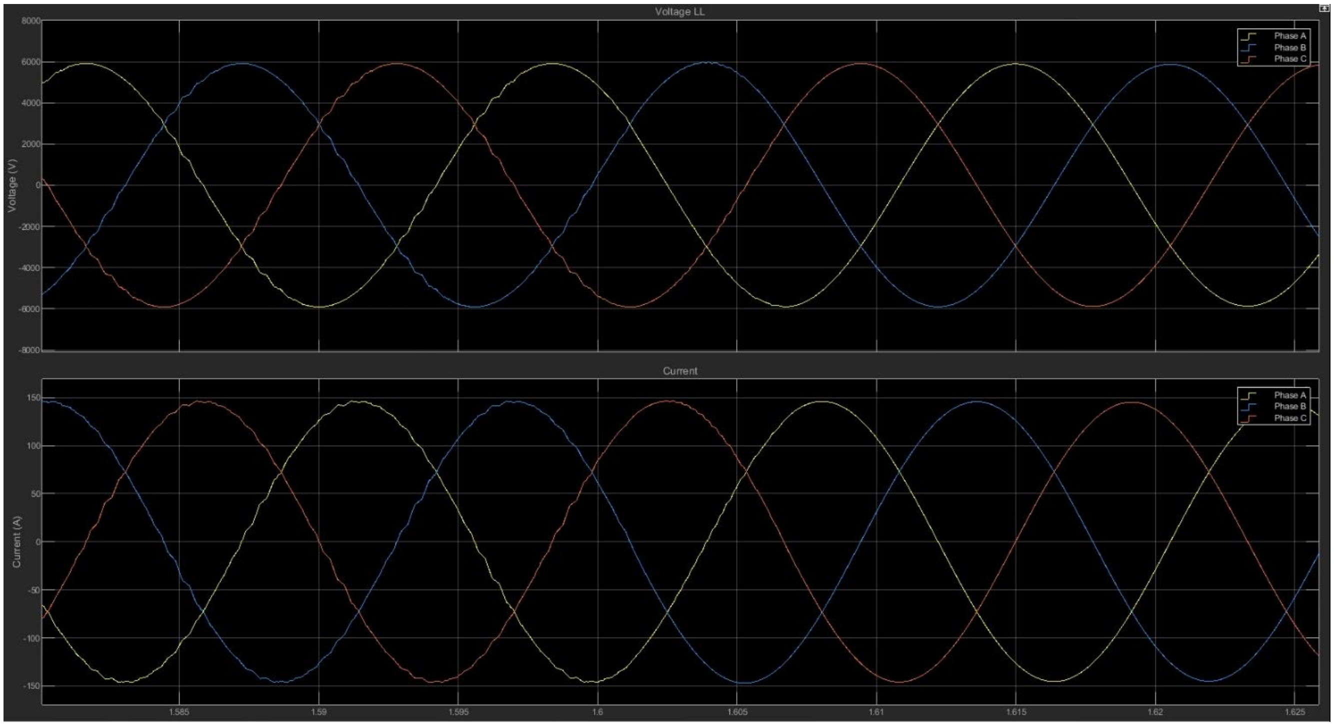


Figure 156: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 30% – Load

E.16. Fort Simpson 50% Renewable Energy Penetration

E.16.1. Load Increase and Decrease

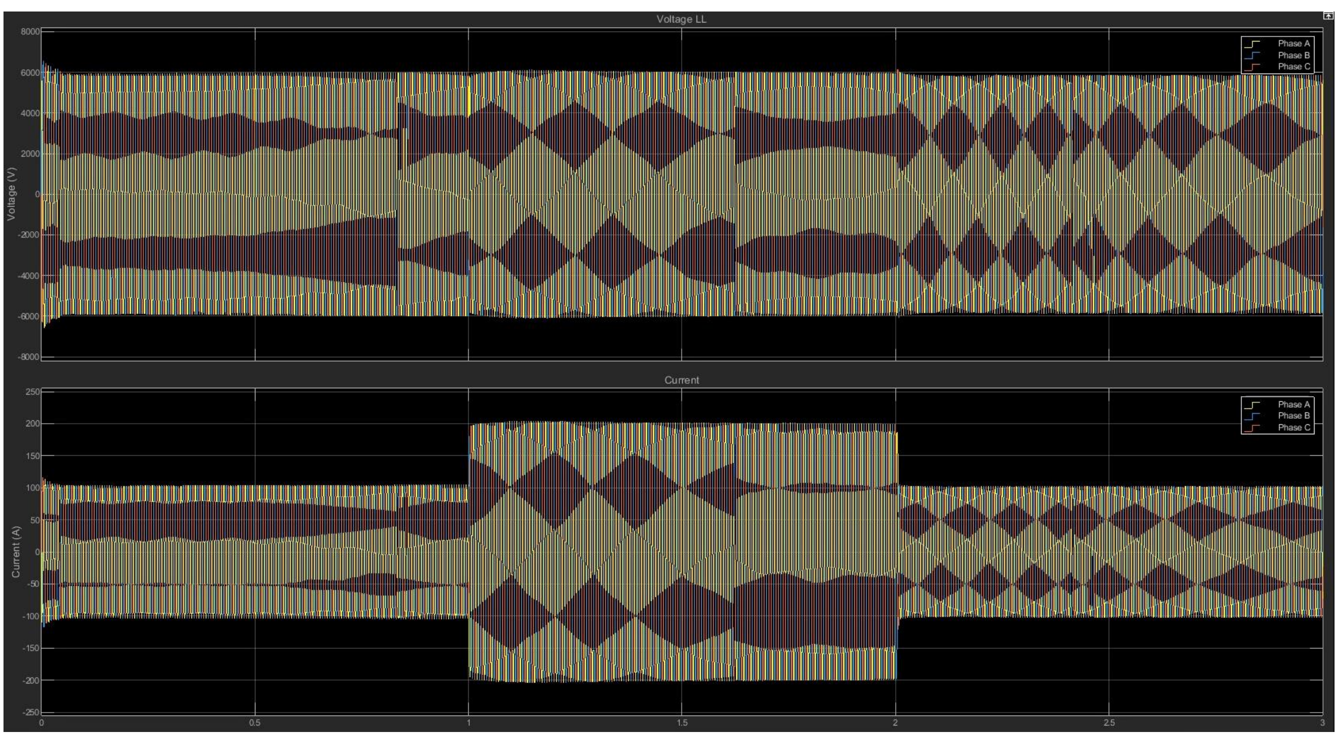


Figure 157: Dynamic Results – Fort Simpson Load Variations – 50%

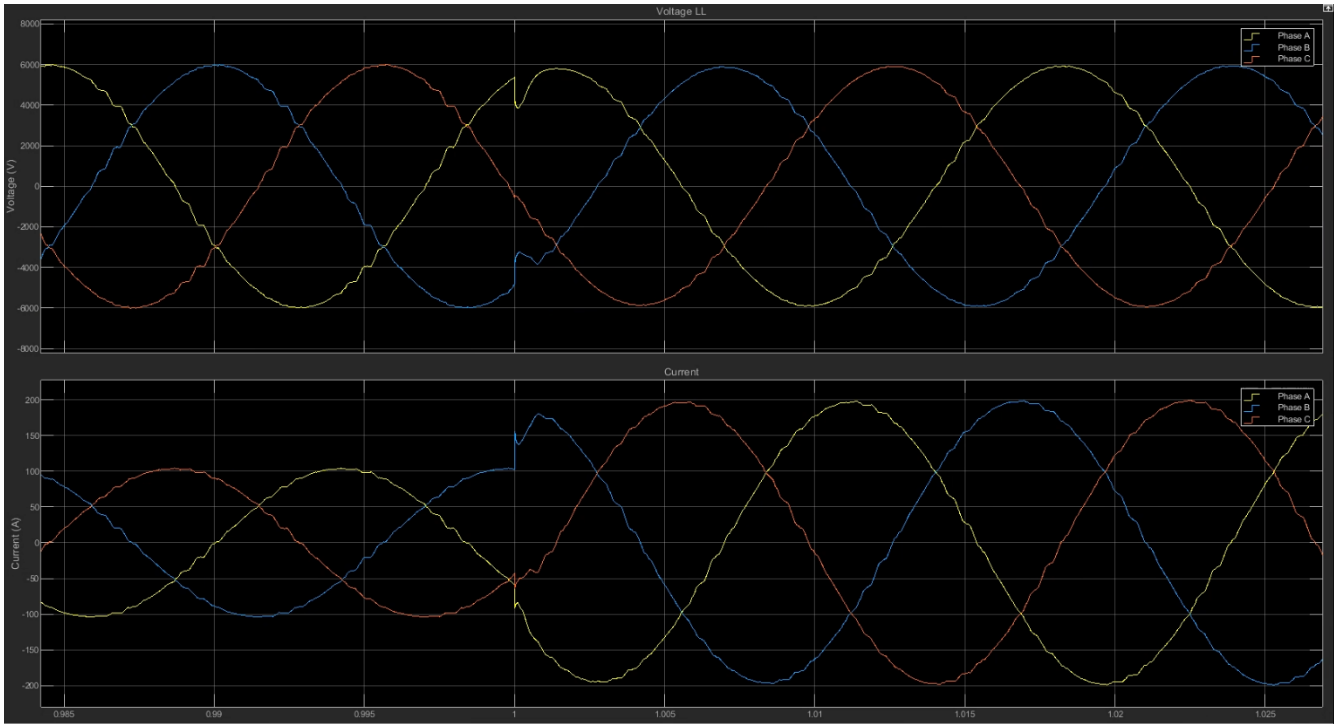


Figure 158: Dynamic Results – Fort Simpson Load Increase – 50%

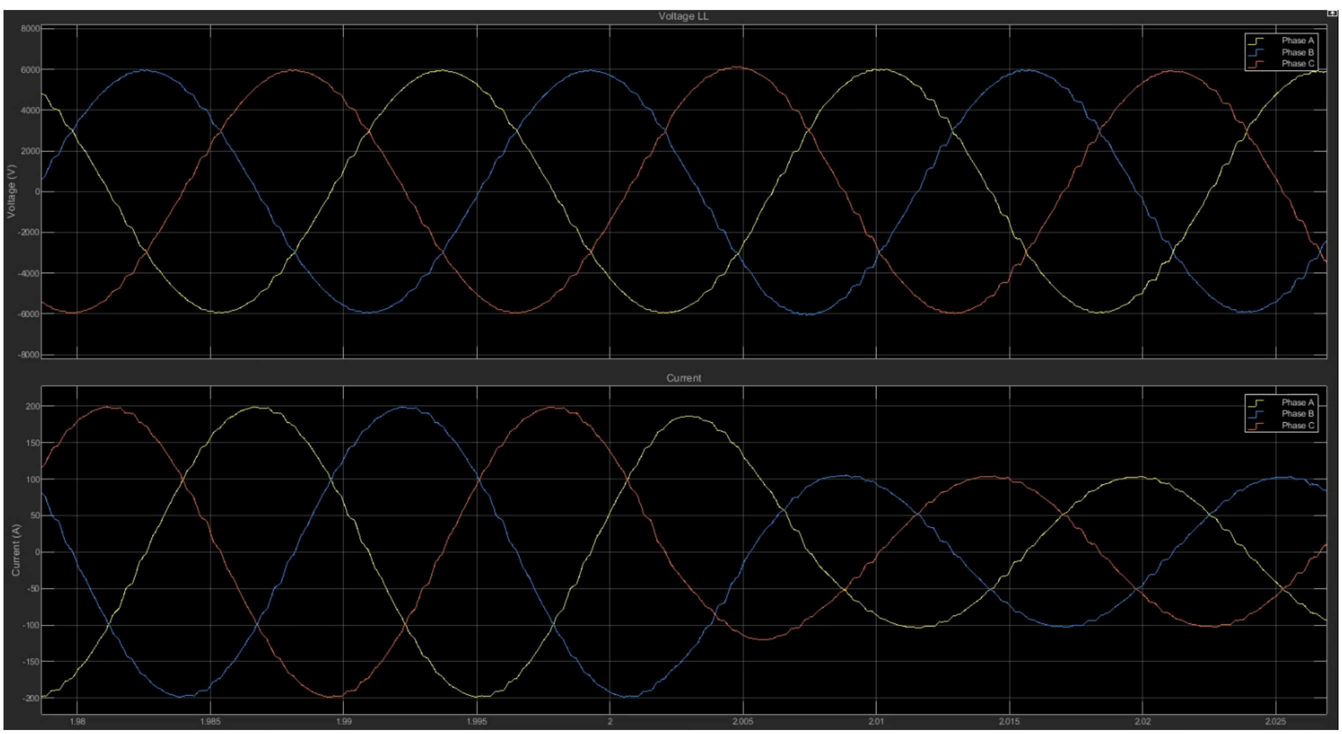


Figure 159: Dynamic Results – Fort Simpson Load Decrease – 50%

E.16.2. Renewable Connection / Disconnection

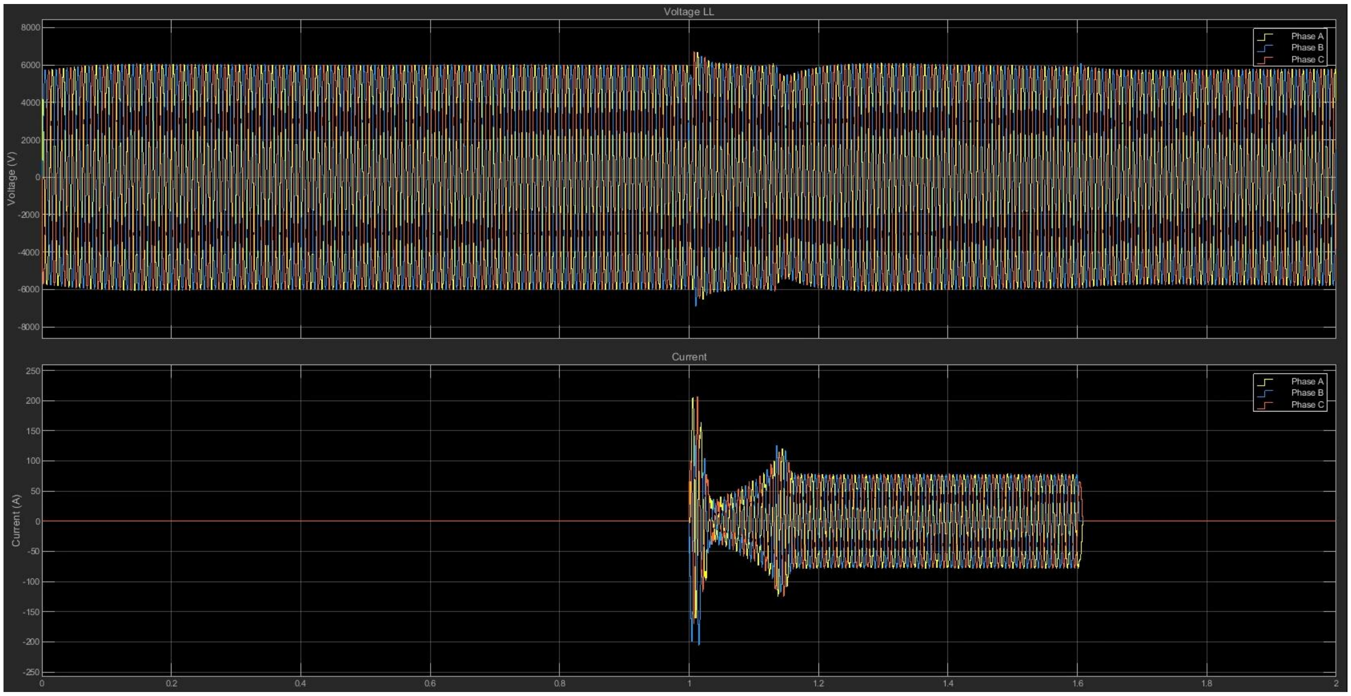


Figure 160: Dynamic Results – Fort Simpson Renewable Sources Variation – 50% – PV

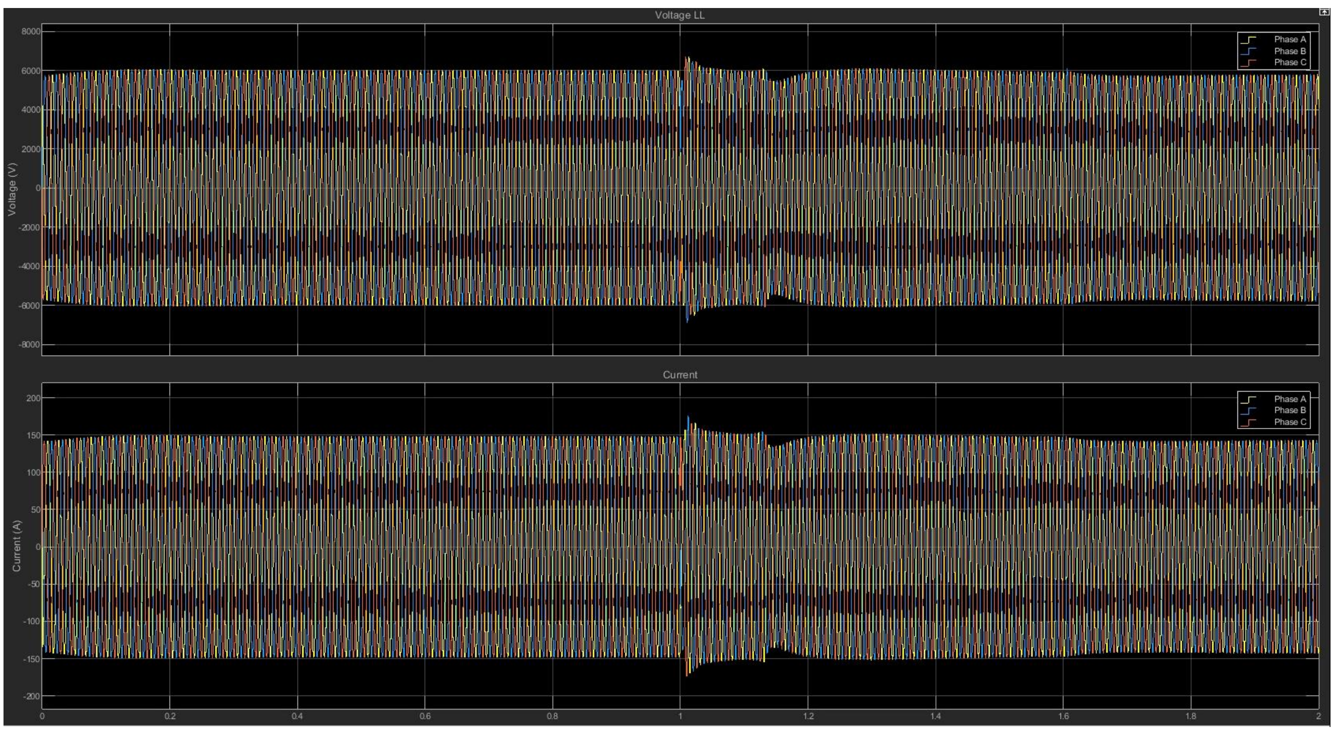


Figure 161: Dynamic Results – Fort Simpson Renewable Sources Variation – 50% – Load

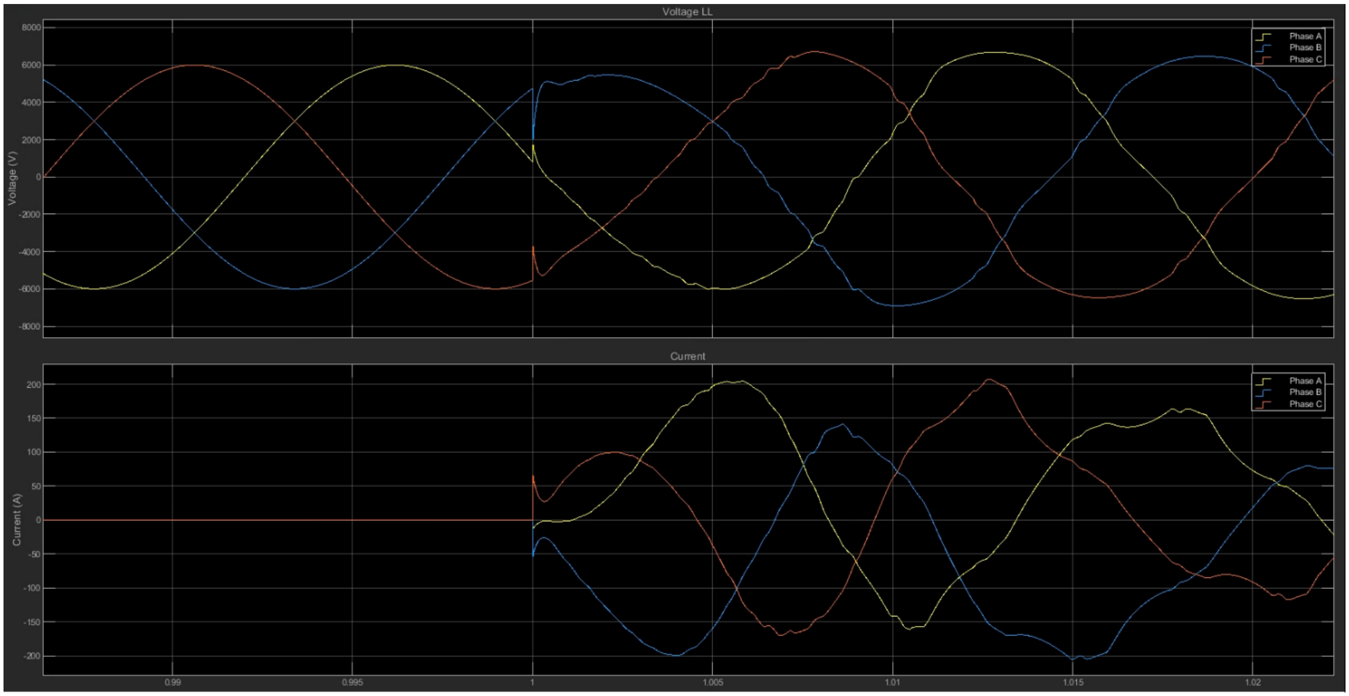


Figure 162: Dynamic Results – Fort Simpson Renewable Sources Connection – 50% – PV

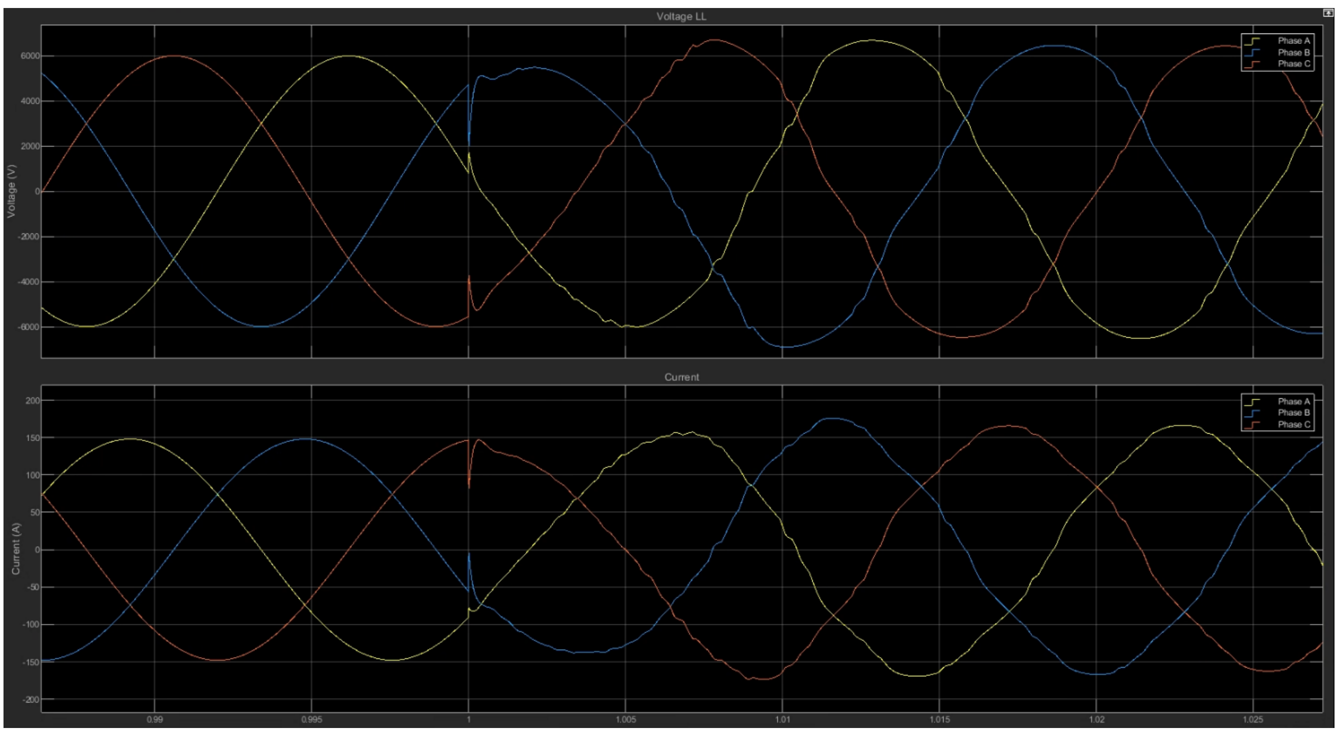


Figure 163: Dynamic Results – Fort Simpson Renewable Sources Connection – 50% – Load

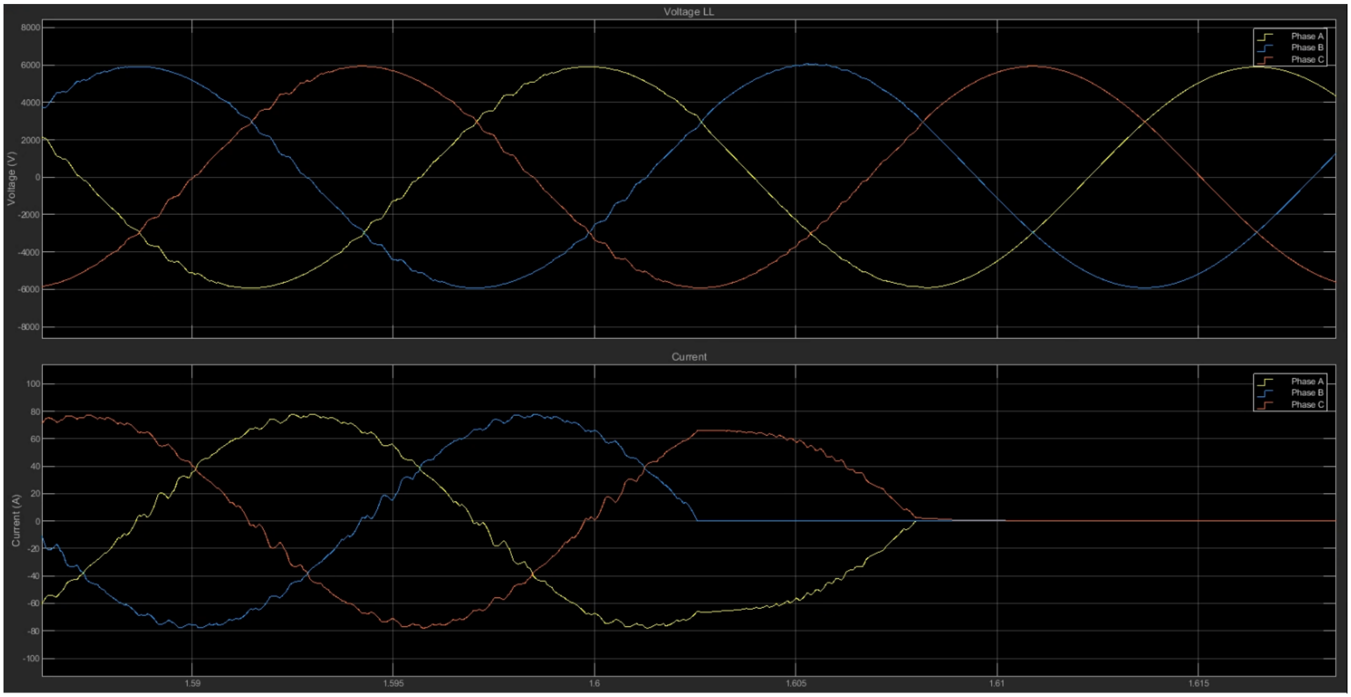


Figure 164: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 50% – PV

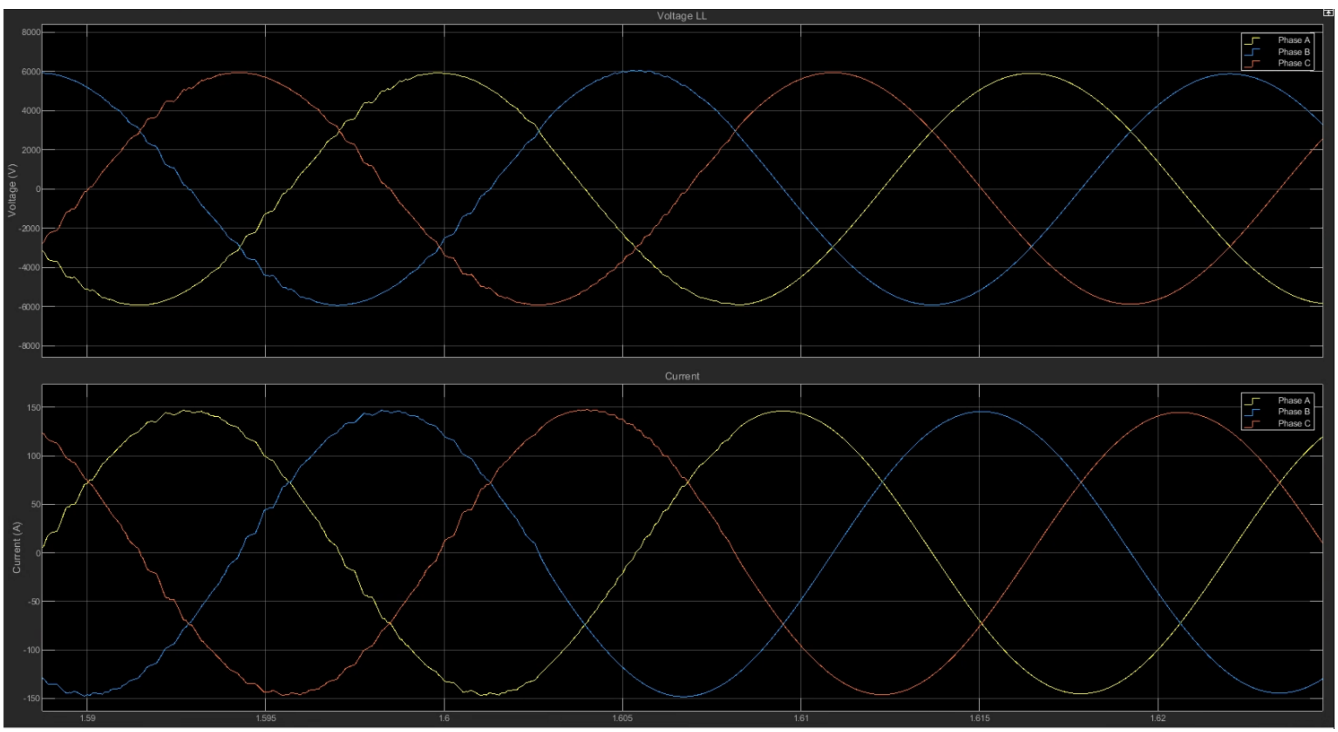


Figure 165: Dynamic Results – Fort Simpson Renewable Sources Disconnection – 50% – Load

E.17. Inuvik 20% Renewable Energy Penetration

E.17.1. Load Increase and Decrease

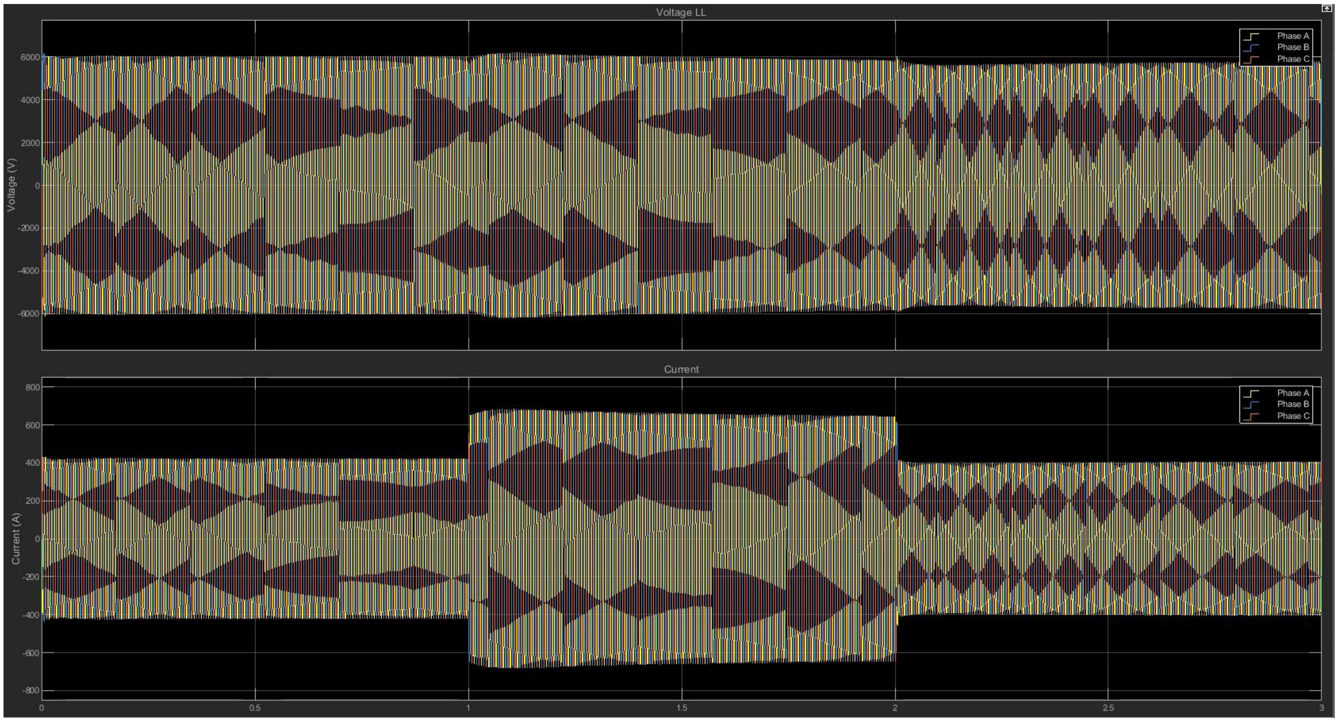


Figure 166: Dynamic Results – Inuvik Load Variations – 20%

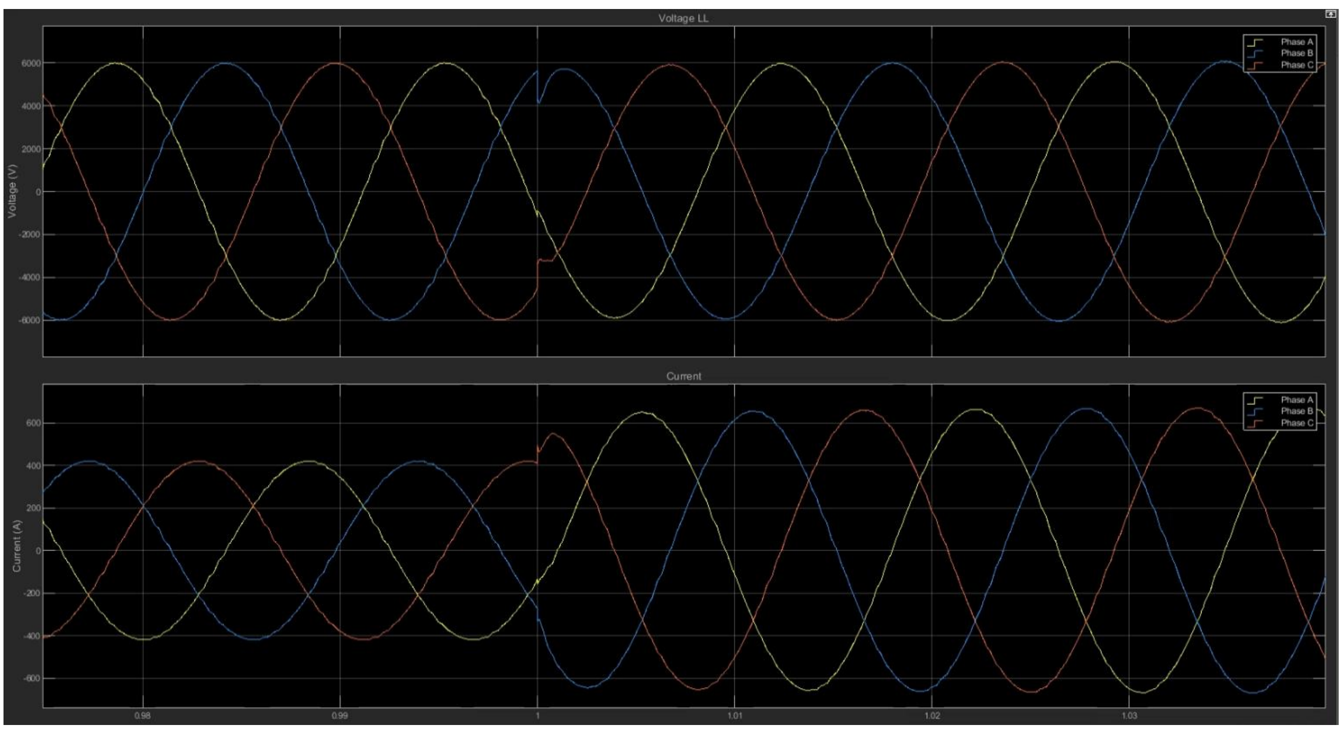


Figure 167: Dynamic Results – Inuvik Load Increase – 20%

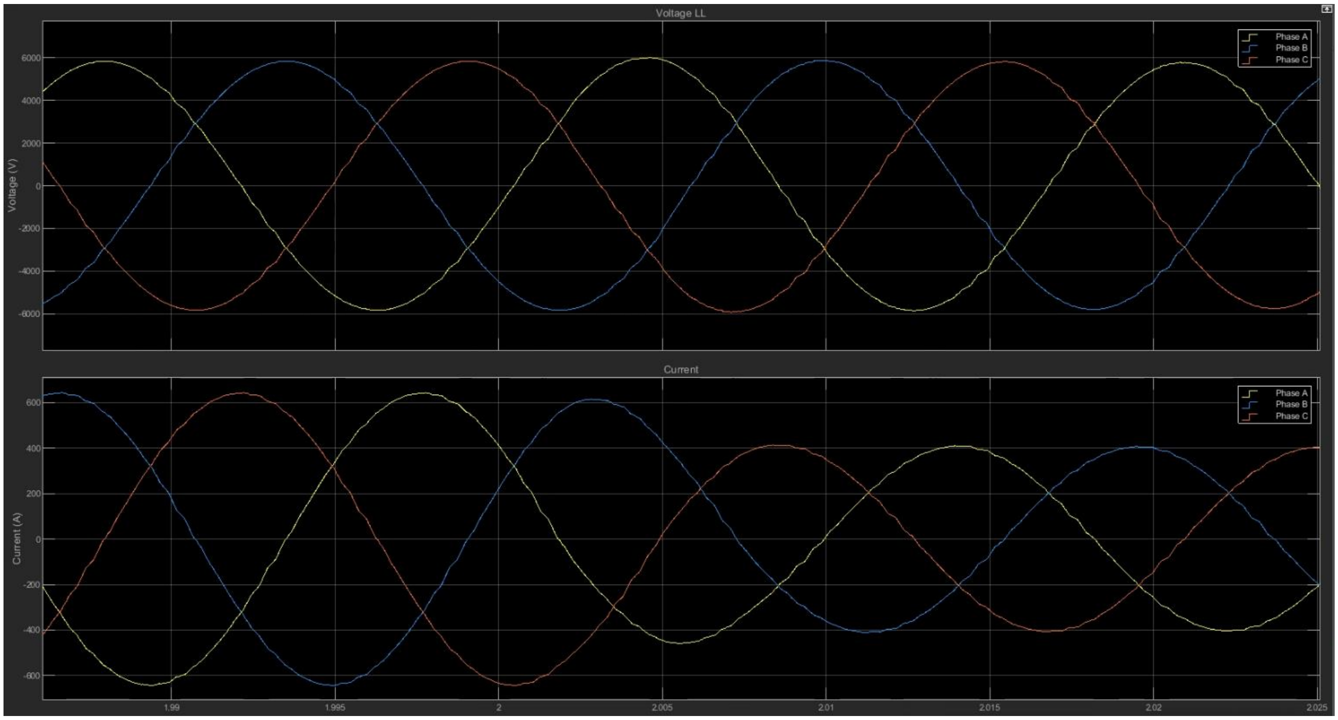


Figure 168: Dynamic Results – Inuvik Load Decrease – 20%

E.17.2. Renewable Connection / Disconnection

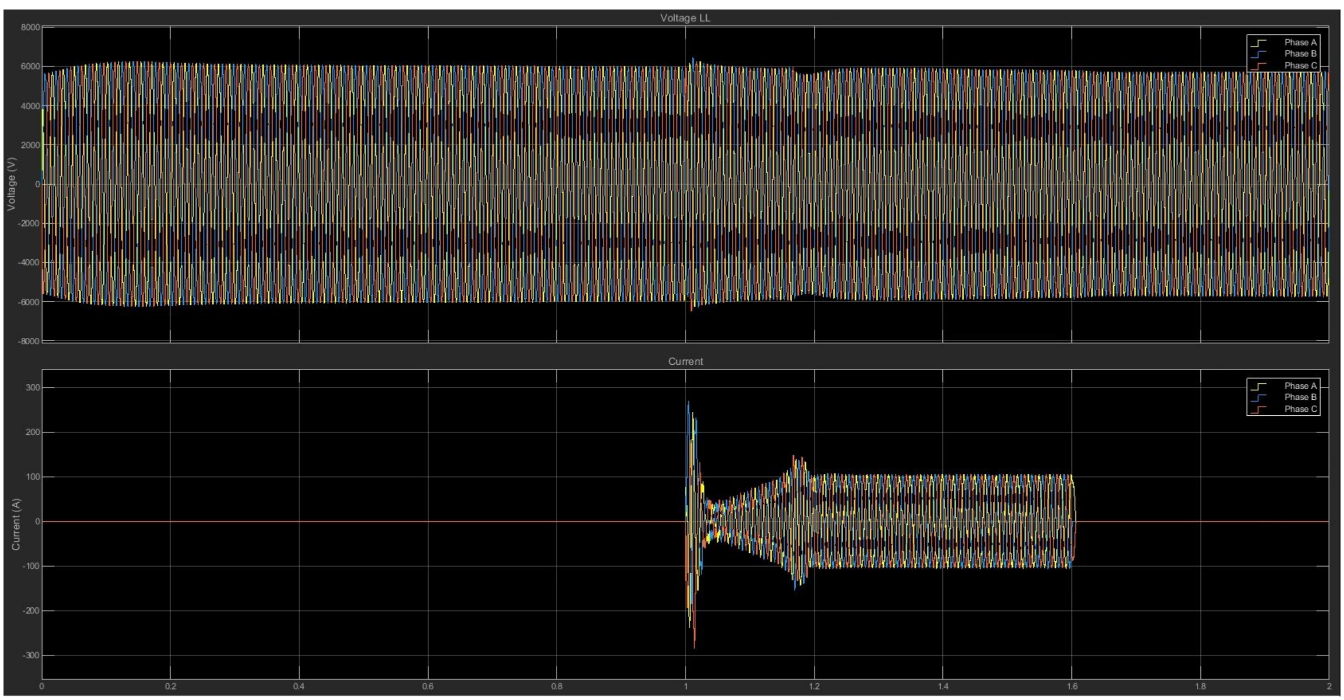


Figure 169: Dynamic Results – Inuvik Renewable Sources Variation – 20% – PV

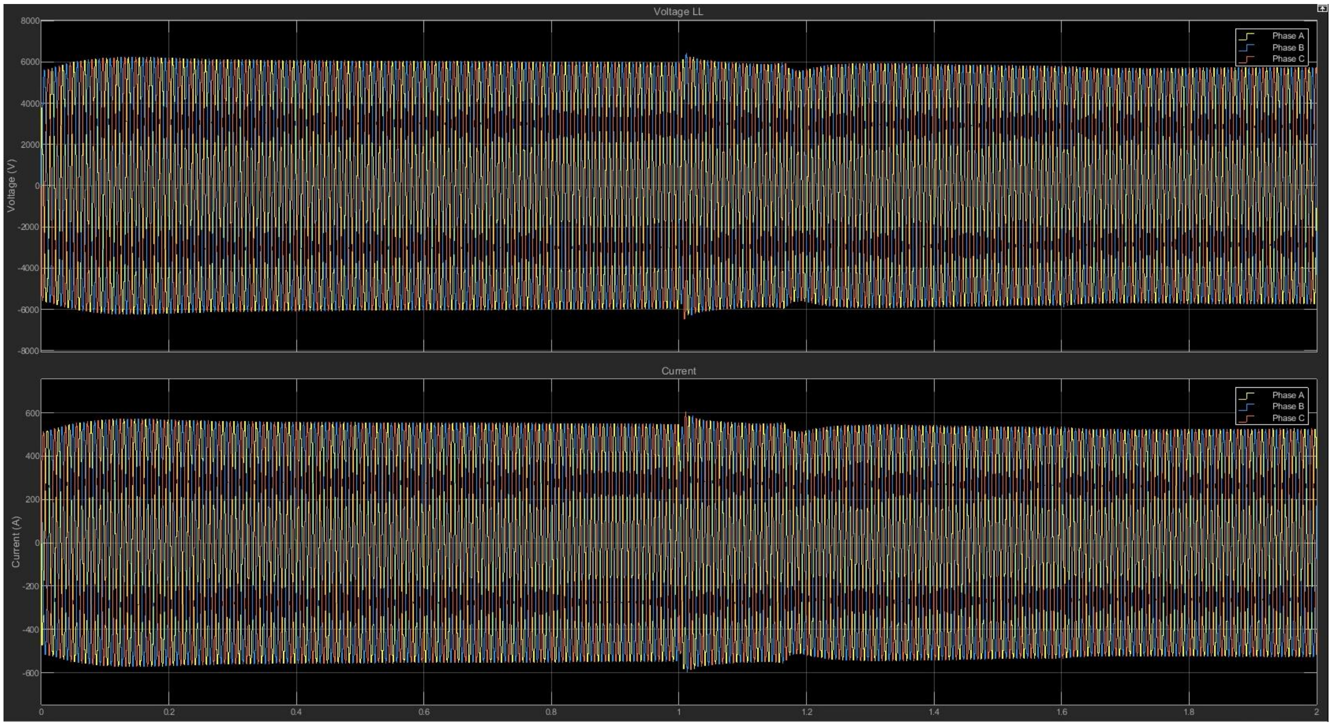


Figure 170: Dynamic Results – Inuvik Renewable Sources Variation – 20% – Load

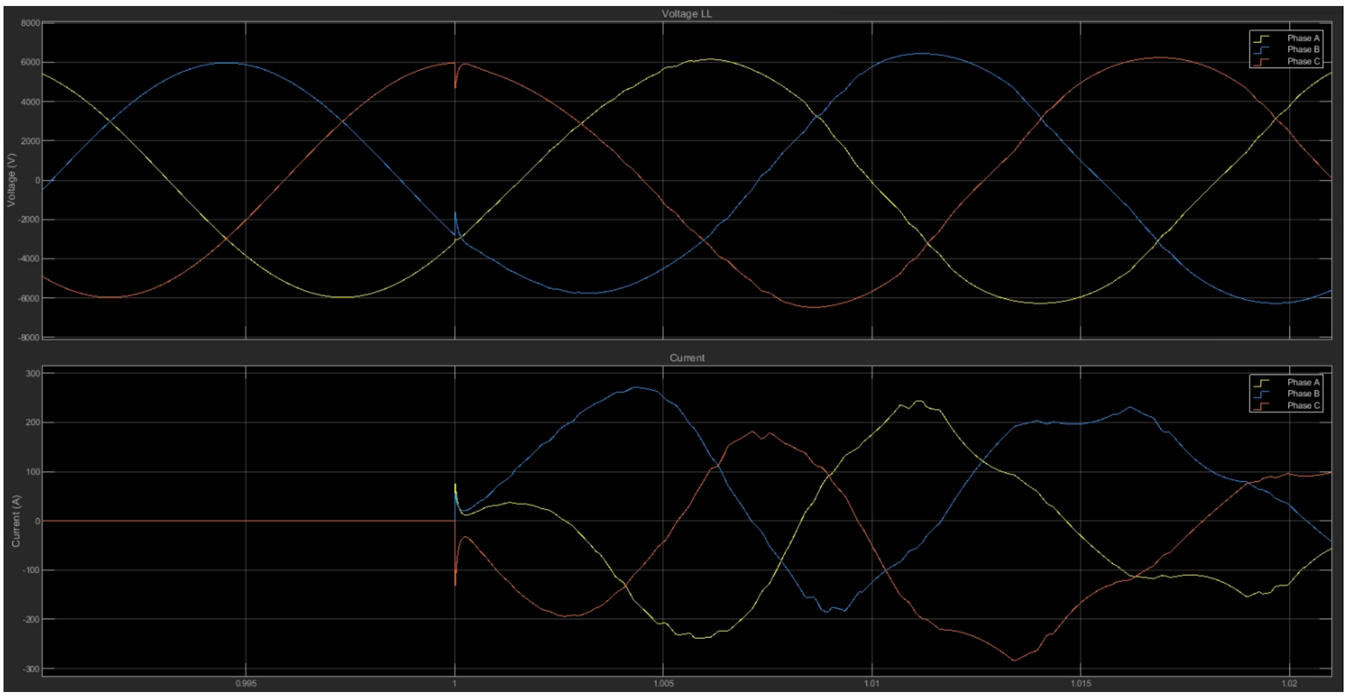


Figure 171: Dynamic Results – Inuvik Renewable Sources Connection – 20% – PV

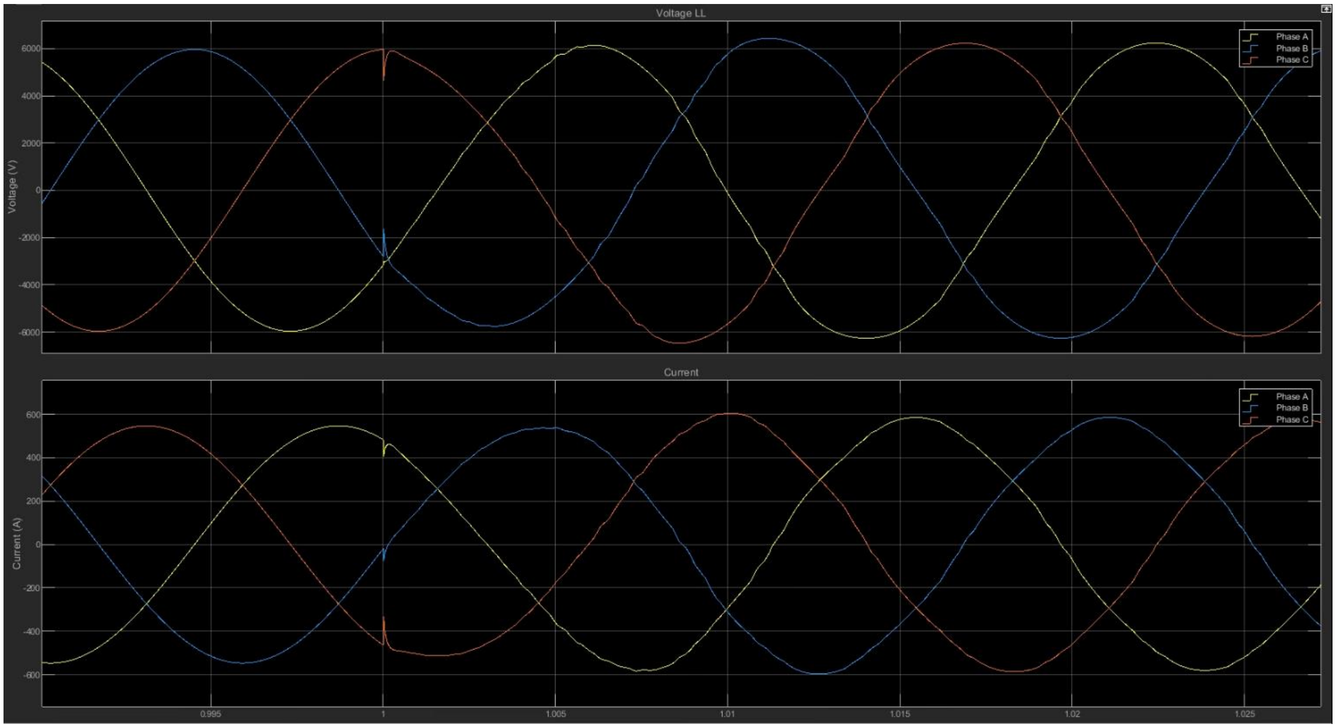


Figure 172: Dynamic Results – Inuvik Renewable Sources Connection – 20% – Load

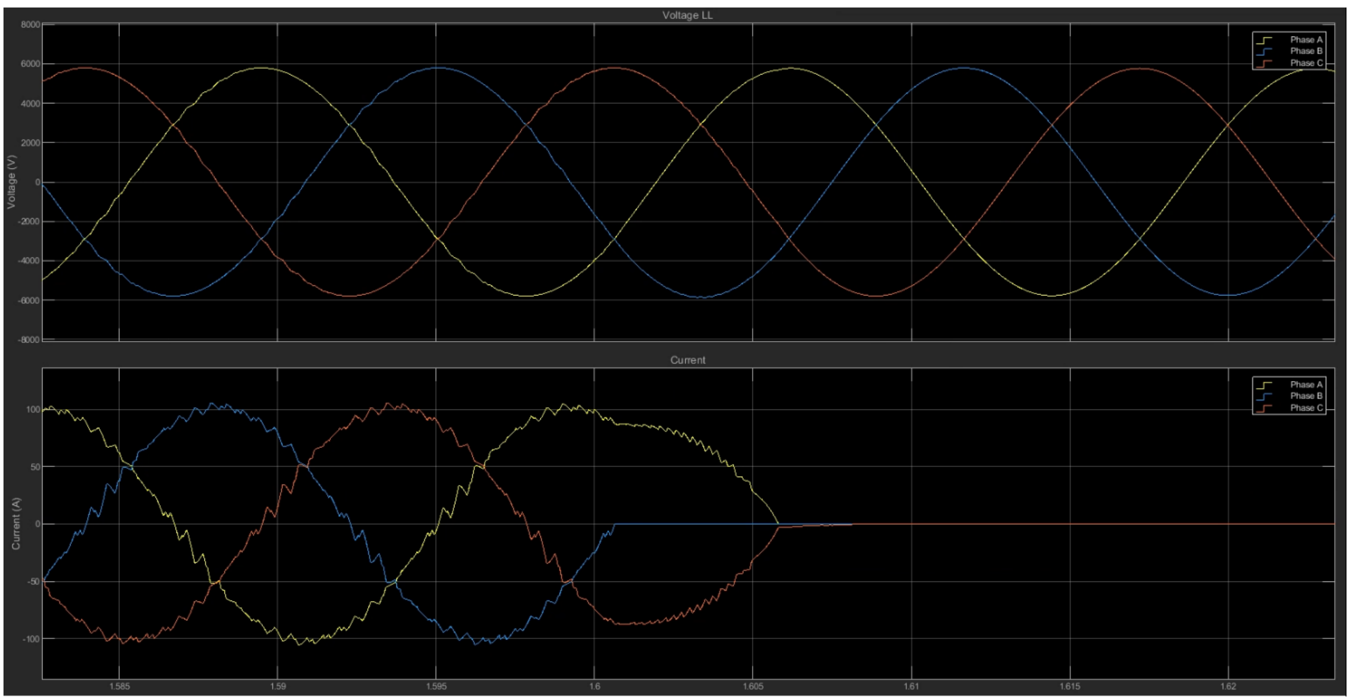


Figure 173: Dynamic Results – Inuvik Renewable Sources Disconnection – 20% – PV

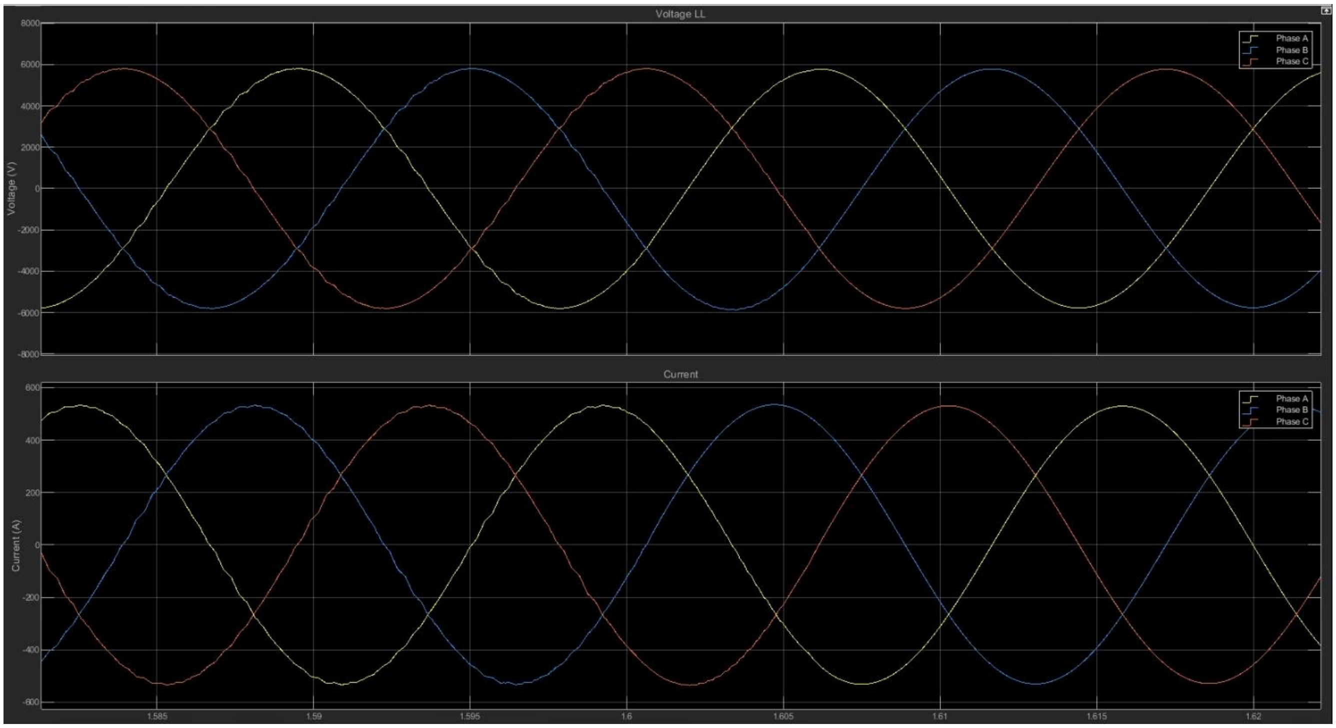


Figure 174: Dynamic Results – Inuvik Renewable Sources Disconnection – 20% – Load

E.18. Inuvik 25% Renewable Energy Penetration

E.18.1. Load Increase and Decrease

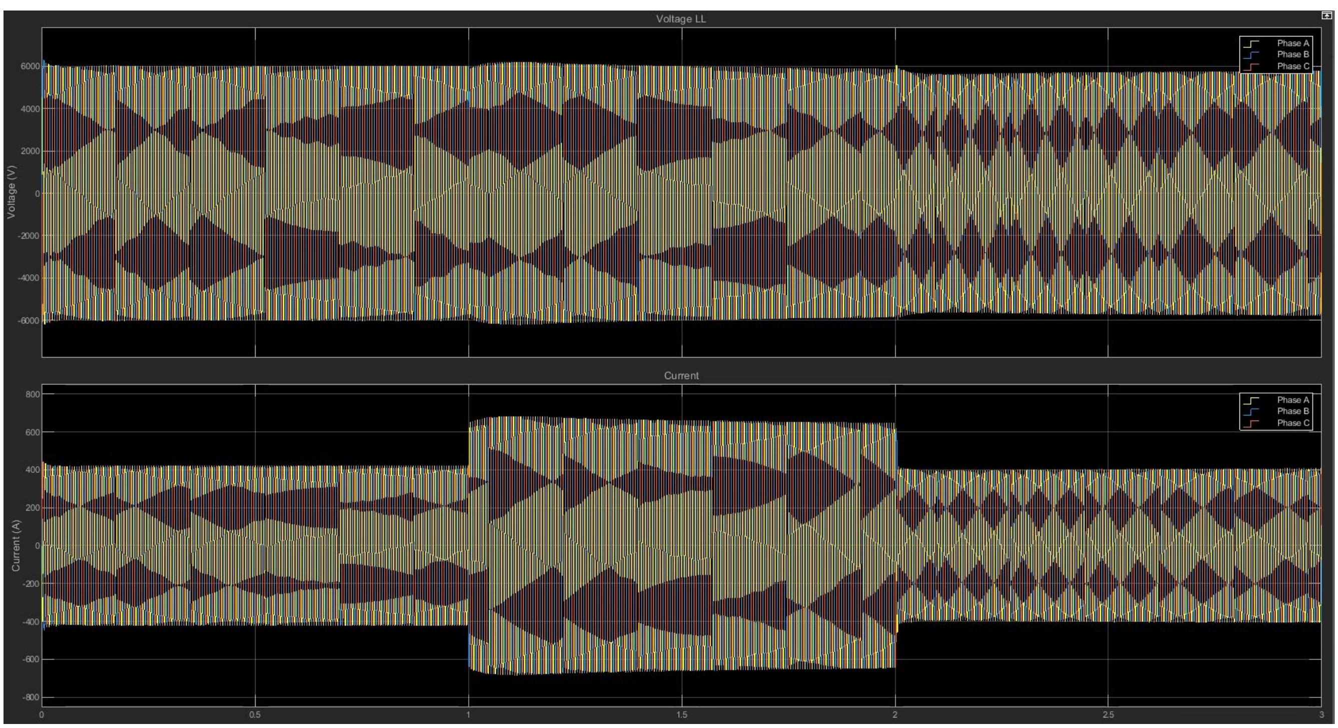


Figure 175: Dynamic Results – Inuvik Load Variations – 25%

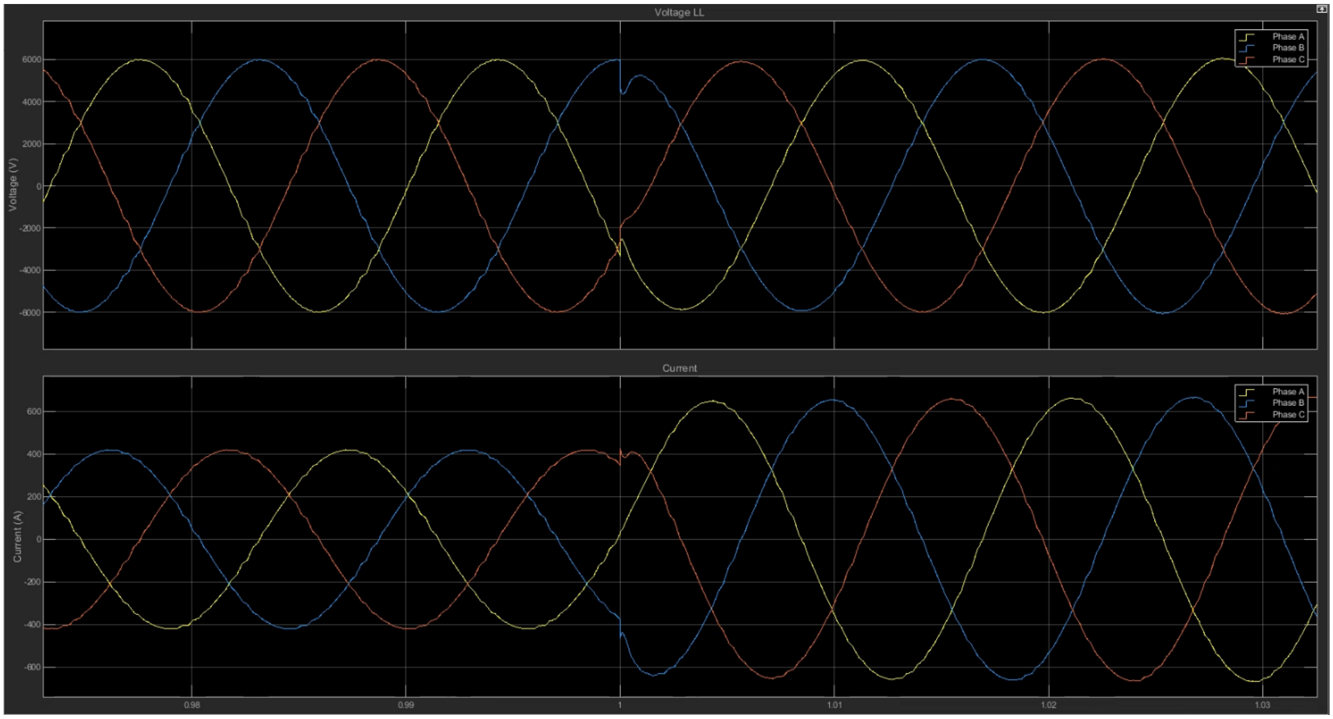


Figure 176: Dynamic Results – Inuvik Load Increase – 25%

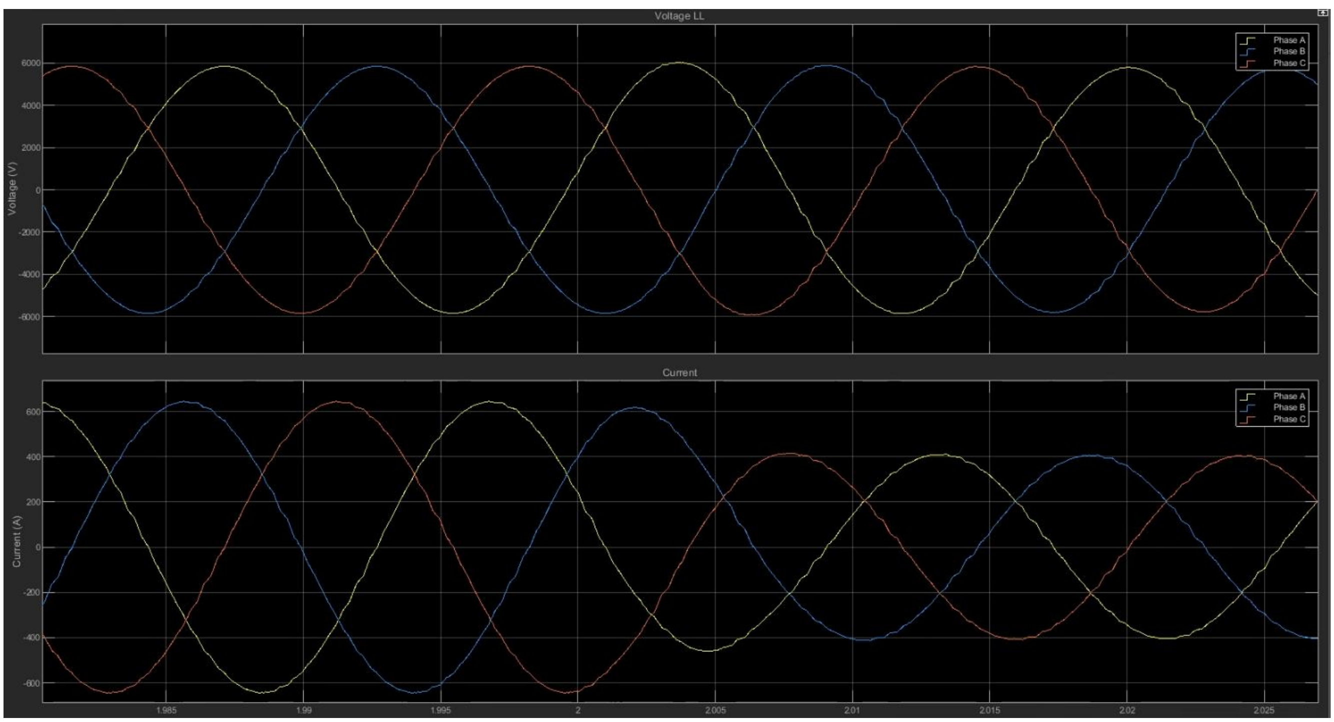


Figure 177: Dynamic Results – Inuvik Load Decrease – 25%

E.18.2. Renewable Connection / Disconnection

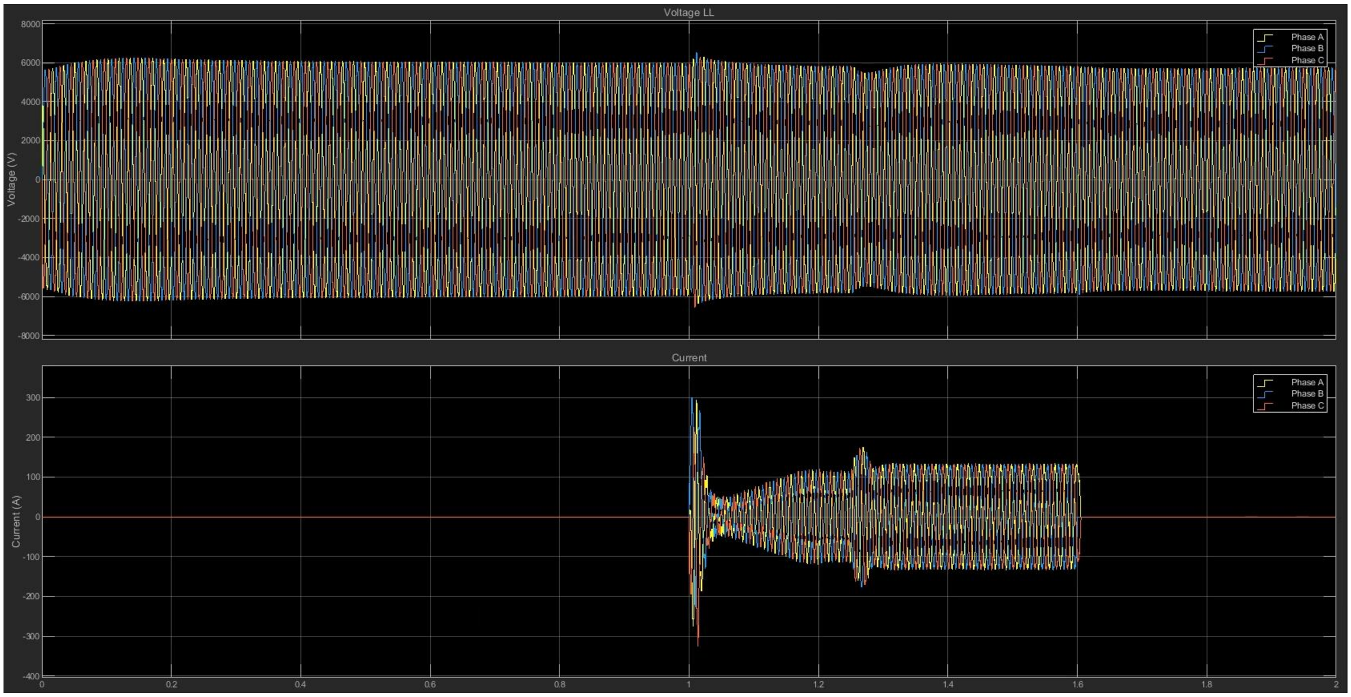


Figure 178: Dynamic Results – Inuvik Renewable Sources Variation – 25% – PV

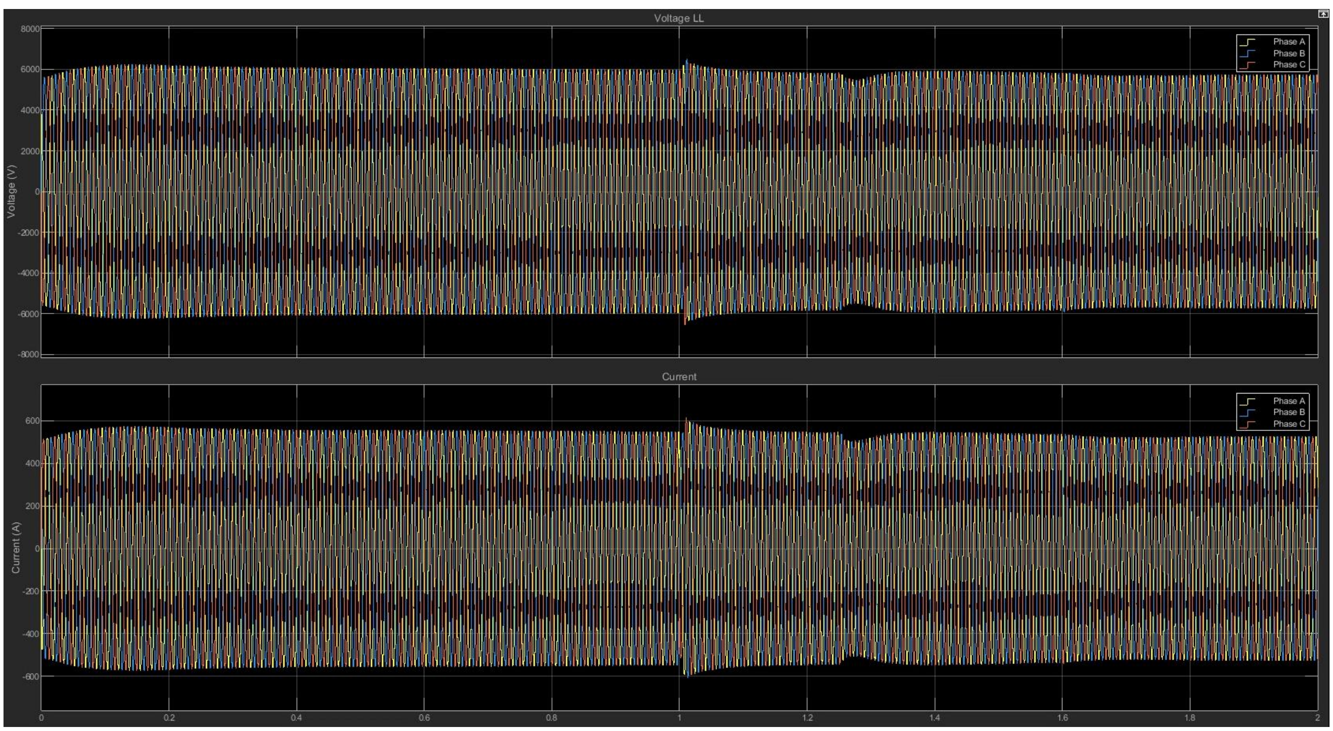


Figure 179: Dynamic Results – Inuvik Renewable Sources Variation – 25% – Load

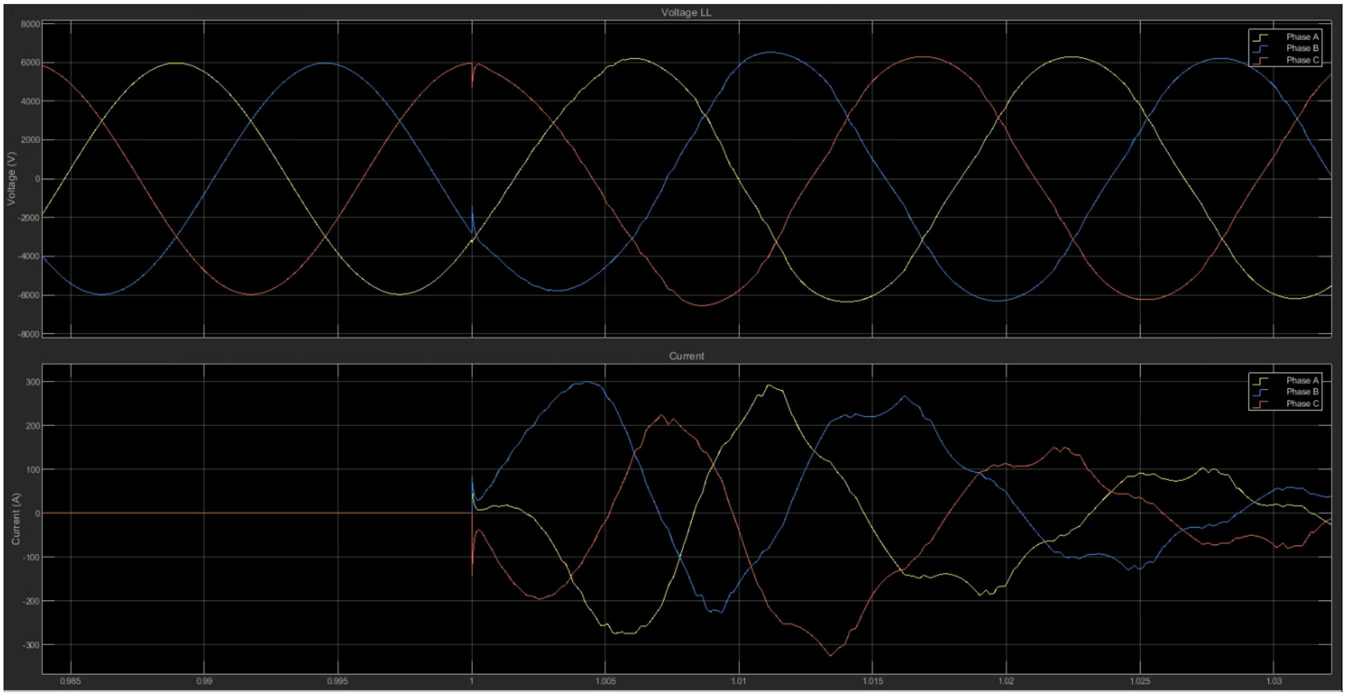


Figure 180: Dynamic Results – Inuvik Renewable Sources Connection – 25% – PV

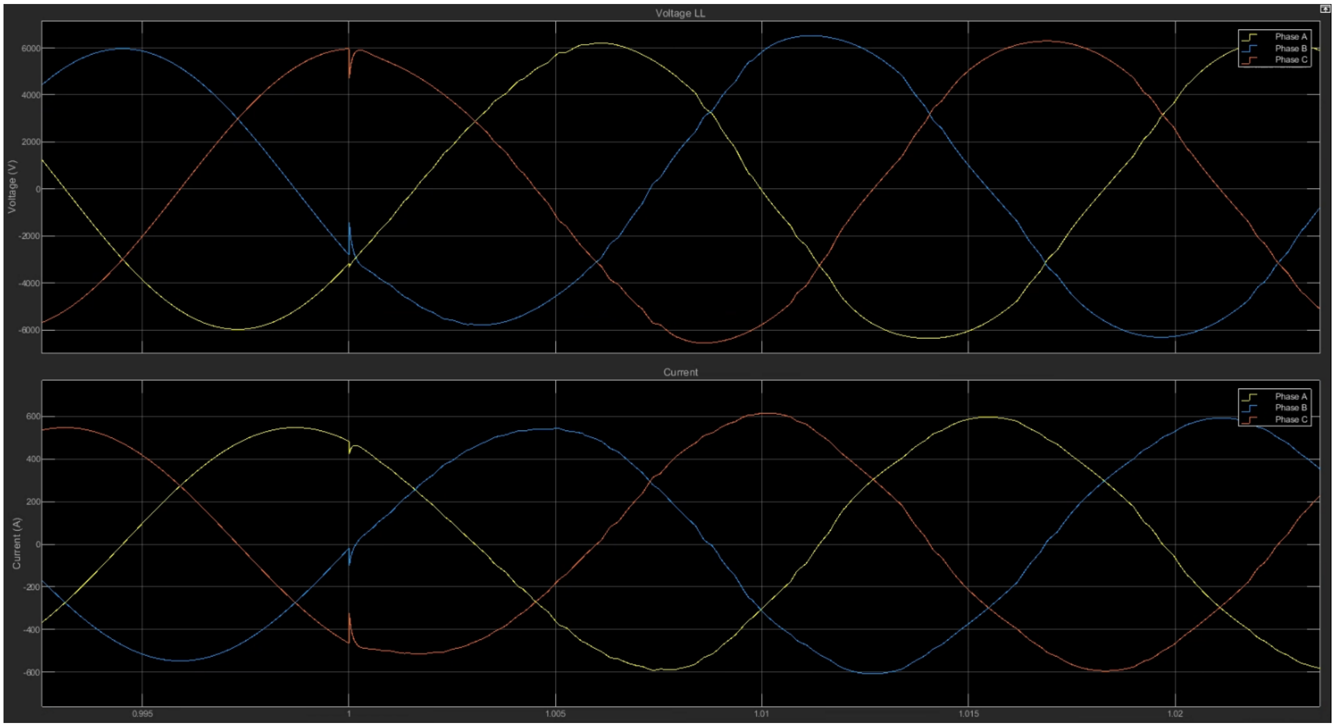


Figure 181: Dynamic Results – Inuvik Renewable Sources Connection – 25% – Load

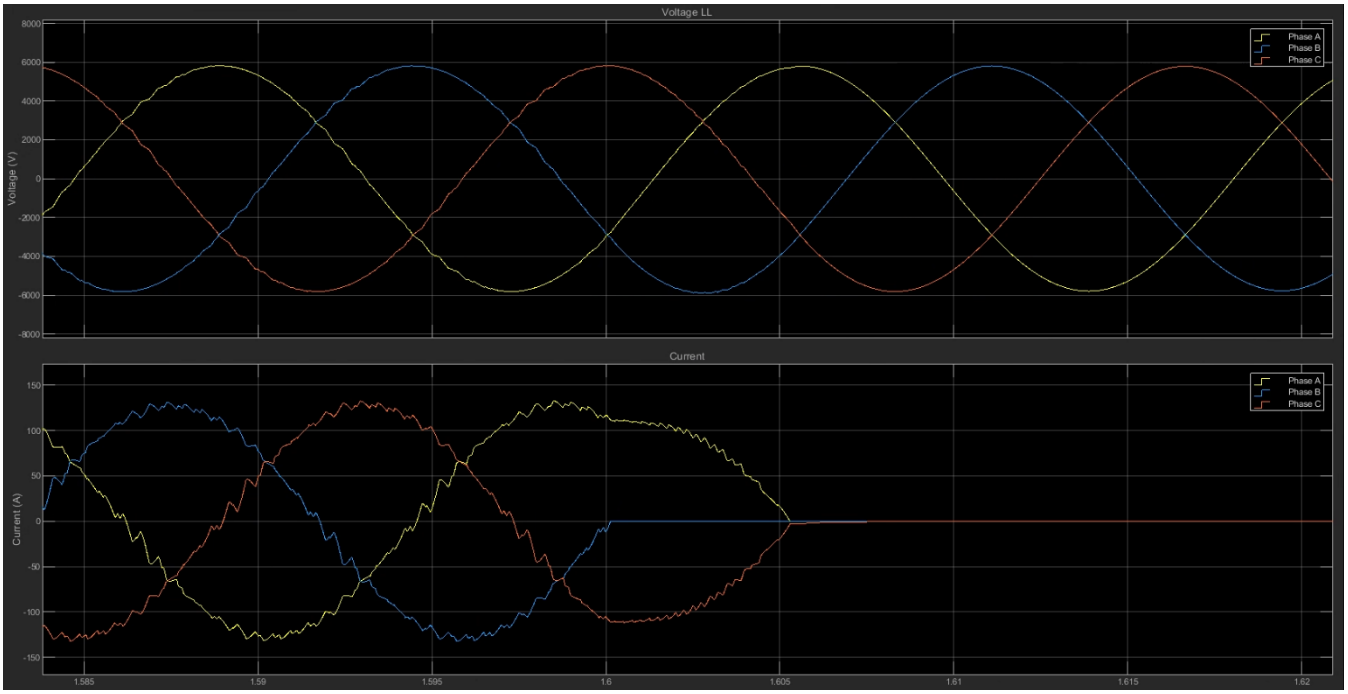


Figure 182: Dynamic Results – Inuvik Renewable Sources Disconnection – 25% – PV

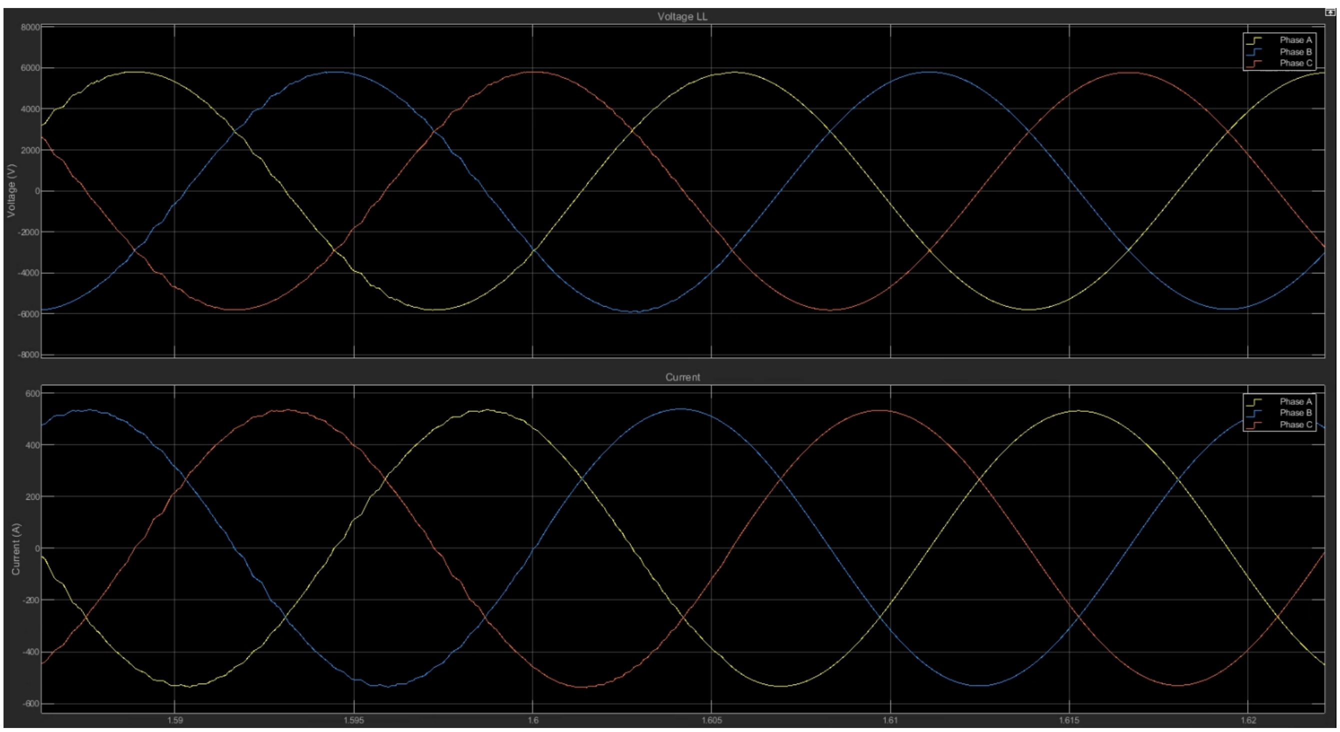


Figure 183: Dynamic Results – Inuvik Renewable Sources Disconnection – 25% – Load

E.19. Inuvik 30% Renewable Energy Penetration

E.19.1. Load Increase and Decrease

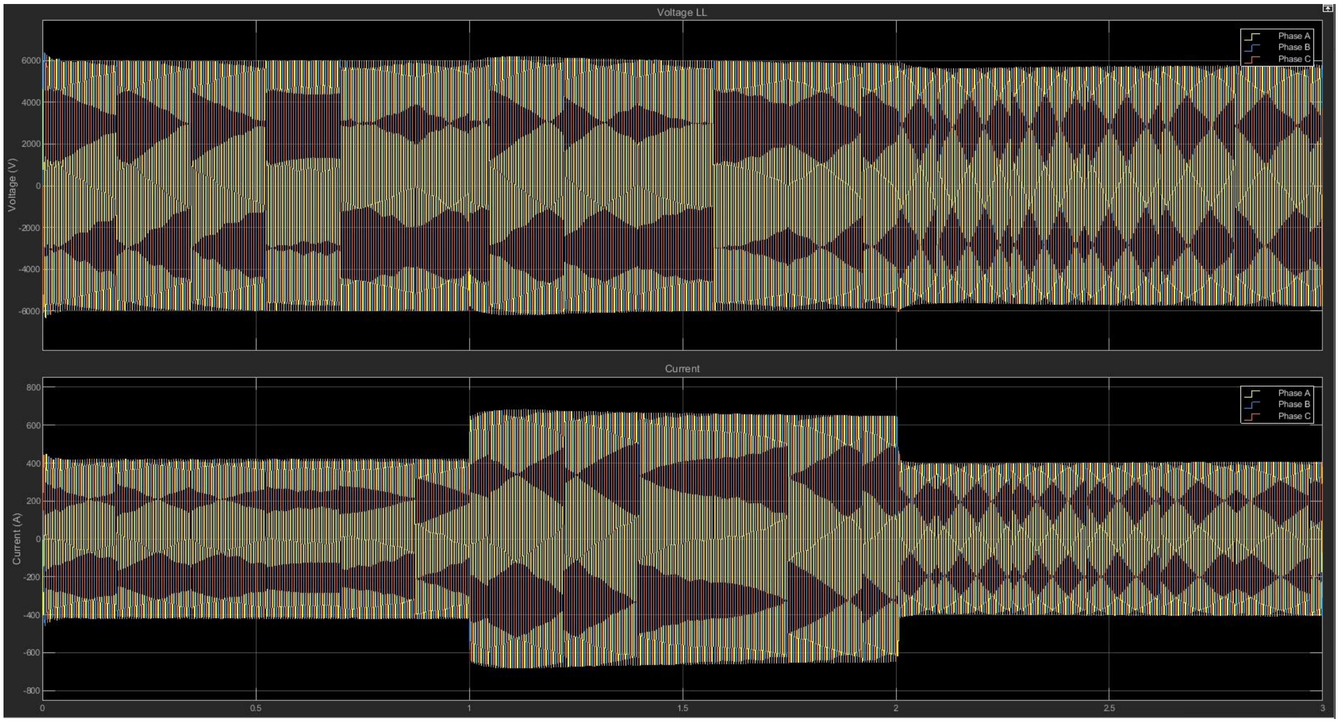


Figure 184: Dynamic Results – Inuvik Load Variations – 30%

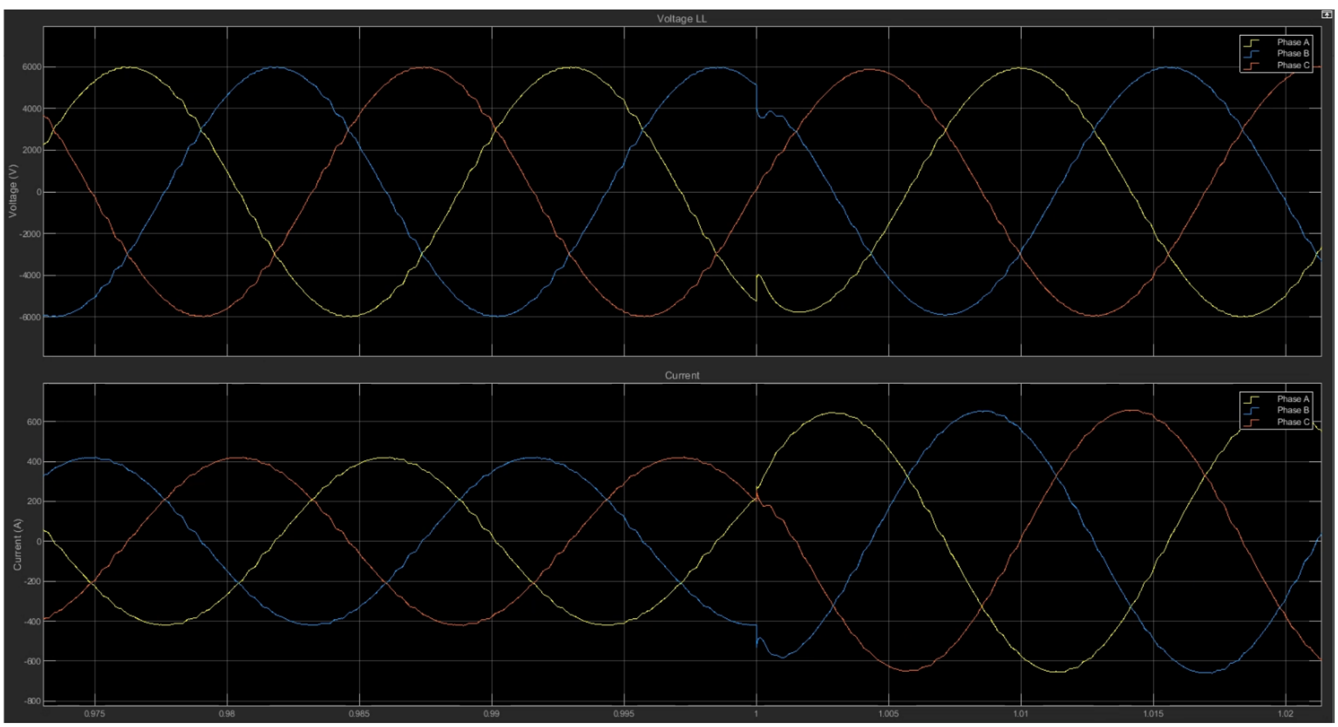


Figure 185: Dynamic Results – Inuvik Load Increase – 30%

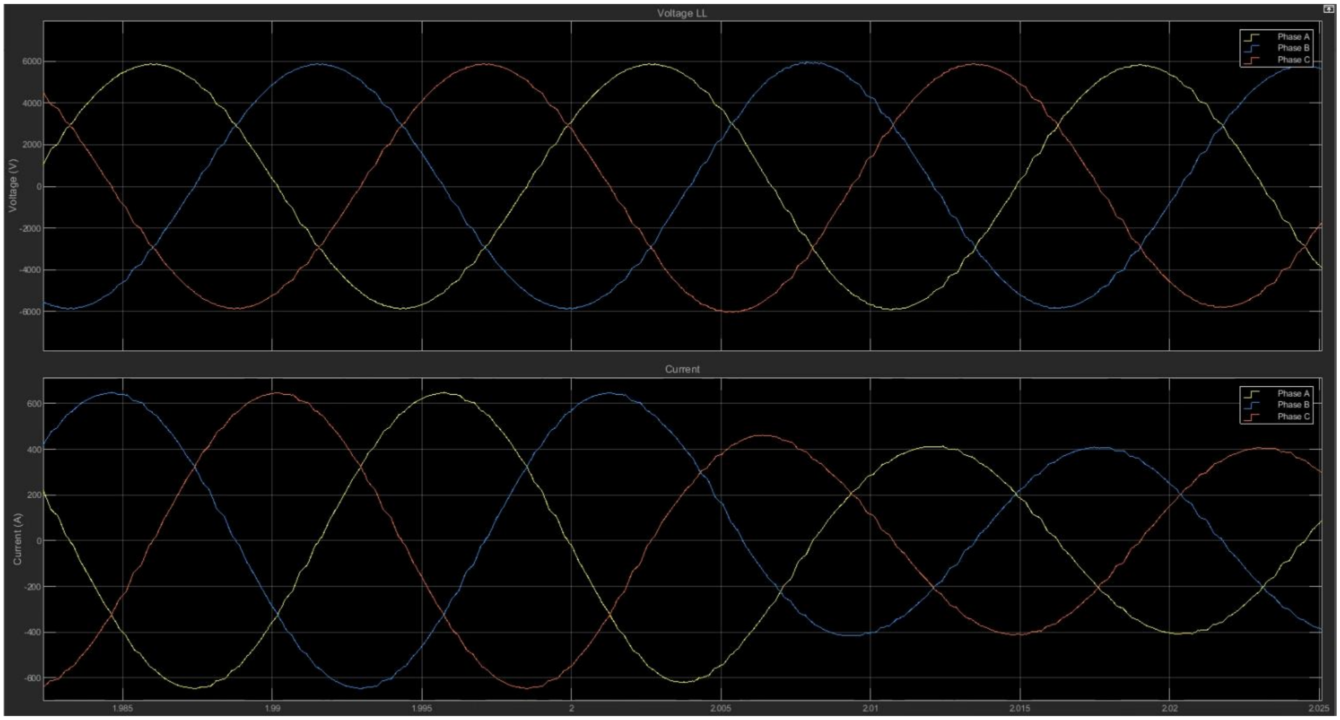


Figure 186: Dynamic Results – Inuvik Load Decrease – 30%

E.19.2. Renewable Connection / Disconnection

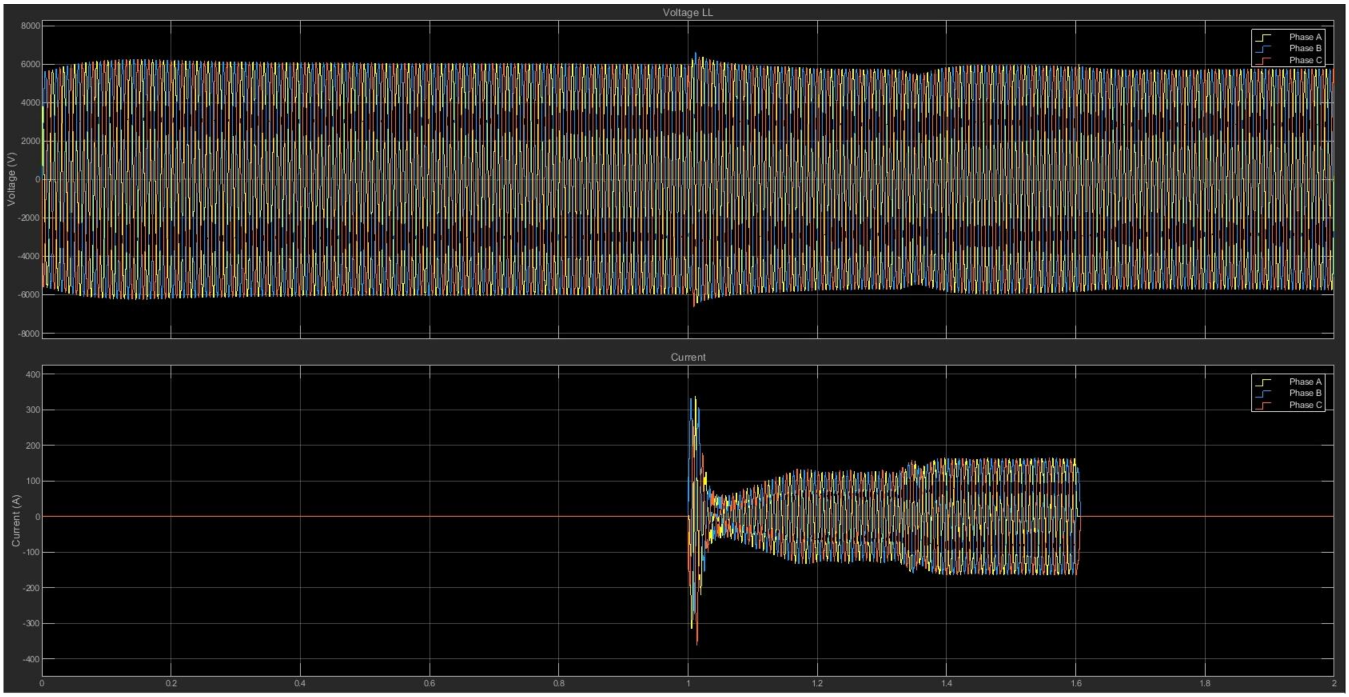


Figure 187: Dynamic Results – Inuvik Renewable Sources Variation – 30% – PV

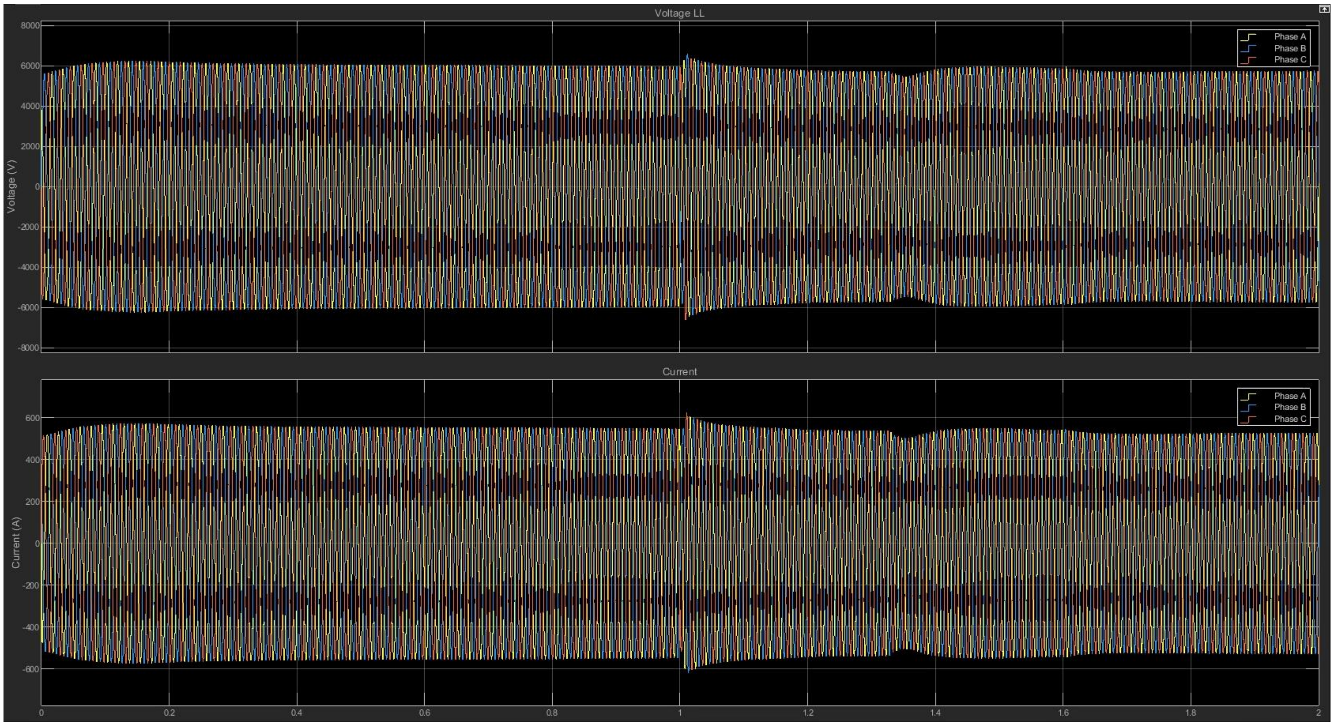


Figure 188: Dynamic Results – Inuvik Renewable Sources Variation – 30% – Load

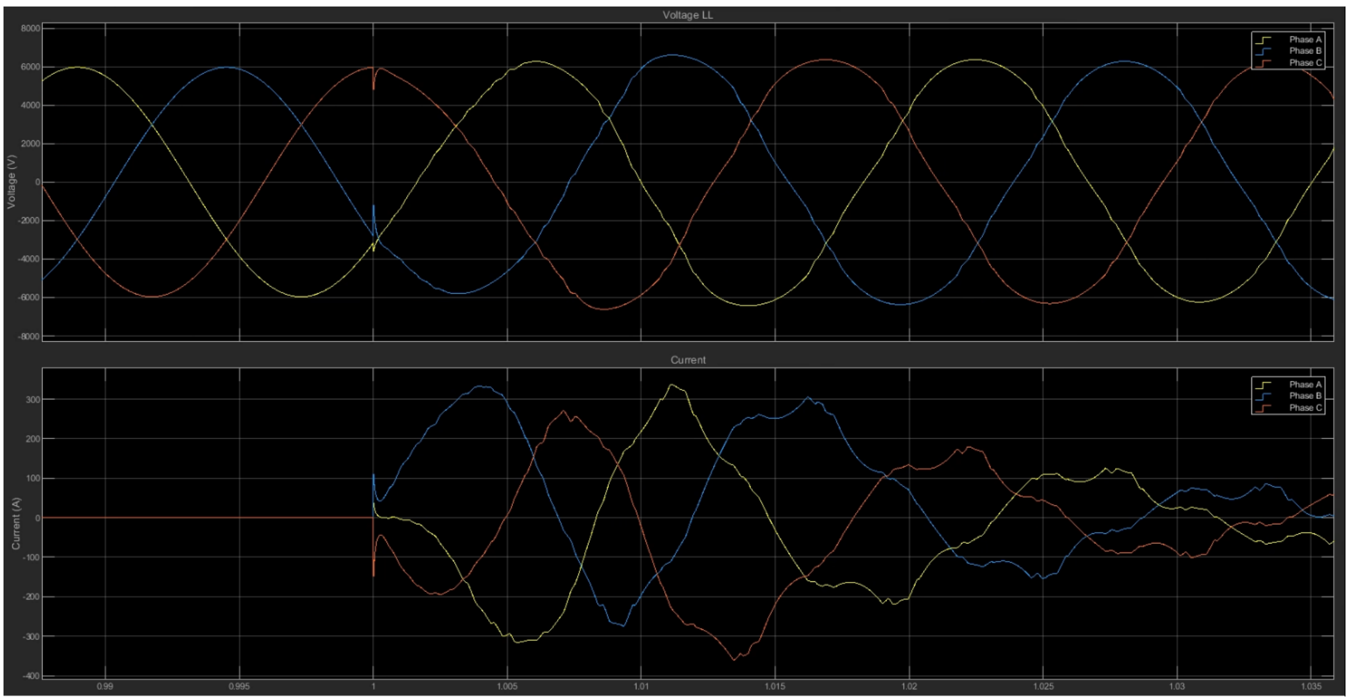


Figure 189: Dynamic Results – Inuvik Renewable Sources Connection – 30% – PV

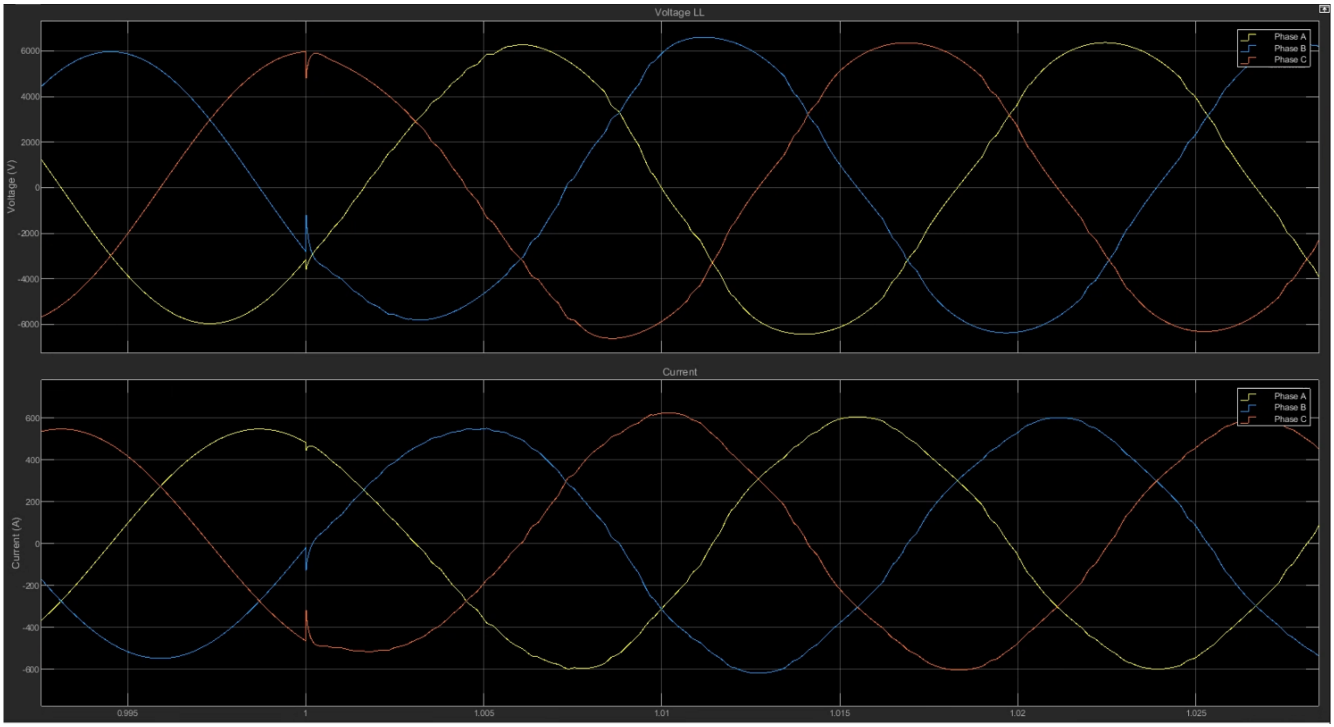


Figure 190: Dynamic Results – Inuvik Renewable Sources Connection – 30% – Load

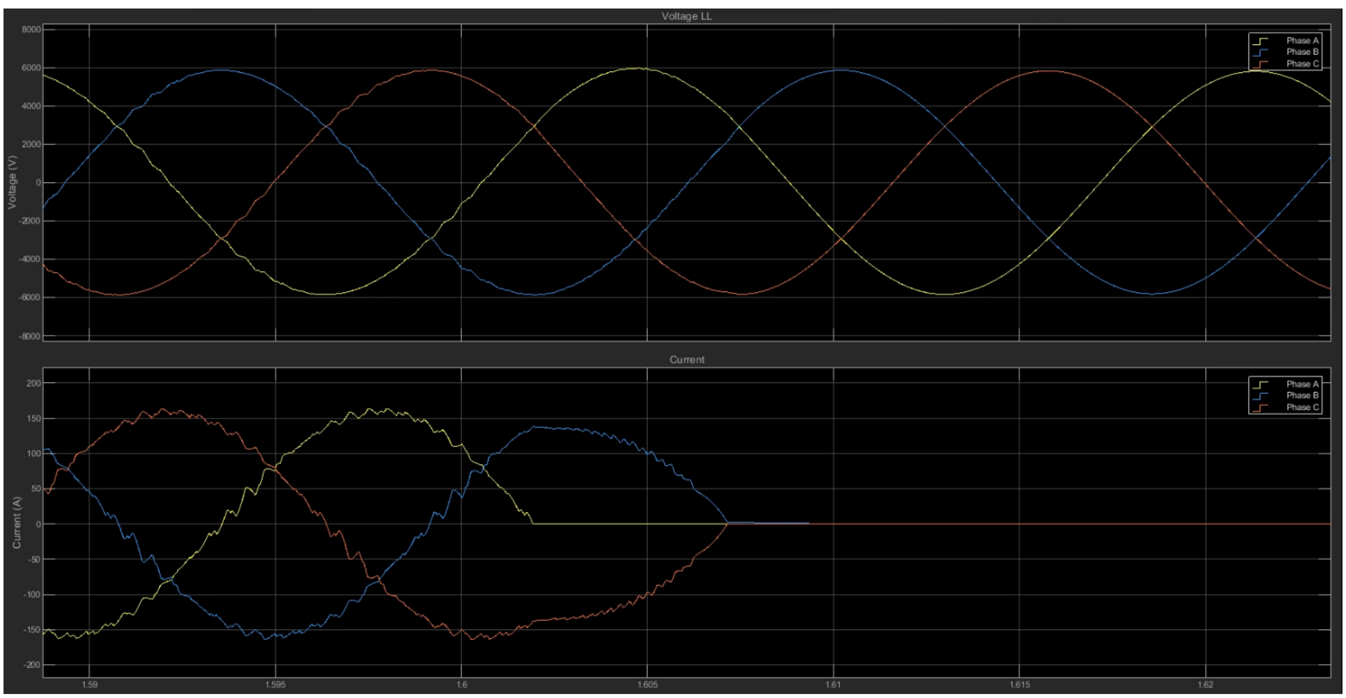


Figure 191: Dynamic Results – Inuvik Renewable Sources Disconnection – 30% – PV

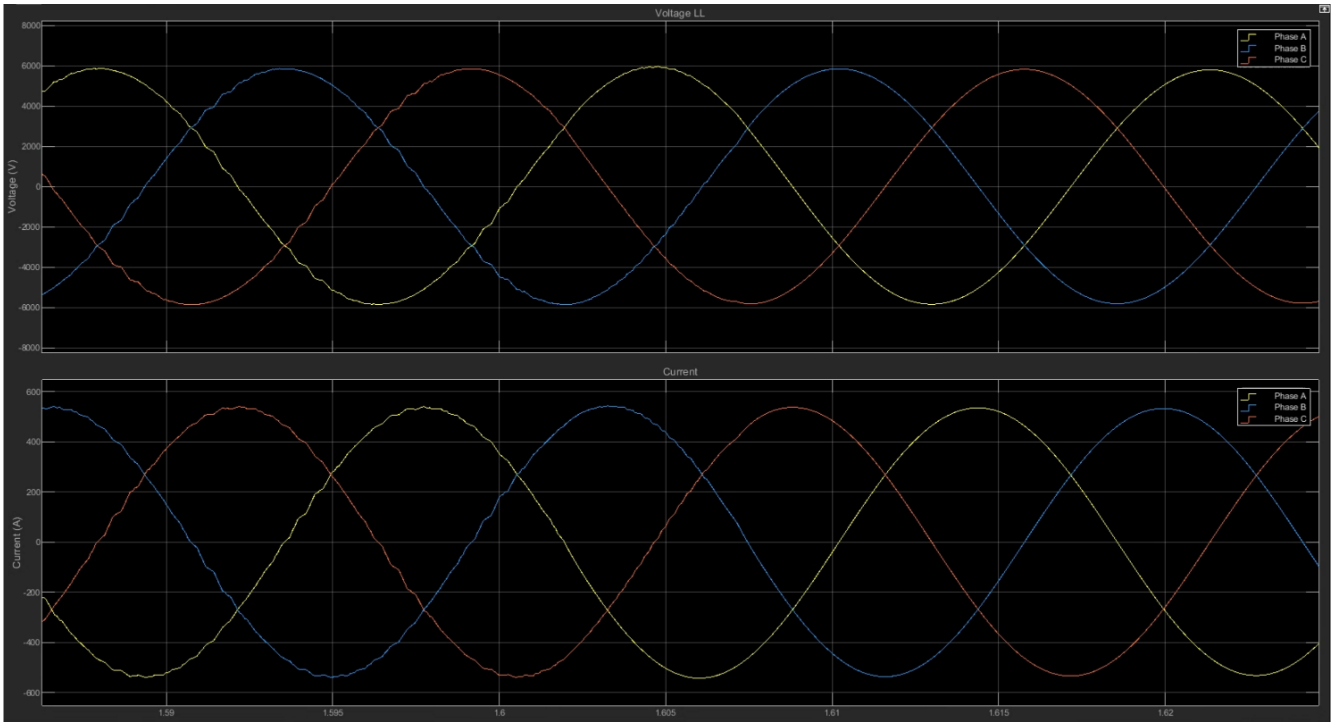


Figure 192: Dynamic Results – Inuvik Renewable Sources Disconnection – 30% – Load

E.20. Inuvik 50% Renewable Energy Penetration

E.20.1. Load Increase and Decrease

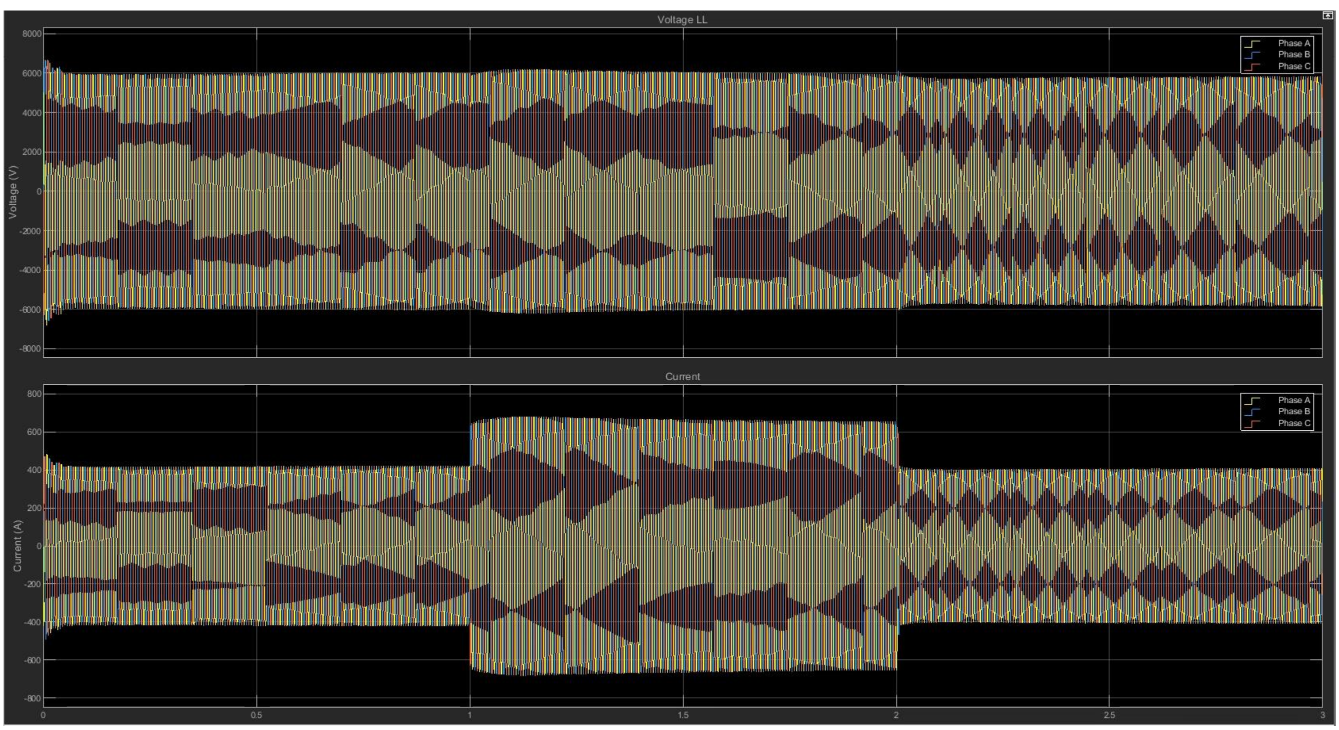


Figure 193: Dynamic Results – Inuvik Load Variations – 50%

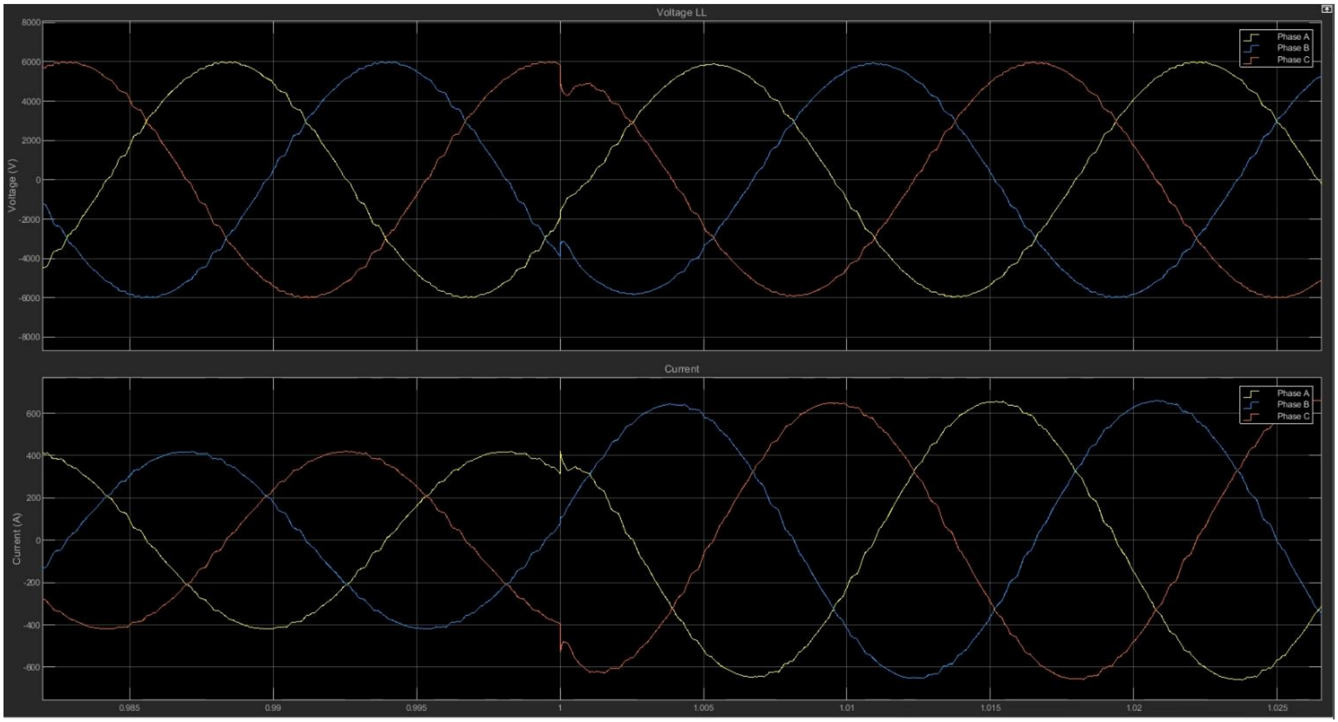


Figure 194: Dynamic Results – Inuvik Load Increase – 50%

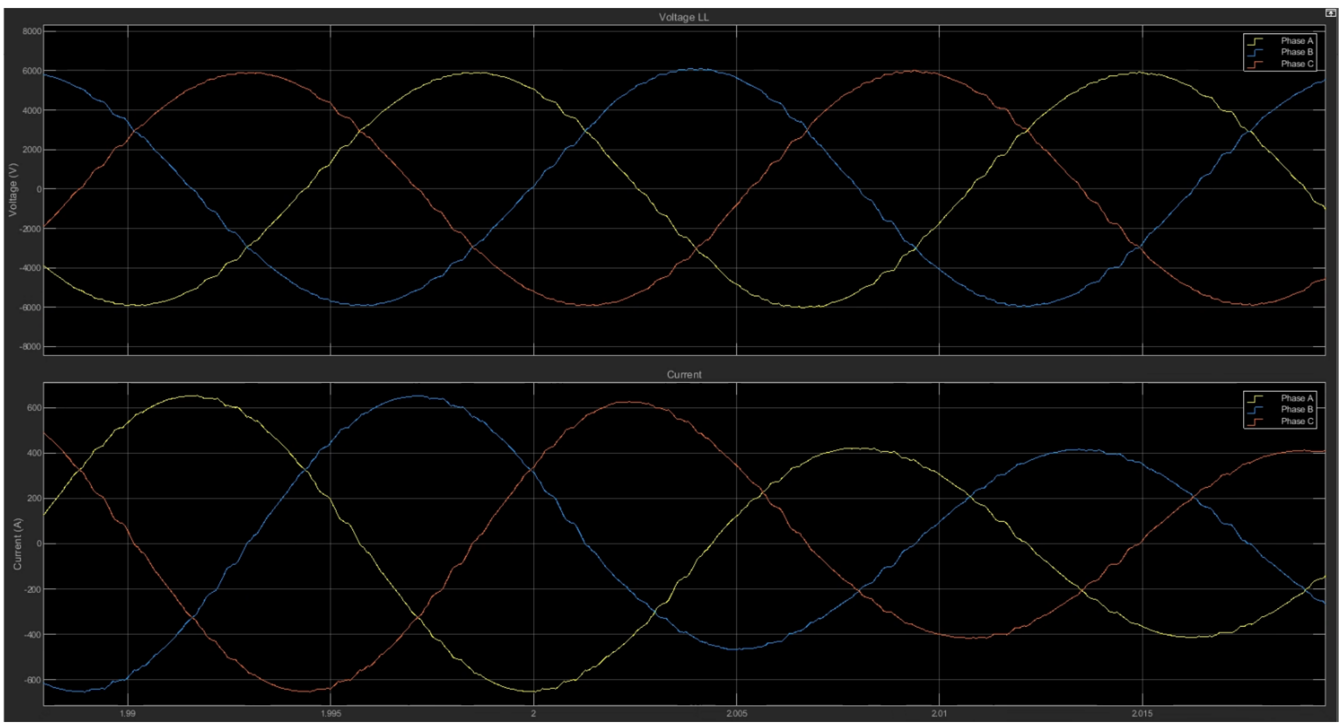


Figure 195: Dynamic Results – Inuvik Load Decrease – 50%

E.20.2. Renewable Connection / Disconnection

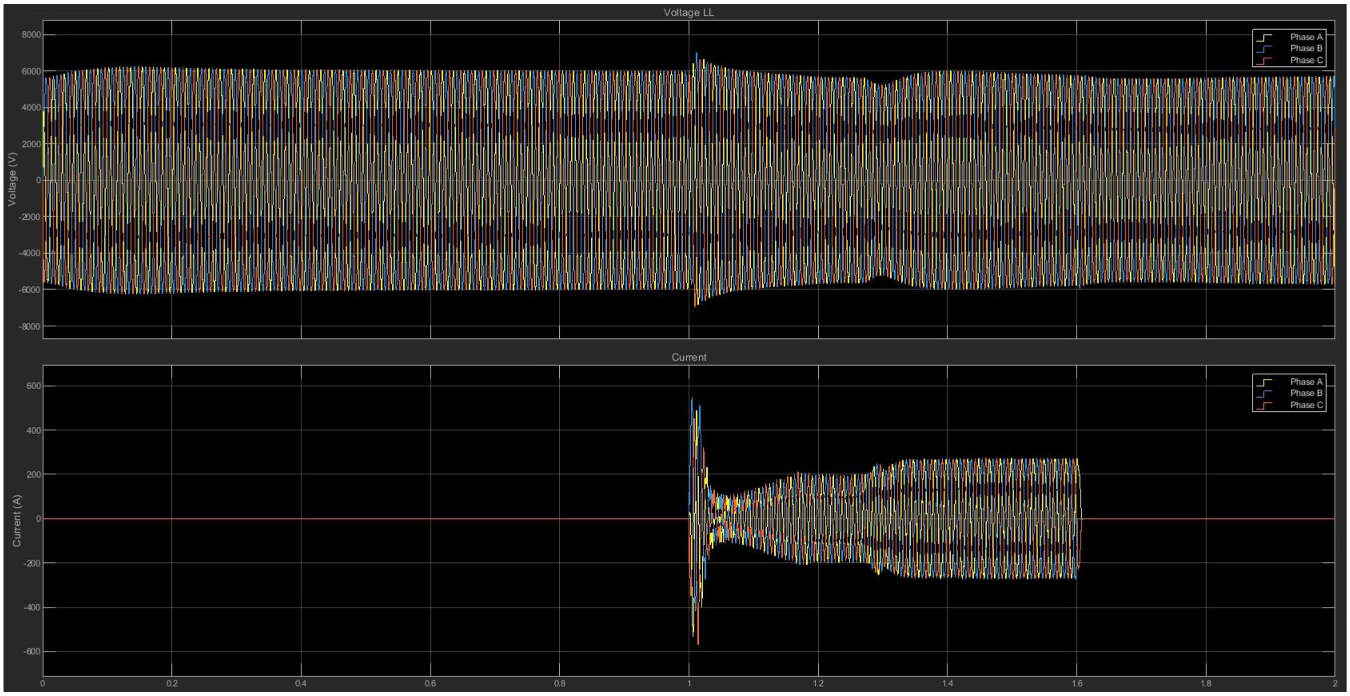


Figure 196: Dynamic Results – Inuvik Renewable Sources Variation – 50% – PV

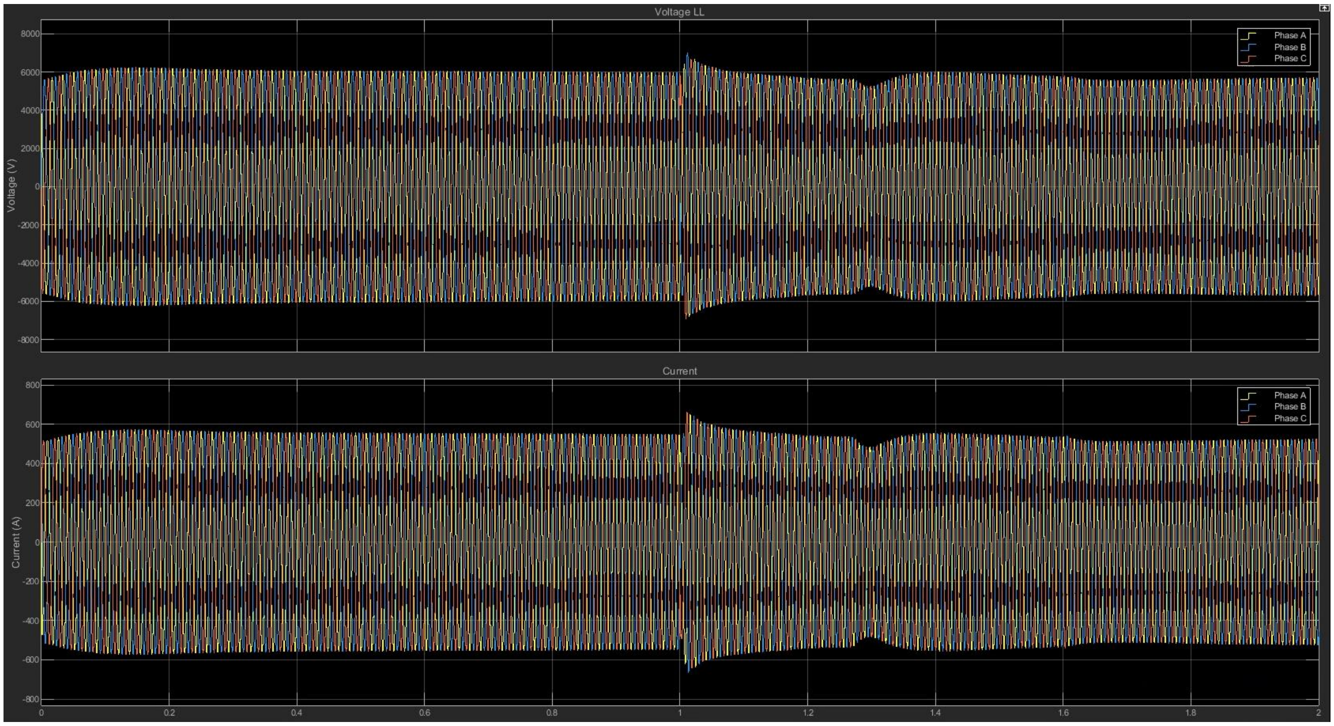


Figure 197: Dynamic Results – Inuvik Renewable Sources Variation – 50% – Load

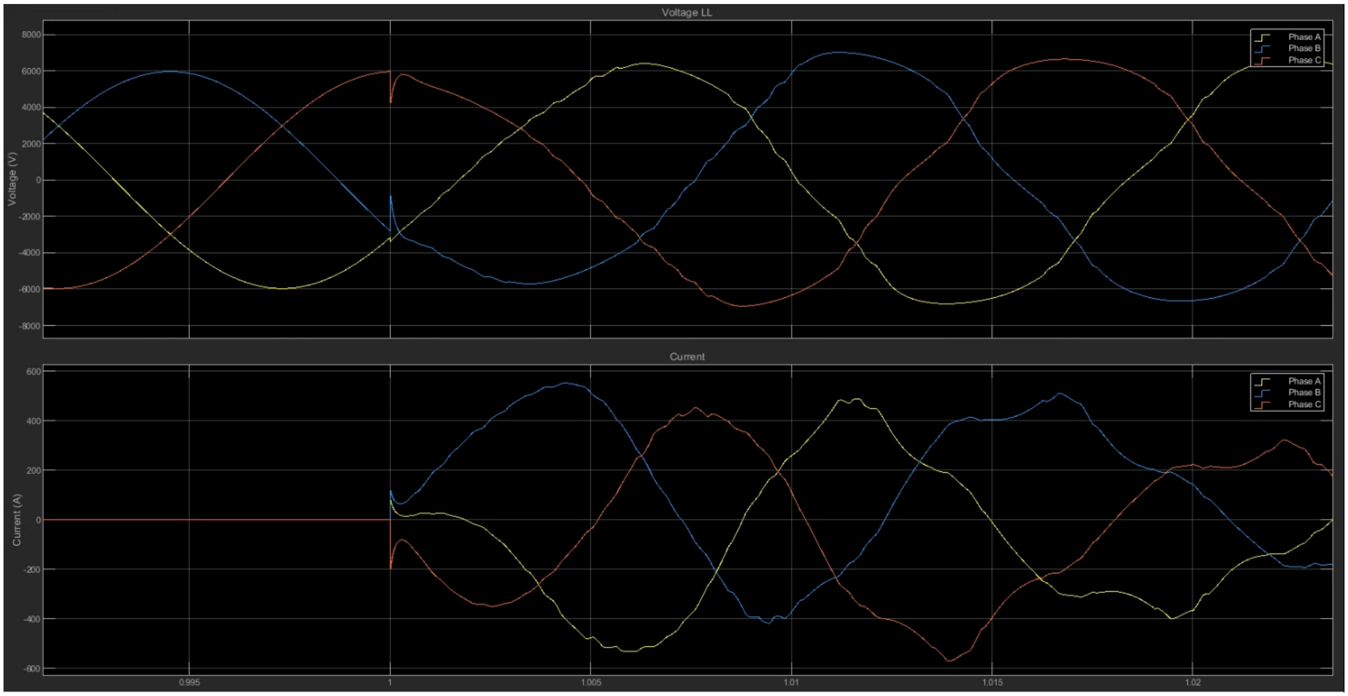


Figure 198: Dynamic Results – Inuvik Renewable Sources Connection – 50% – PV

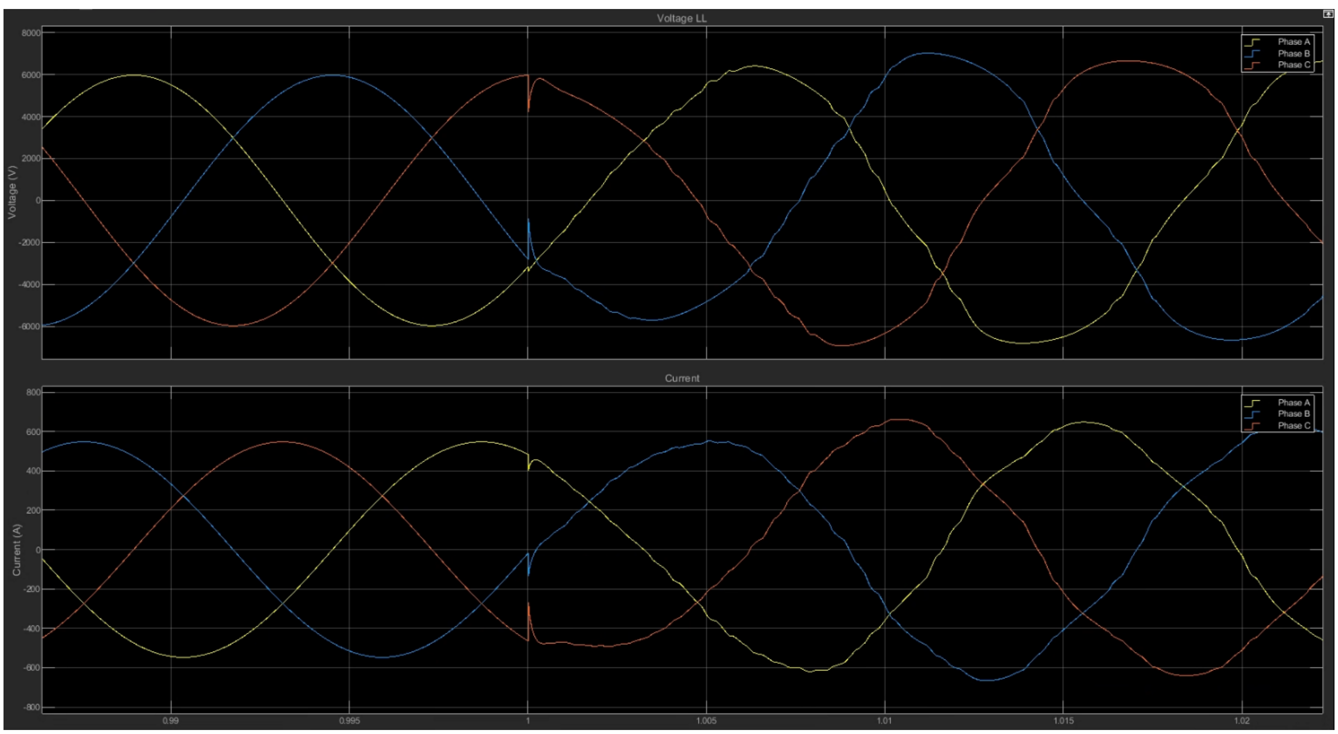


Figure 199: Dynamic Results – Inuvik Renewable Sources Connection – 50% – Load

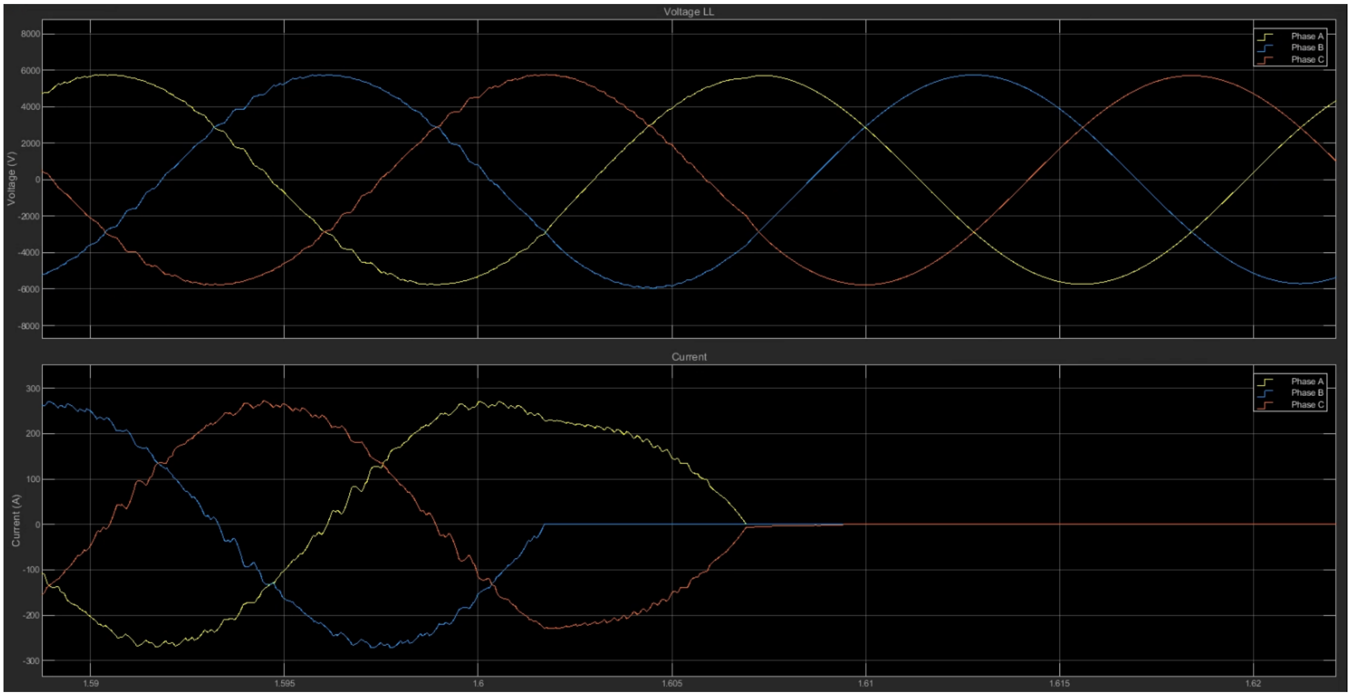


Figure 200: Dynamic Results – Inuvik Renewable Sources Disconnection – 50% – PV

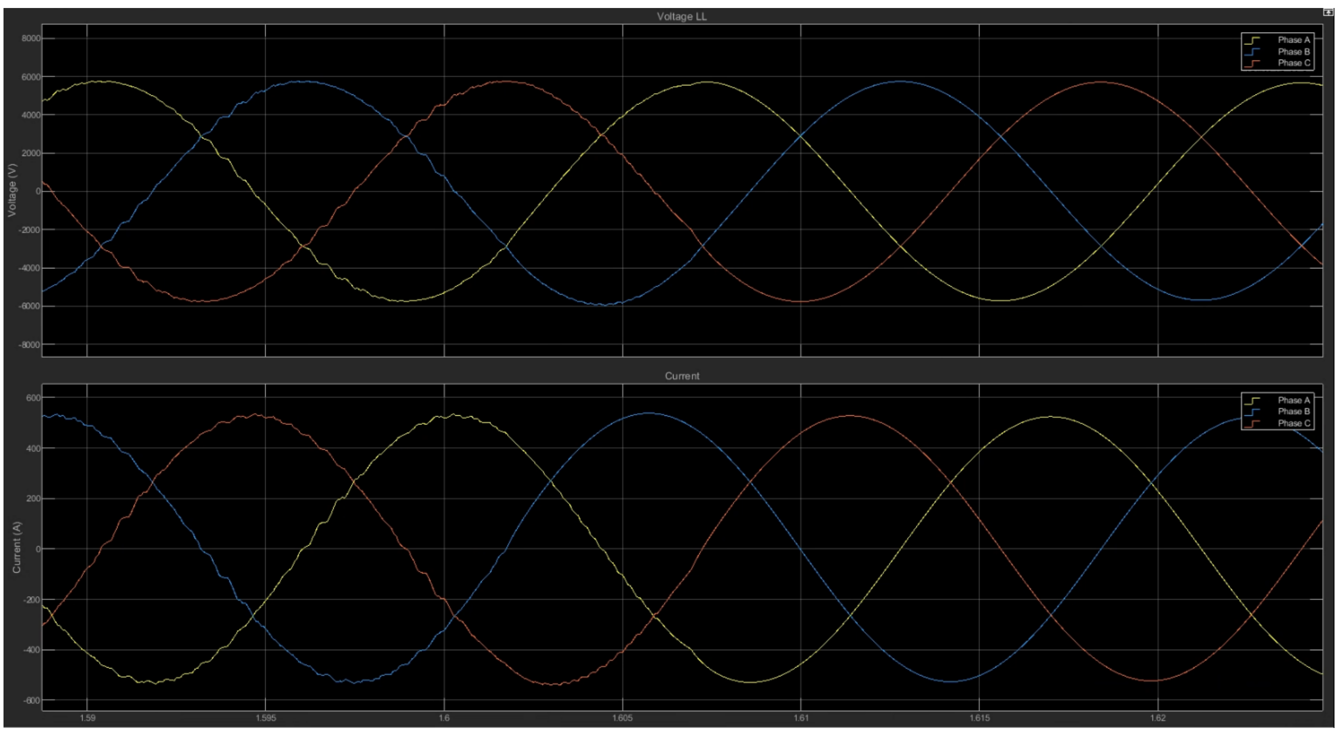


Figure 201: Dynamic Results – Inuvik Renewable Sources Disconnection – 50% – Load

F

Appendix F
Losses Analysis Detailed Results

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Distribution savings (MWh)	0	1.1	1.4	1.7	2.7	3.9
Production losses (MWh)	0	-35	-44	-53	-88	-132
Total losses (MWh)	0	-34	-43	-51	-85	-128

Table 21: Detailed Losses (MWh) Information – Fort Liard

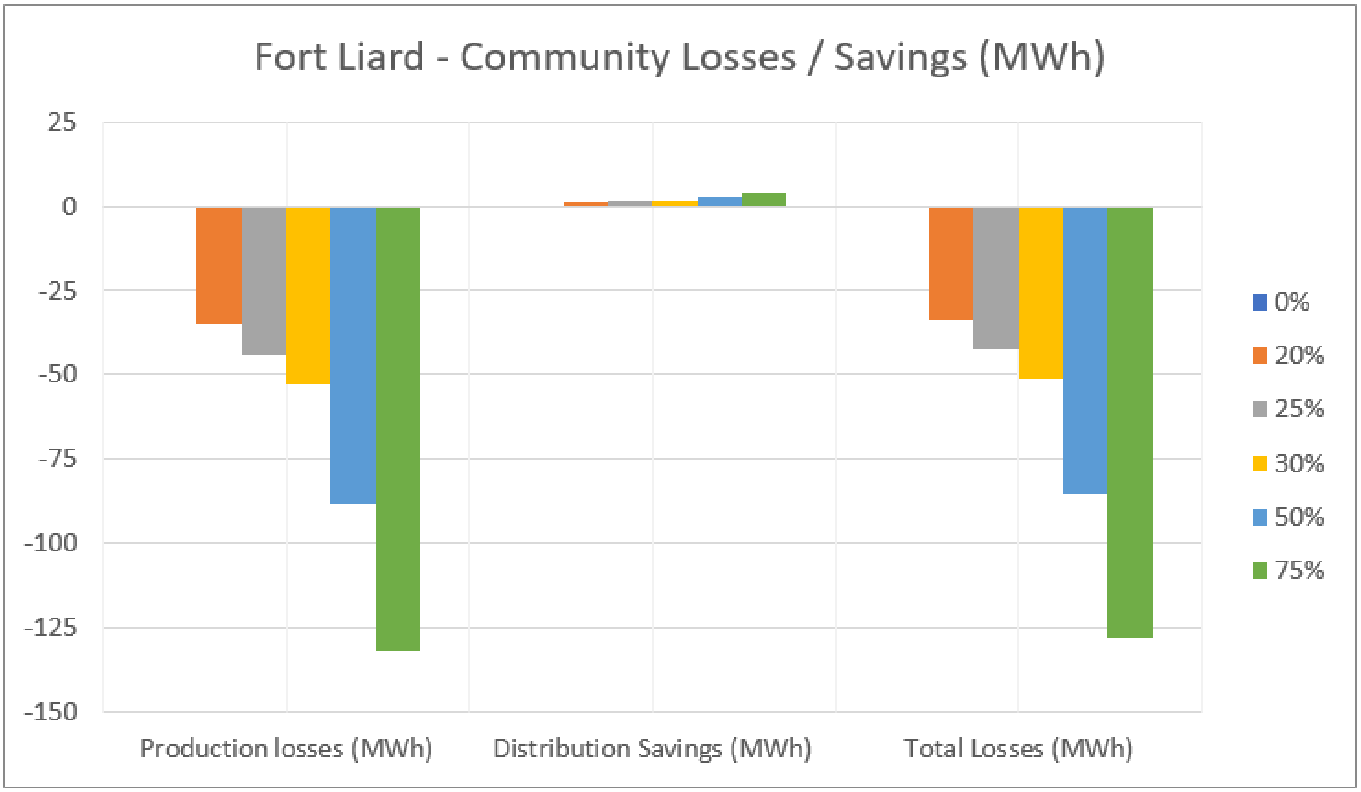


Figure 202: Losses Results – Fort Liard – Community Losses (MWh)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Diesel savings (k$)	0	8	10	11	19	28
Distributions savings (k$)	0	0.9	1.1	1.3	2.1	3.1
Production losses (k$)	0	-27	-34	-41	-68	-102
Revenue losses (k$)	0	-19	-23	-28	-47	-71

Table 22: Detailed Losses (k$) Information – Fort Liard

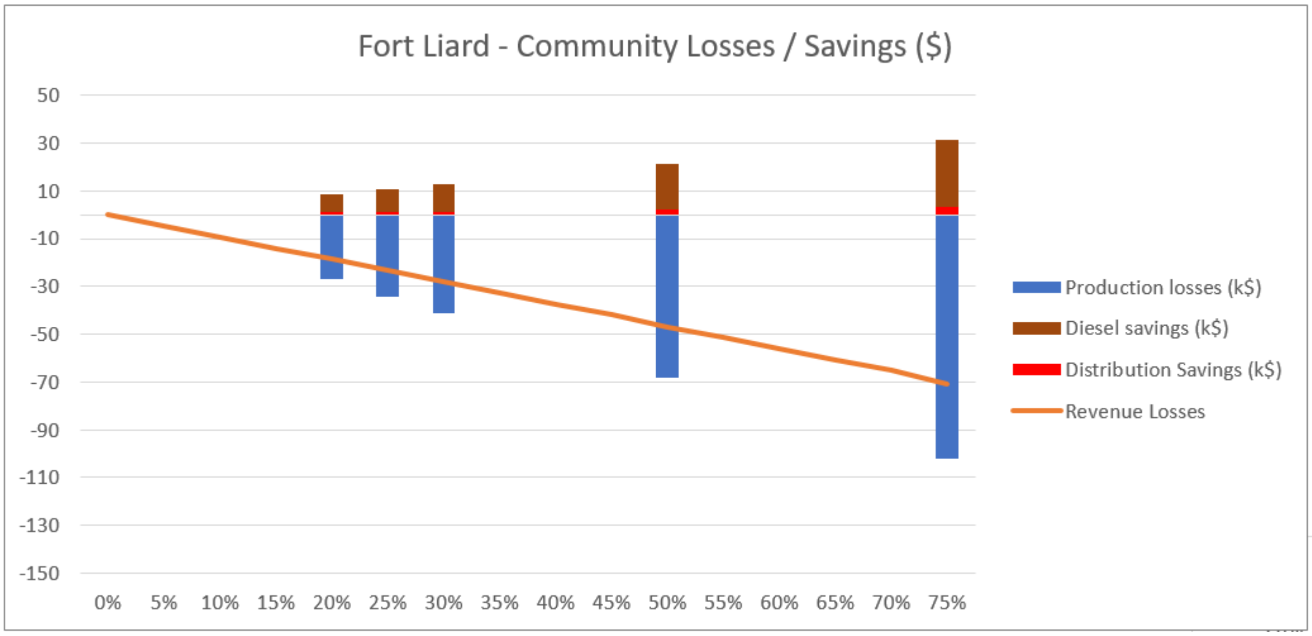


Figure 203: Losses Results – Fort Liard – Community Losses/ Saving ($)

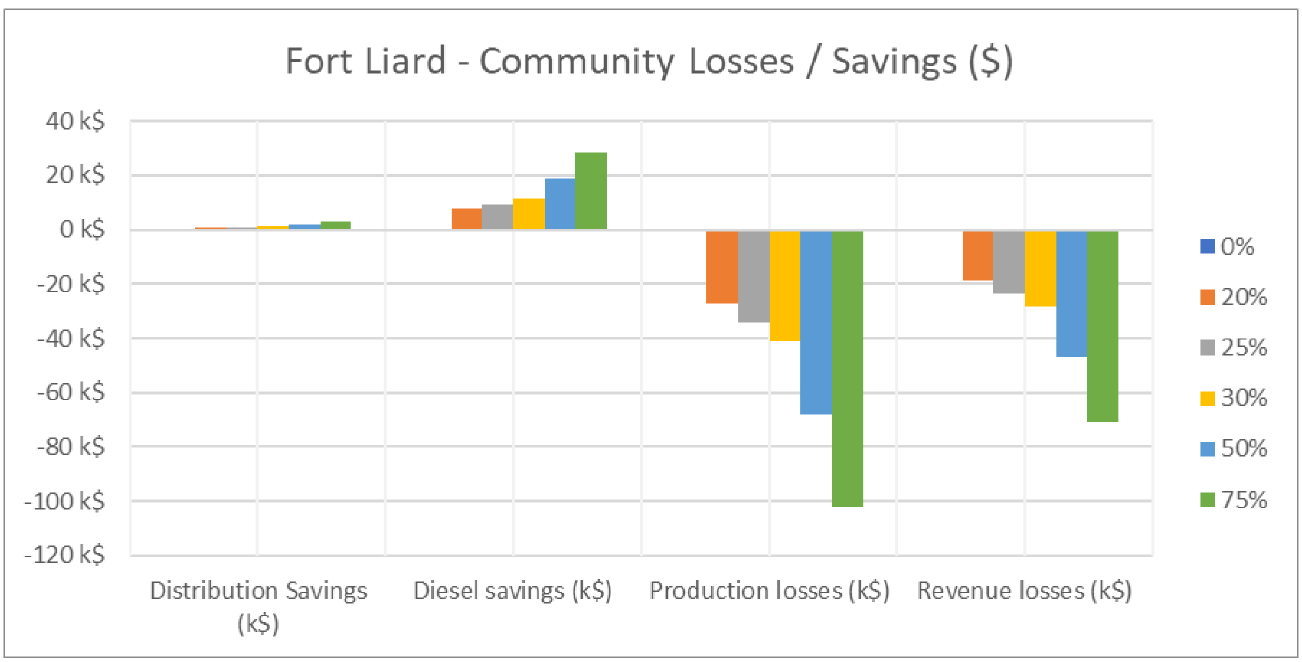


Figure 204: Losses Results – Fort Liard – Community Losses/ Saving ($)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Distribution savings (MWh)	0	0.9	1.1	1.3	2.1	3.0
Production losses (MWh)	0	-40	-49	-59	-99	-148
Total losses (MWh)	0	-39	-48	-58	-96	-145

Table 23: Detailed Losses (MWh) Information – Tulita

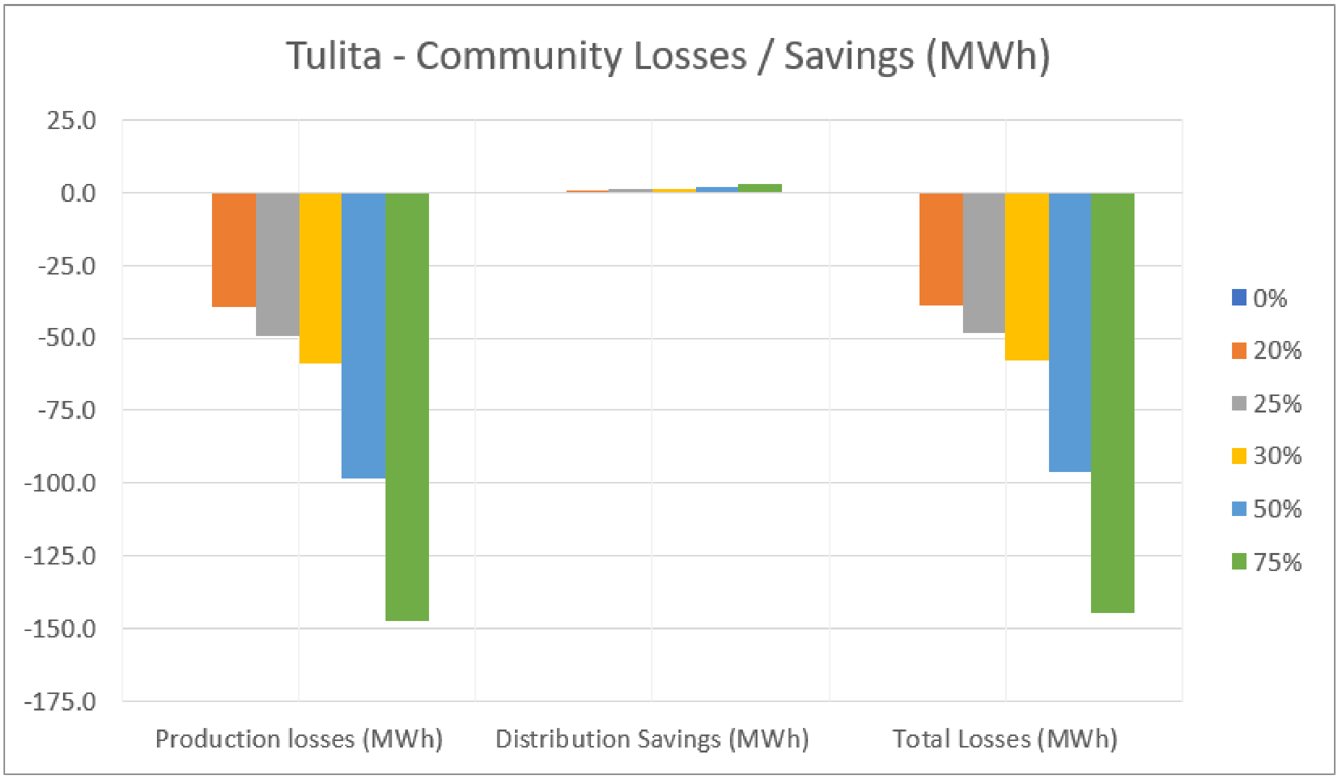


Figure 205: Losses Results – Tulita – Community Losses (MWh)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Diesel savings (k$)	0	10	12	15	24	36
Distributions savings (k$)	0	0.8	0.9	1.1	1.8	2.6
Production losses (k$)	0	-35	-43	-52	-87	-130
Revenue losses (k$)	0	-24	-30	-36	-61	-92

Table 24: Detailed Losses (k$) Information – Tulita

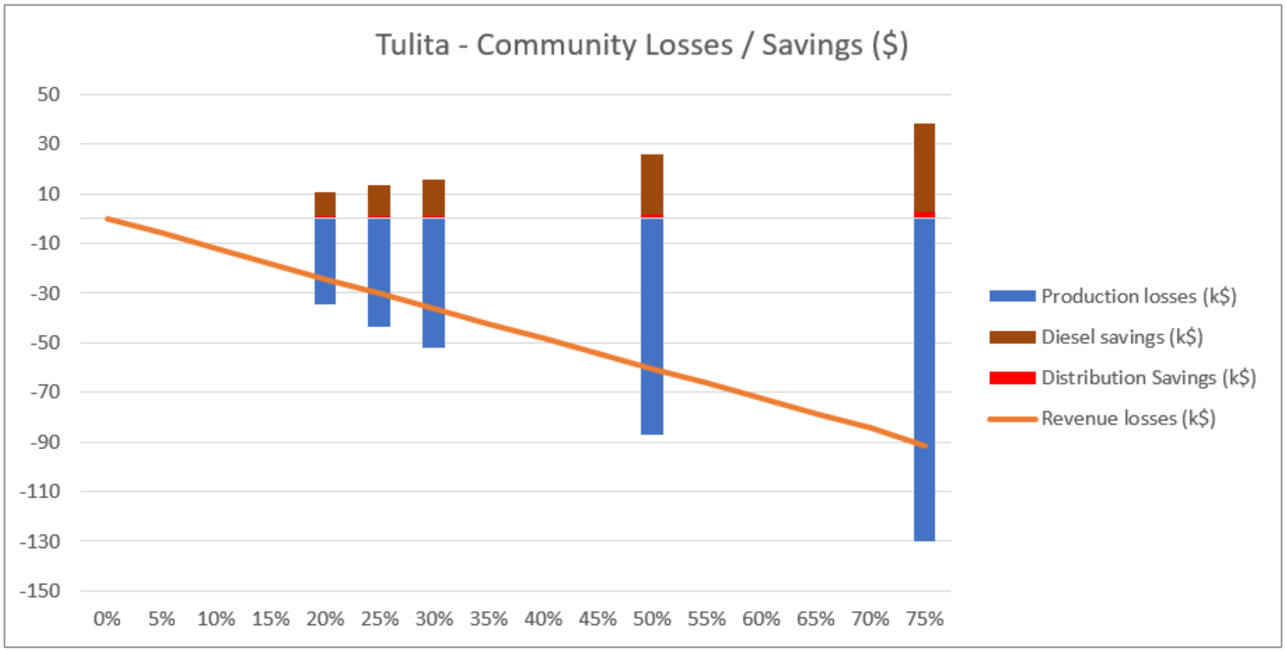


Figure 206: Losses Results – Tulita – Community Losses/ Saving ($)

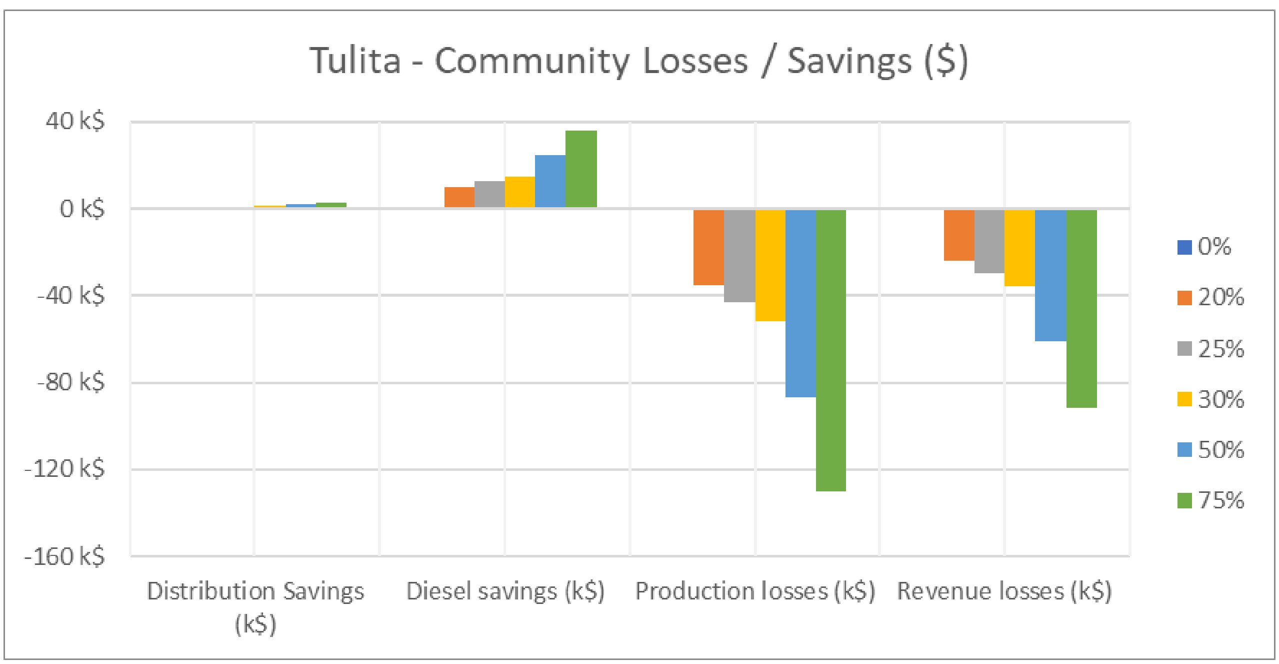


Figure 207: Losses Results – Tulita – Community Losses/Savings ($)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Distribution savings (MWh)	0	0.5	0.6	0.8	1.2	1.8
Production losses (MWh)	0	-26	-33	-39	-65	-98
Total losses (MWh)	0	-26	-32	-38	-64	-96

Table 25: Detailed Losses (MWh) Information – Lutselk'e

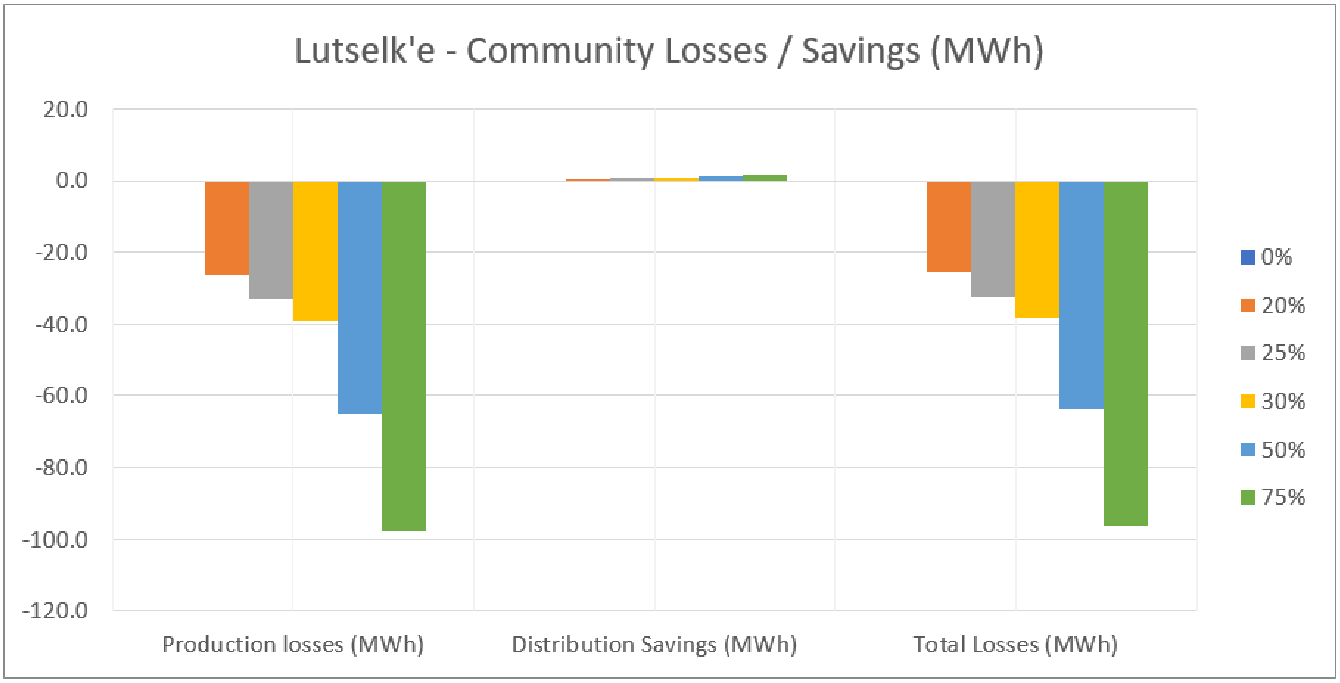


Figure 208: Losses Results – Lutselk'e – Community Losses (MWh)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Diesel savings (k$)	0	7	8	10	16	25
Distributions savings (k$)	0	0.5	0.6	0.7	1.1	1.6
Production losses (k$)	0	-23	-29	-35	-58	-87
Revenue losses (k$)	0	-16	-20	-24	-40	-61

Table 26: Detailed Losses (k$) Information – Lutselk'e

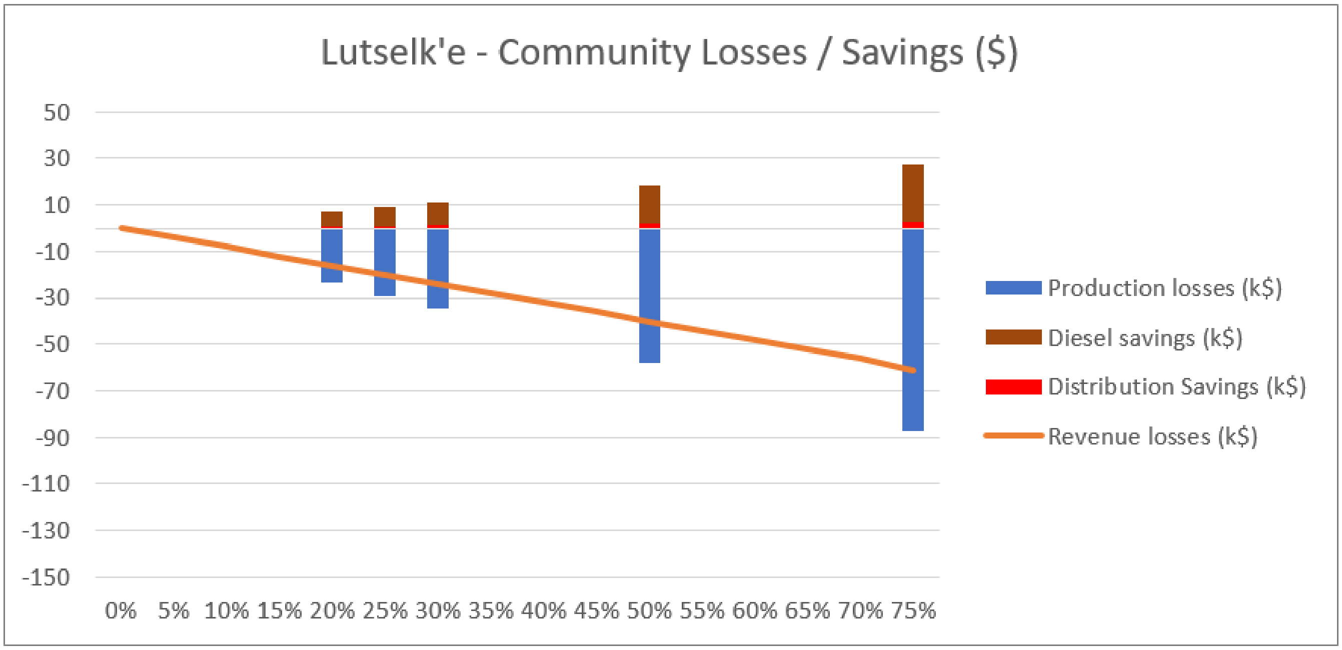


Figure 209: Losses Results – Lutselk'e – Community Losses/ Saving ($)

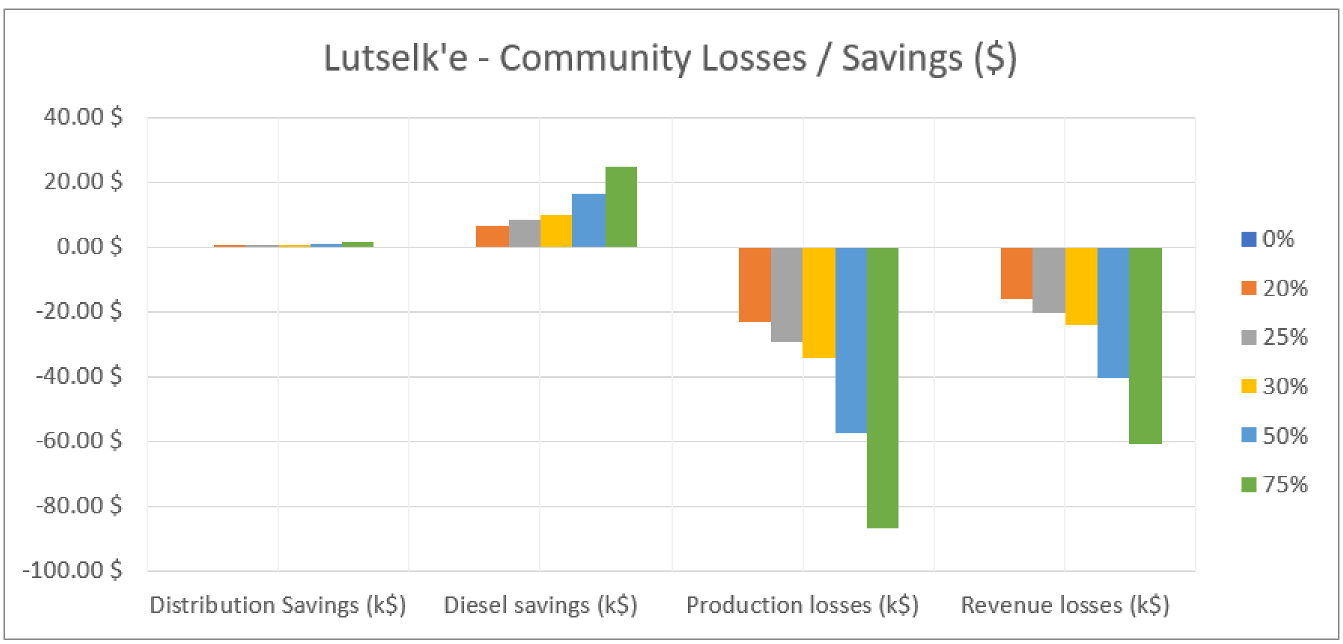


Figure 210: Losses Results – Lutselk'e – Community Losses/Savings ($)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Distribution savings (MWh)	0	5.1	6.3	7.5	12.1	17.4
Production losses (MWh)	0	-128	-159	-191	-319	-478
Total losses (MWh)	0	-123	-153	-184	-307	-461

Table 27: Detailed Losses (MWh) Information – Fort Simpson

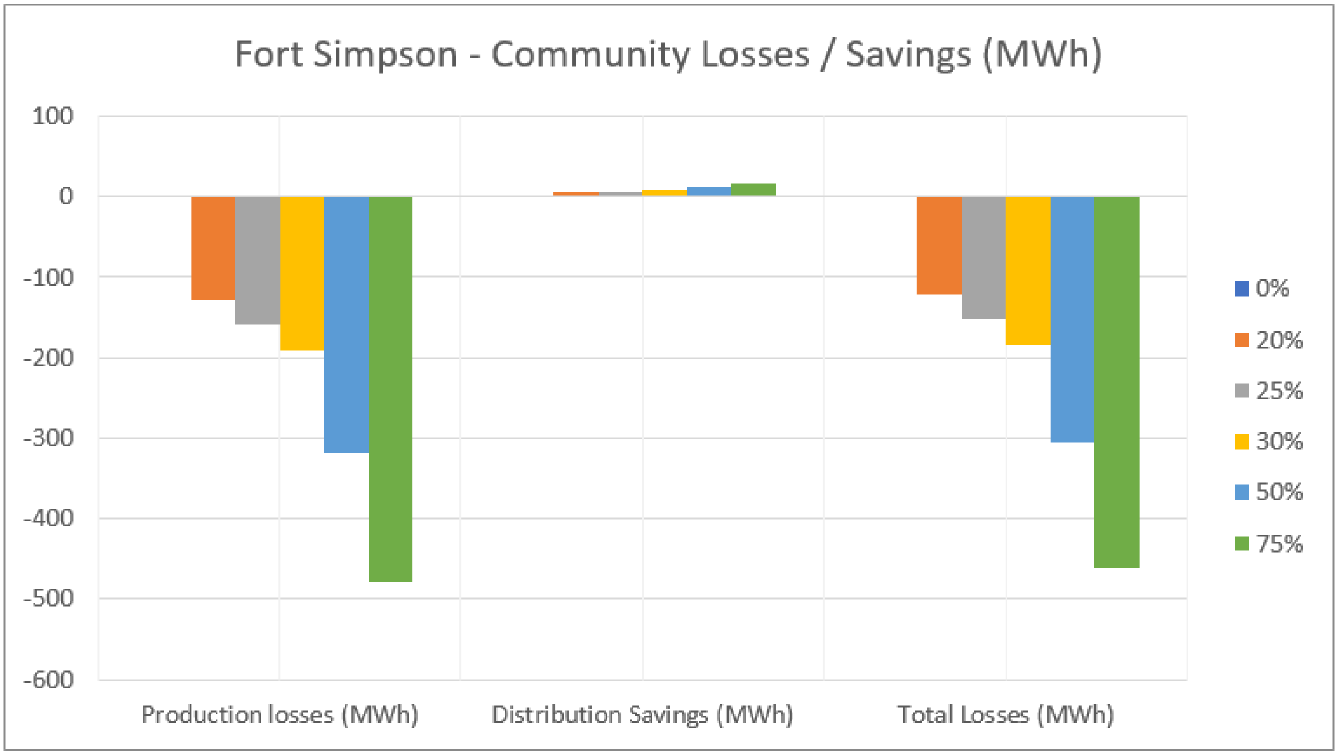


Figure 211: Losses Results – Fort Simpson – Community Losses (MWh)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Diesel savings (k$)	0	30	37	45	74	110
Distributions savings (k$)	0	4.5	5.6	6.7	10.7	15.5
Production losses (k$)	0	-113	-141	-170	-284	-425
Revenue losses (k$)	0	-79	-99	-119	-199	-299

Table 28: Detailed Losses (k$) Information – Fort Simpson

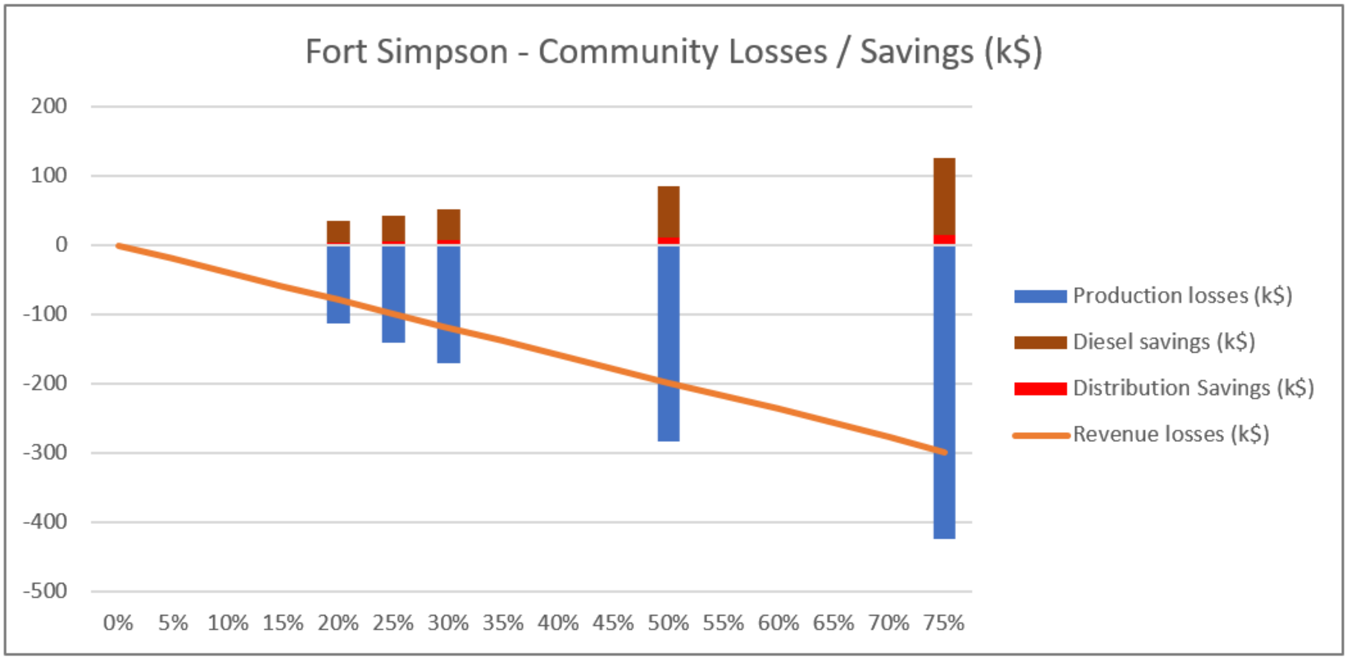


Figure 212: Losses Results – Fort Simpson – Community Losses/ Saving ($)

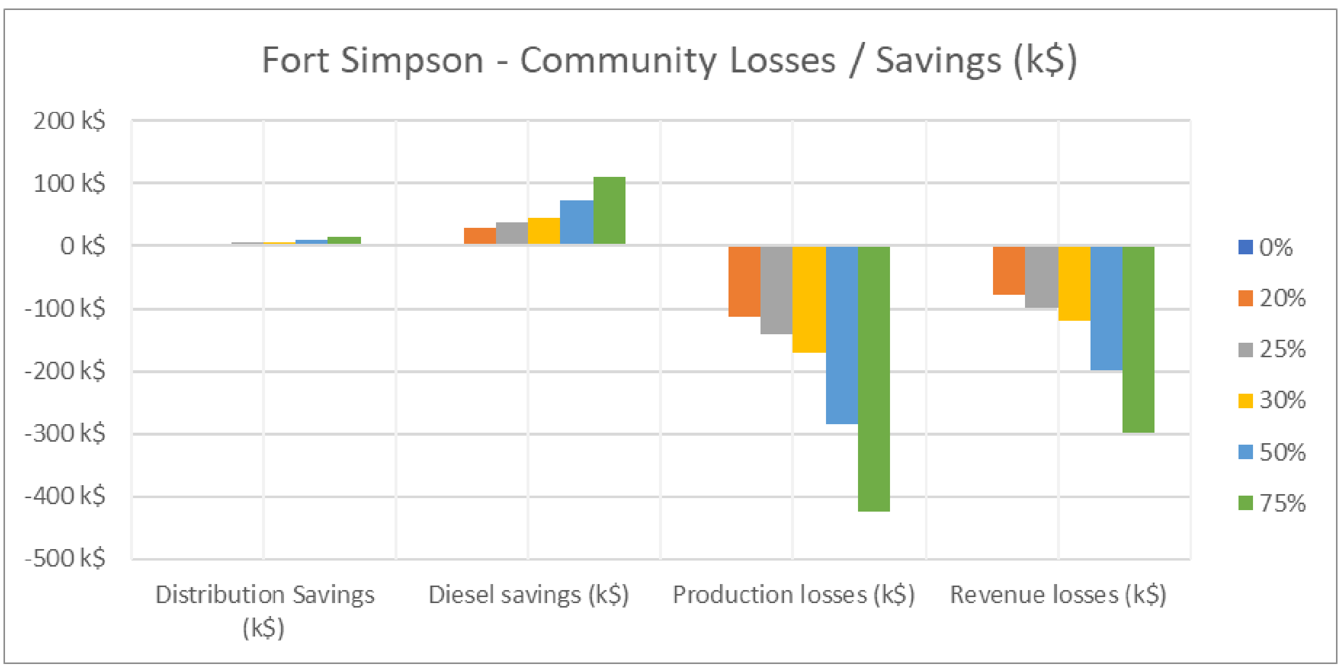


Figure 213: Losses Results – Fort Simpson – Community Losses/Savings ($)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Distribution savings (MWh)	0	20	25	30	49	70
Production losses (MWh)	0	-447	-559	-671	-1118	-1677
Total losses (MWh)	0	-427	-534	-641	-1069	-1607

Table 29: Detailed Losses (MWh) Information – Inuvik

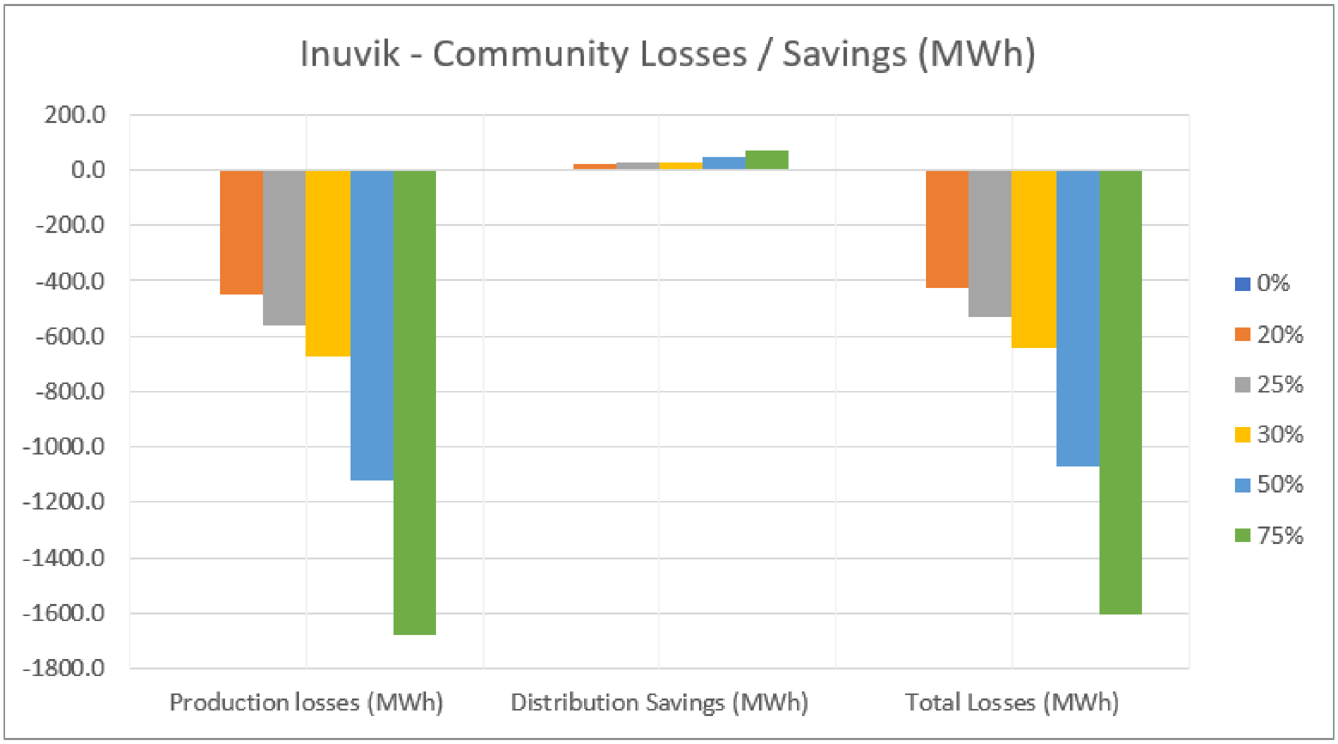


Figure 214: Losses Results – Inuvik – Community Losses (MWh)

	Renewable Energy Penetration (%)					
	0%	20%	25%	30%	50%	75%
Diesel savings (k$)	0	85	107	129	219	333
Distributions savings (k$)	0	15	18	22	36	51
Production losses (k$)	0	-326	-407	-489	-814	-1221
Revenue losses (k$)	0	-226	-282	-338	-560	-837

Table 30: Detailed Losses (k$) Information – Inuvik

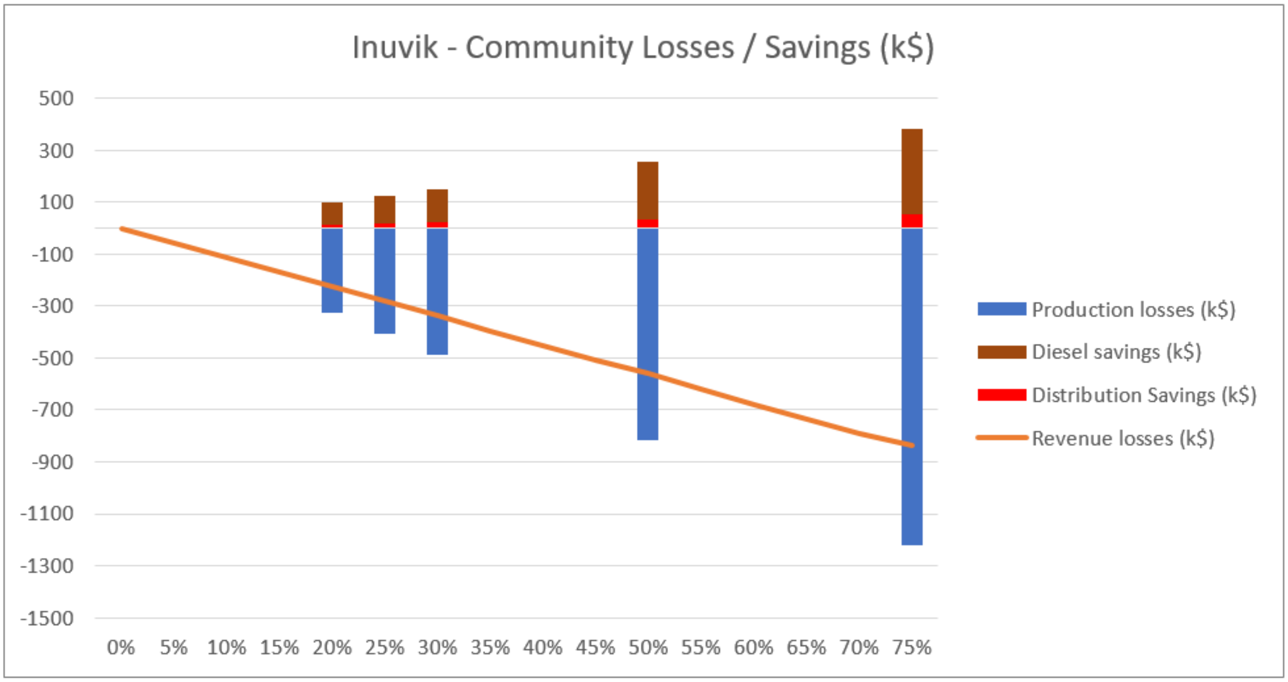


Figure 215: Losses Results – Inuvik – Community Losses/ Saving ($)

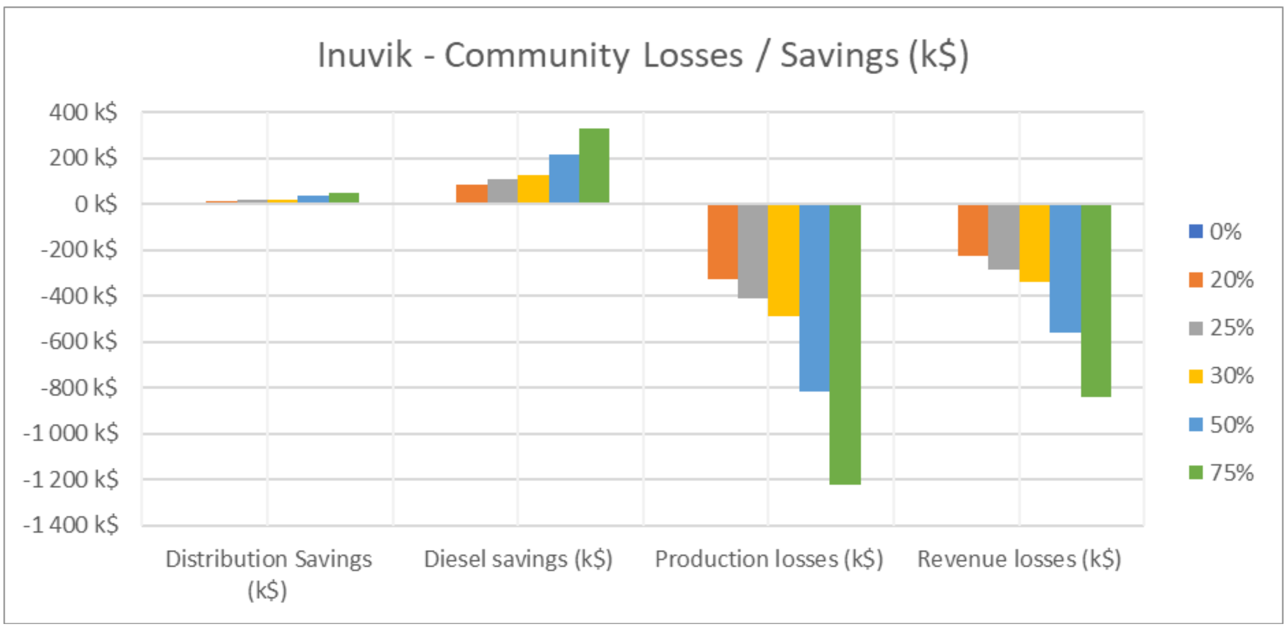


Figure 216: Losses Results – Inuvik – Community Losses/Savings ($)