Open Sea Operating Experience to Reduce Wave Energy Costs

Technical Note

Voltage and current data for IEC 62600-30 power quality monitoring from the Mutriku Wave Power Plant and Lir National Ocean Test Facility electrical laboratory

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EXECUTIVE SUMMARY

This Technical Note describes the electrical data collected from the Mutriku Wave Power Plant (MWPP) and the Lir National Ocean Test Facility (NOTF) electrical laboratory at the MaREI Centre in the Environmental Research Institute, at University College Cork.

In summary, the electrical data collect is for the purpose of analysing the power quality output of a Wave Energy Converter (WEC). The data includes voltage and current signals from the output of a WEC sampled at 15 kHz from the MWPP and a WEC emulator sampled at 20 kHz from the Lir NOTF electrical laboratory. There are 24 datasets from the MWPP taken at various sea state conditions, and there are 56 datasets from the Lir NOTF which are taken with at various sea state conditions, with different control laws, and grid connections.

This data is published for purpose of power quality analysis and comparison for future tests. For OPERA, power quality analysis was performed as part of WP5 T5.2 and T5.5, and presented in depth in Deliverables D5.2 and D5.4.

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ABBREVIATIONS AND ACRONYMS

H_s: Significant Wave Height
T_e: Energy Period

HIL: Hardware-in-the-Loop
MWPP: Mutriku Wave Power Plan
NI: National Instruments
NOTF: National Ocean Test Facility
OWC: Oscillating Water Column
PCC: Point of Common Coupling
PTO: Power Take-Off
PWM: Pulse-Width Modulation
SCADA: Supervisory Control and Data Acquisition
UCC: University College Cork
VFD: Variable Frequency Drive
WEC: Wave Energy Converter

1. DESCRIPTIONS OF ELECTRICAL SYSTEMS AND SCADA

This section briefly describes the electrical generation systems that were monitored and the SCADA systems installed to collect the datasets presented here.

1.1 MUTRIKU WAVE POWER PLANT

The MWPP is a fixed-type Oscillating Water Column (OWC) Wave Energy Converter (WEC) array. The OWC array consists of 16 chambers built into the breakwater protecting the harbour in Mutriku, Spain, which is located in the Basque Country along the Bay of Bisque. Each of the 16 OWC chambers has a two-stage Wells turbine and an 18 kW electrical generator that act as the Power Take-Off (PTO) system. Each OWC generator is controlled by an individual Variable Frequency Drive (VFD), which allows the turbines to operate efficiently over a wide range of sea state conditions. The VFDs feed into a DC-Bus, which is one of two within the plant. A single DC-bus accounts for 8 generators, and each DC-Bus supplies the grid though a 158 kW DC-AC converter that uses a variable frequency drive (VFD) to sync the AC out frequency with the local grid.

1.2 LIR NOTF ELECTIRCAL LABORATORY

The Lir NOTF electrical laboratory testing facilities are used to create generate the electrical datasets for power quality analysis include a WEC Hardware-in-the-Loop (HIL) emulator and an electrical microgrid. A brief description of the WEC emulator and the microgrid are presented in this section.

1.2.1 WAVE ENERGY EMULATOR

The medium speed rotary emulator at the Lir NOTF in UCC is an electromechanical system used to duplicate the rotating electrical power take-off (PTO) system of a renewable energy device. The emulator is composed of two electrical machines directly coupled by a mechanical shaft, with a torque transducer between them. The mechanical drive shaft also includes a stainless-steel flywheel that is connected to the system by a five-position gear box. The flywheel allows the drive shaft to be composed of one of five different inertial masses, which can be implemented to replicate the inertia of a system being tested. The prime mover, which is used to emulate the forces applied by the turbine, is a 4-pole Squirrel Cage Induction Machine (SCIM) with a rated power of 22 kW, a rated speed of 1467 rpm, and a rated torque of 143 Nm. The generator is a slip ring 4-pole induction machine with rated power of 22 kW, a rated speed of 1472 rpm, and a rated torque of 143 Nm. As described in [1], the generator rotor can be set in multiple configurations depending on the system which is being emulated. For the OPERA project, the rotor is configured as a SCIM. Both machines are controlled by a

Variable Frequency Drive (VFD), which allows for both speed and torque control of each machine.

The emulator is controlled by a HIL system that allows it to be fully integrated with software models running on the MATLAB® Simulink® platform. The conditions modelled in the Simulink® software are relayed to the emulator to drive its behaviour, and the conditions of the physical testing equipment are fed back into the Simulink® model to affect the model and complete the loop. The emulator-HIL integration was meticulously characterised and verified to ensure accuracy of the software-hardware link [2]. A Simulink model developed as part of OPERA WP4 was used with the HIL system to model a single OWC chamber of the MWPP to produce the datasets presented.

1.2.2 MICROGRID

The Lir NOTF microgrid is a dual bus (labelled as Bus A and Bus B), three-phase, 400 V system that can exist as an islanded system or in connection with the local 50 Hz grid. The microgrid has several sinks and sources. The microgrid dedicated source devices are the medium speed rotary emulator and a 33 kVA diesel generator. The microgrid dedicated sinks are a 10 kW adjustable resistive load bank and a 50 kVA resistive and reactive load bank with adjustable power factor. There are also three Pulse-Width Modulation (PWM) based power converters: A 90 kW voltage control converter that can be used to adjust grid conditions, including frequency and line voltage. Along with the voltage controller, there are 15 kW current control converters, one connected to a small battery bank to act as a power storage unit, current control converter connected to the local grid, which can act as an unlimited, flexible source or sink as needed. Two different experimental configurations were utilized during the laboratory testing used for verification of the model and data set expansion. The configurations included a strong grid and a weak grid and are described below.

1.2.2.1 STRONG GRID CONFIGURATION

The configuration for the strong grid testing was a simple set up using the local 400 V, 50 Hz grid feeding the Lir NOTF as the source grid. The generator was connected through the microgrid Bus A directly to the local grid with nothing else connected to the microgrid. The voltages and currents for all three phases were measured and recorded. The configuration is illustrated in Figure 1 below.

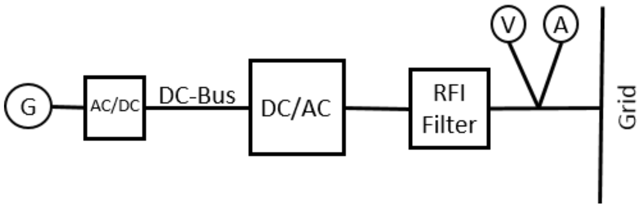

FIGURE 1. LIR NOTF MICROGRID SINGLE LINE DIAGRAM FOR STRON GRID CONFIGURATION, INCLUDING THE PLACEMENT OF THE VOLTAGE AND CURRENT TRANSDUCERS.

1.2.2.2 WEAK GRID CONFIGURATION

The configuration for monitoring power quality on a weak grid was more complex than the strong grid testing and required several elements of the microgrid. As with the strong grid tests, the weak grid configuration was maintained by the microgrid. The main power source for the weak grid testing was the 33 kVA diesel generator, resulting in a weak grid as the power rating of the MEC is approximately 65% of the main generating source. An electrical load of 25 kW with a power factor of 1.0 was used as the sink on the microgrid to both induce a current from the diesel generator and ensure that all power generated by the MEC was consumed within the islanded grid. Figure 2 below illustrates the weak grid configuration.

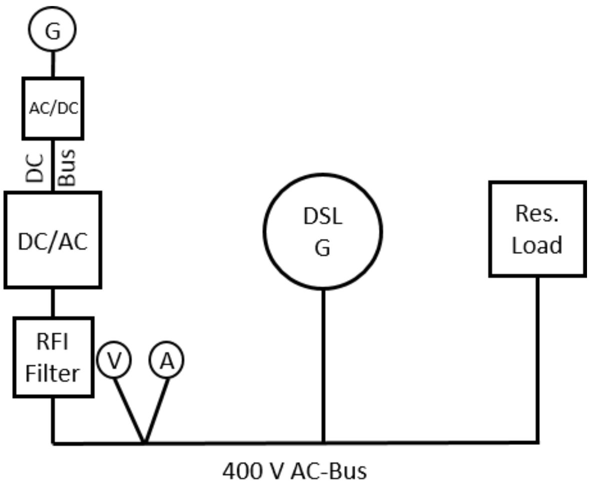

FIGURE 2: LIR NOTF MICROGRID SINGLE LINE DIAGRAM FOR WEAK GRID CONFIGURATION, SHOWING THE PLACEMENT OF THE VOLTAGE AND CURRENT TRANSDUCERS.

1.3 SCADA SYSTEMS

The main processing unit of the SCADA was a National Instruments (NI) cRIO-9082 operating NI Labview software. The cRIO-9082 is an 8-slot cRIO with a 1.33 GHz dual-core CPU, 2 GB of DRAM, 32 GB of ROM, and a Xilinx Spartan-6 LX150 FPGA. Both the MWPP and the Lir NOTF employed cRIO-9082s, but some of the subsidiary equipment differed between the two test sites.

1.3.1 MUTRIKU SCADA SYSTEMS

For data collection at the MWPP, the cRIO was populated with NI-9239 analogue input modules with a voltage measuring range of -10 to 10 Volts. Each NI-9239 card measured 3 signals, and as a result, the maximum sampling rate was set for 15 kHz. The voltages and currents were measured using current and voltage transducers that, in conjunction with high tolerance resistors, produced voltage signals within the measuring range of the NI-9239 cards. The voltage transducers were LEM DVL 750, which provide bipolar and insulated measurement up to 1125 V, and the current transducers were LEM LA 305-S, what are Hall Effect closed loop transducers, with a maximum range of +/- 500A.

The SCADA system installed at the MWPP had to be retrofitted into the electrical cabinets of the plant, which led to some necessary compromises in signal measurement. As is common for grid VFD-based renewable energy generating systems, a radio-frequency inference (RFI) filter separates the output of the grid connected VFD-based DC-AC converter from the local grid, which is used to attenuate the high frequency switching from VFD. The current transducers could not be physically fitted to the grid side of the RFI filter, and as a result the signal monitored by the SCADA system at the plant were located on the converter side of the filter rather than the point of common coupling (PCC) between the plant and the grid. Additionally, the voltage measurements were line-to-line voltage rather than line-to-neutral at the MWPP because there was no available neutral line on the DC-AC converter side of the RFI filter. This SCADA configuration represented a departure from the Lir NOTF SCADA system, which had the voltage and current transducers located on the grid side of the RFI filter and measured the voltage from line-to-neutral. Figure 3 is a single-line diagram of the MWPP and includes the placement of the current and voltage meters.

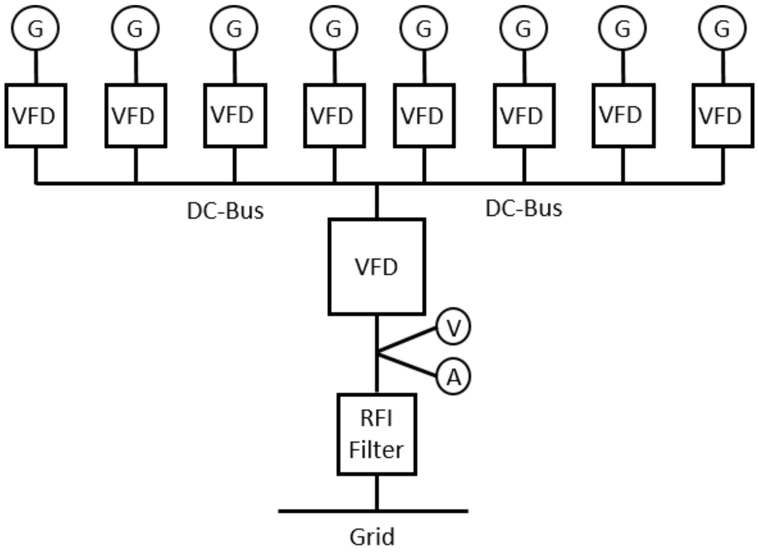

FIGURE 3. MWPP SINGLE LINE DIAGRAM SHOWING THE PLACEMENTS OF THE VOLTAGE ADN CURRENT TRANSDUCERS.

1.3.2 LIR NOTF SCADA SYSTEMS

The SCADA system of the Lir NOTF electrical laboratory is installed within the microgrid The cRIO installed in the microgrid included NI-9225 cards rated for 300 V-RMS and NI-9239 cards with a voltage measuring range of -10 to 10 Volts. The NI-9225 cards were used to measure the line-to-neutral voltage at the point of common coupling (PCC) between the grid and the DC-AC converter output of the medium speed rotary emulator. The NI-9239 cards were monitoring the output of the current transducers for each of the three phases of the converter. The current transducers installed within the microgrid were LEM LA 55-P with a current range of 0 to 50 A. The output of the current transducers were analogue current signals with a step-down ratio of 1000:1. The cRIO was fit with high tolerance resistors rated to LEM specification to produce a voltage that could be monitored by the cRIO NI-9239 cards. The data was collected at a sampling frequency of 20 kHz for 10-minute windows for each laboratory generated dataset. Figure 1 and Figure 2 show the placement of the current and voltage meters within the Lir NOTF microgrid set up.

2. DESCRIPTION OF THE DATASETS AND DATA STRUCTURE

The datasets are structured as Comma Separated Variable (.csv) files. There are a total of 80 datasets arranged in .csv files, with 24 generated from sea trials at the MWPP and 56 generated in the Lir NOTF electrical laboratory. Each separate .csv file represented a 10-minute testing period, as required by the IEC 62600-30 technical specification.

Each dataset includes 7 columns with numerical data.

- Column 1 is sample time and represented in seconds (s);
- Columns 2 through 4 are current values and represented in amps (A);
- Columns 5 through 7 are voltage values and represented in volts (V).

The columns do not include headers in the .csv files, so the headers are provided in this section. This section also provides the sea state summary statistics required by the IEC 62600-30 for categorizing the sea conditions and sample datasets to better articulate the data available for download. This section is subdivided by data origin.

2.1 MUTRIKU WAVE POWER PLANT DATA

There are 24 datasets in total collected from the MWPP, which were sampled at 15 kHz. The data was collected over a 4-month period in early 2018. Table 1 give the date and summery sea state conditions for each of the 24 datasets. The file naming structure of the Mutriku datasets was selected to give the information in Table 1 for convenience.

The structure is as follows OPERA_Mutriku_[YYYMMDD]_[H_s]_[T_e].csv.
For example: OPERA_Mutriku_20180216_3.22_16.19.csv is a dataset from 16 February 2018 with a significant wave height of 3.22 m and an energy period of 16.19 s.

TABLE 1. DATE AND SUMMERY SEA STATE CONDITIONS FOR THE DATASETS COLLECTED AT THE MWPP.

Mutriku Wave Power Plant Dataset Information								
Date	H_s (m)	T_e (s)	Date	H_s (m)	T_e (s)	Date	H_s (m)	T_e (s)
07/02/2018	2.74	15.54	16/02/2018	3.22	16.19	28/02/2018	0.54	8.06
08/02/2018	2.23	14.33	16/02/2018	4.14	16.81	02/03/2018	1.33	12.53
10/02/2018	3.35	15.65	17/02/2018	2.62	14.31	07/03/2018	1.09	10.12
10/02/2018	3.69	15.68	23/02/2018	0.90	13.03	08/03/2018	0.69	10.81
11/02/2018	1.86	13.61	25/02/2018	1.39	16.43	11/03/2018	0.50	17.80
12/02/2018	2.66	13.28	25/02/2018	1.58	15.51	12/03/2018	1.00	11.55
13/02/2018	1.93	15.05	26/02/2018	0.94	13.34	13/03/2018	2.11	12.89
14/02/2018	2.64	13.65	27/02/2018	0.74	9.98	17/03/2018	2.41	13.85

The datasets from the MWPP include a timestamp that begins at 0 seconds, the current measurement for all three phases individually in Amperes (A), and the phase-to-phase voltages across each of the three phases in Volts (V). As the datasets do not contain column headings, the appropriate column headings are provided in Table 2.

TABLE 2. COLUMN HEADING FOR MUTRIKU WAVE POWER PLANT DATASETS

1	2	3	4	5	6	7
Time (s)	Current (A)			Voltage (V)		
	L1	L2	L3	L1-L2	L2-L3	L3-L1

Sample data is produced in Table 3 and Figure 4. In Figure 4, the effects of having the transducers placed between the VFD and the RFI filter can be observed in the strength of the high frequency signals for both current and voltage.

TABLE 3. TEN ROWS OF SAMPLE DATA FROM THE MUTRIKU WAVE POWER PLANT.

Time (s)	Current (A)			Voltage (V)		
	L1	L2	L3	L1-L2	L2-L3	L3-L1
1	269.71	-186.26	-89.545	-697.32	63.315	629.17
1.0001	269.37	-171.7	-101.95	-715.52	2.37	714.03
1.0001	286.6	-137.12	-149.88	-645.53	8.505	629.03
1.0002	288.12	-140.31	-146.98	-713.99	82.665	633.16
1.0002	273.41	-158.01	-105.13	-688.23	688.59	2.43
1.0003	248.76	-156.38	-89.81	-309.23	311.19	-0.165
1.0003	240.69	-173.82	-64.71	-699.96	716.9	-20.97
1.0004	261.74	-161.86	-97.85	-712.59	28.365	673.5
1.0004	266	-133.75	-133.28	-434.66	-0.555	444.38
1.0005	285.08	-123.11	-165.94	-703.05	-8.37	706.29

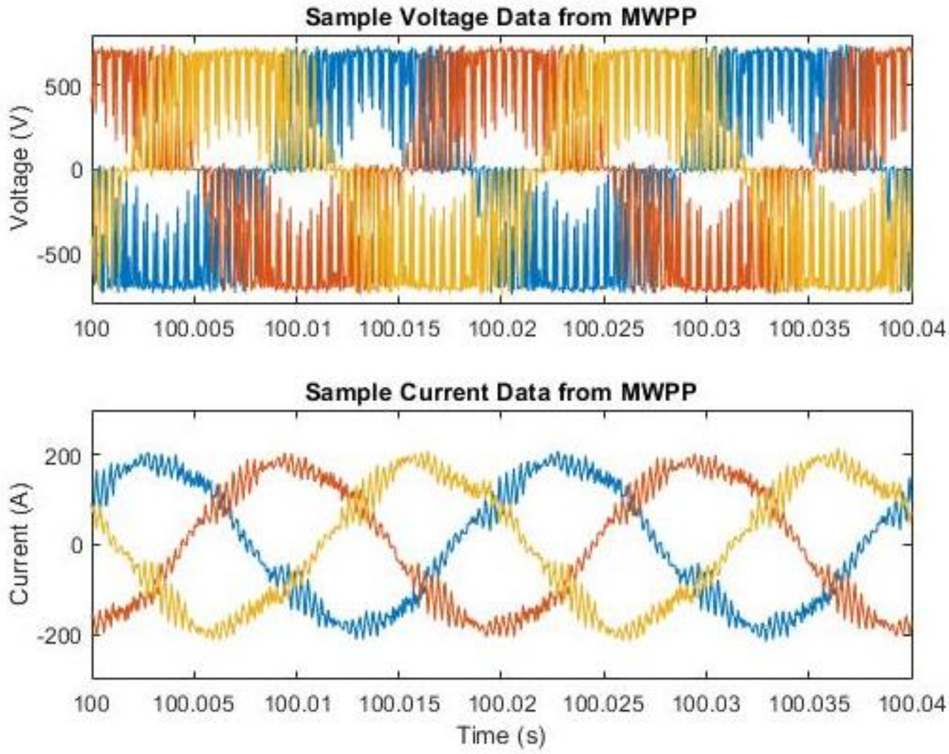

FIGURE 4. SAMPLE DATA FROM THE MUTRIKU WAVE POWER PLANT

2.2 LIR NATIONAL OCEAN TEST FACILITY DATA

There are 56 datasets generated using the Lir NOTF WEC emulator and microgrid. Which were sampled at 20 kHz. The datasets are further split into 4 subsets of 14, with the 14 datasets in each subset occurring under different sea state conditions. As in Section 2.1, the summary statistics for the 14 sea states are given in Table 4. As this was laboratory generated data, there are no dates associated with the datasets, but they are numbered for convenience because they are repeatedly tested under four different conditions. The file naming structure of the Lir NOTF datasets was selected to give general information of the dataset in Table 4 plus the operating control law and grid strength for convenience. The sea state conditions are based on the Dataset number. The file naming structure is as follows OPERA_LirNOTF_[Dataset]_[Control Law]_[Grid Strength].csv. For example: OPERA_LirNOTF_SS07_CL1_StrongGrid.csv is from dataset with sea state 7 and a strong grid connection.

TABLE 4. SUMMARY SEA STATE CONDITIONS OF DATA GENERATED AT LIR NOTF ELECTRICAL LABORATORY.

Sea State Summary Statistics for Lir NOTF Generated Data					
Dataset	Hs (m)	Te (s)	Dataset	Hs (m)	Te (s)
1	0.88	5.50	8	1.81	12.50
2	1.03	6.50	9	2.07	13.50
3	1.04	7.50	10	2.11	12.50
4	1.02	8.50	11	2.59	14.50
5	1.08	9.50	12	2.88	15.50
6	1.19	10.50	13	3.16	16.50
7	1.48	11.50	14	3.20	11.50

The datasets from the Lir NOTF lab include a timestamp that begins at 0 seconds, the current measurement for all three phases individually in Amperes (A), and the phase-to-neutral voltages across each of the three phases in Volts (V). As the datasets do not contain column headings, the appropriate column headings are provided in Table 5.

TABLE 5. COLUMN HEADING FOR MUTRIKU WAVE POWER PLANT DATASETS

1	2	3	4	5	6	7
Time (s)	Current (A)			Voltage (V)		
	L1	L2	L3	L1-N	L2-N	L3-N

The 4 subsets of tests are arranged by grid configuration and generator control law. The grid configurations are briefly explained in Section 1.2.2. The generator control law refers to the method deployed to control the turbine-generator set of the OWC. Control laws CL1 and CL2 from [3]. For more information about the control laws used to generate these datasets, please refer to [3].

Sample data from strong grid testing is produced in Table 6 and Figure 5, and for weak grid testing in Table 7 and Figure 6. In Figure 5 and Figure 6, the effects of having the transducers placed between the VFD and the RFI filter can be observed in the strength of the high frequency signals for both current and voltage.

TABLE 6. TEN ROWS OF SAMPLE DATA FROM THE LIR NOTF STRONG GRID TESTING

Time (s)	Current (A)			Voltage (V)		
	L1	L2	L3	L1-L2	L2-L3	L3-L1
1	-8.17	18.31	-7.77	263.29	41.98	-306.14
1.0001	-10.03	16.71	-10.29	260.08	48.29	-308.52
1.0001	-13.39	14.85	-5.23	257.61	52.01	-309.50
1.0002	-9.93	17.01	-4.77	256.70	61.28	-308.94
1.0002	-7.92	20.94	-9.14	256.28	67.39	-315.65
1.0003	-14.81	13.26	-5.65	245.74	69.33	-312.96
1.0003	-10.60	17.50	-5.34	247.45	77.49	-316.10
1.0004	-10.43	16.42	-6.26	240.94	82.72	-318.04
1.0004	-11.21	15.97	-9.59	236.97	86.90	-323.44
1.0005	-15.05	10.42	-0.42	228.27	89.69	-317.48

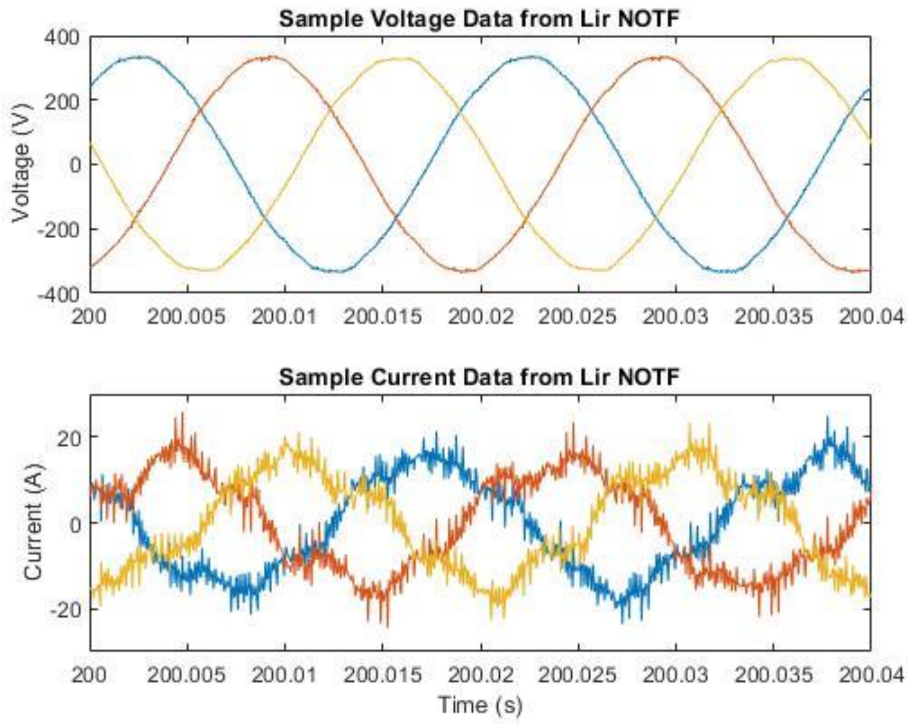

FIGURE 5. SAMPLE DATA FROM LIR NOTF STRONG GRID TESTING

TABLE 7. TEN ROWS OF SAMPLE DATA FROM THE LIR NOTF WEAK GRID TESTING

Time (s)	Current (A)			Voltage (V)		
	L1	L2	L3	L1-L2	L2-L3	L3-L1
1	-9.39	8.65	2.63	-217.78	336.34	-86.66
1.0001	-7.45	8.95	2.52	-237.22	321.85	-75.64
1.0001	-7.72	8.31	2.29	-238.92	318.50	-83.73
1.0002	-8.51	7.07	1.98	-253.11	309.74	-56.48
1.0002	-9.48	6.03	1.01	-230.76	329.82	-73.79
1.0003	-10.85	4.91	2.71	-250.33	316.46	-44.58
1.0003	-8.89	5.98	3.98	-227.37	330.98	-42.63
1.0004	-7.05	6.65	4.27	-232.87	327.09	-32.04
1.0004	-6.59	6.09	3.35	-235.92	317.51	-40.86
1.0005	-7.85	4.52	3.57	-252.95	302.44	-52.81

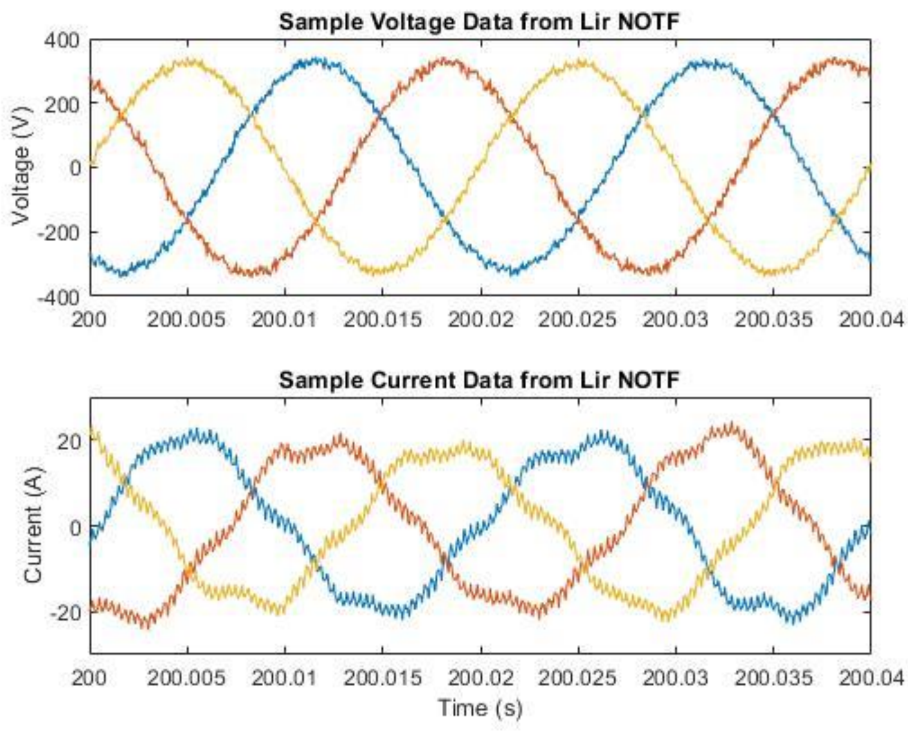

FIGURE 6. SAMPLE DATA FROM LIR NOTF WEAK GRID TESTING

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