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Design of a Massively Open Online Course on Electrical Microgrids with Real Datasets

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Abstract

Smart Grids represent one of the most suitable and relevant applications in a sustainable scenario, where it is of high importance to provide electricity to millions of customers using advance technology and efficient methods. Microgrids are key subsystems forming the Smart Grid. Microgrid infrastructure may be seen as a combination of information technology and equipment, becoming a target for cybersecurity attacks, vulnerable both in software and hardware. In research areas associated with Smart Grids and Microgrids, the U.S. National Science Foundation (NSF) has offered support for projects for workforce development and research in cybersecurity, state estimation and optimization in electrical microgrids through several programs. Further research is needed specially using real dataset. Also, in a post-pandemic scenario, the design and implementation of MOOCs became a valuable tool to reach students and professionals around the world. This paper focuses on the description of the elements associated with the design of a Massive Open Online Course (MOOC) on Microgrid State Estimation, Optimization and Cybersecurity as well as the presentation of the generalities related to MATLAB simulations that will be part of the MOOC. For the present study, the simulations for cybersecurity cover the utilization of real dataset associated with the electrical power system of the Dominican Republic by means of deep learning tools offered by the MATLAB software. All this relevant research work has been funded by the Engineering Postdoctoral Fellowship eFellows program, administered by the American Society of Engineering Education (ASEE), funded by the National Science Foundation (NSF). The MOOC is planned to be offered as a free resource for the community. The real datasets used for the Cybersecurity simulations will be available in an Open Science website.

1. Introduction

1.1 MOOCs in Electrical Microgrids

Electrical microgrids are denominated as a fundamental building block of electrical power systems. The US Department of Energy has expressed that multiple efforts will be made with the aim of making microgrids an important element as part of the electricity delivery system, increasing its resilience and reliability [1].

Massive Online Open Courses (MOOCs) represent a powerful tool for learning purposes. MOOCs are courses offered with the aim of covering specific topics for students and professionals in different fields of study. Since electrical microgrids have become one of the most important components of smart grids, the study of these systems is of extreme relevance. As a consequence, the design of a MOOC to cover the basis of cybersecurity, state estimation and optimization in electrical microgrids constitutes a good step towards offering a mechanism of study and analysis for academics and for industry capacity building.

The MOOC related to Cybersecurity, State Estimation and Optimization in electrical microgrids designed by the authors of this paper include the following learning outcomes:

- Simulate, analyze and adapt algorithms related to Cybersecurity, State Estimation and Optimization in Microgrids, by designing and writing Python and MATLAB codes.
- Analyze a power management model for community microgrids.

The objectives of the MOOC are presented below:

- Describe the fundamental components and characteristics of electrical microgrids.
- Analyze the features related to cybersecurity, state estimation and optimization for microgrids.
- Explain the basics of community microgrids.
- Simulate algorithms in Python and MATLAB related to microgrids.
- Simulate power management control algorithm for community microgrids.
- Outline the principal cybersecurity risks and possible mitigation actions.
- Identify and use appropriate techniques utilized for microgrid state estimation.
- Outline various methods used for microgrid optimization.

The MOOC designed by the authors of this paper is divided into several modules (Introduction to Electrical Microgrids, Cybersecurity, State Estimation, Optimization and Community Microgrids) and designed for undergraduate and graduate engineering students. An issue encountered when designing this MOOC is the difficulty to find real datasets to include as part of the different simulations or laboratories that the MOOC can cover. The theory is presented in the different modules and students interact with assignments and simulations associated with Cybsersecurity, Optimization and State Estimation. Algorithms are created based of scenarios for stand-alone microgrids. The MOOC is designed by a team of three engineers with the formation and the experience in this area of study. Real datasets associated with the electrical power system of the Dominican Republic will be available to course takers via the Open Science platform [2]. Also, student assessment will be included for every module.

This paper presents the outcomes and objectives of the MOOC, listing the content of the online course as well as some of the results for laboratories or simulations in cybersecurity, optimization and state estimation that have been included as part of the MOOC. The real datasets used in the simulations for cybersecurity have been made available through the Latin American and Caribbean Consortium of Engineering Institutions (LACCEI) Open Science database.

1.2 Cybersecurity in Microgrids

The main requirements for cybersecurity in Microgrids and in general for electrical power systems are availability, confidentiality and integrity [3]. Distorted data represents one case of cyber-attacks. False data introduced to the communication systems will mislead the microgrid's control elements and the decisions made by this control subsystem will be devastating to the desired optimal performance of the power network. The microgrid operation may turn into an insecure or emergency operation for those cases where the physical portion of the system and/or the cyber portion are compromised. It is of extreme importance to continue creating algorithms that students from different levels can learn to use to analyze the presence of cyber-attacks to electrical microgrids, using available engineering software tools such as MATLAB [4].

1.3 Optimization in Microgrids

Optimization in microgrids is of high relevance [5][6] since power flow is in need of being optimized with the aim of achieving the best technical and economic performance. Usually, the optimization problem is defined through an objective function subject to constraints. The objective function may be defined in terms of operational cost associated with the power generated by each one of the energy sources present in the system. On the other hand, the constraints are expressed in terms of minimum or maximum power generation capacities, power losses, among other parameters. MATLAB represents an engineering tool used to run simulations to optimize microgrid performance.

1.4 State Estimation in Microgrids

State estimation is a critical process for any power system since the resulting parameters of the estimation will allow the network manager to obtain a description of the state of the network in terms of its electrical variables. Voltage and phase angles are among the main parameters to calculate as part of the estimation method. Traditionally state estimation has been supported by the SCADA (supervisory, control and data acquisition) system, where the quantification of the different electrical variables takes place. Sensor transducers, hardware elements and software applications play a vital role to obtain the measurements of distinct numeric data associated with voltage, current, active power, etc.

The microgrid configuration and model are combined with the data for the purpose of determining the operating conditions of the network. The state estimator is the computational procedure that is implemented to obtain the estimate of the state of the microgrid. This estimator takes into consideration some measurements (i.e., active power, reactive power, voltage and current) and the objective is to find the voltage phasors (magnitude and phase) at all buses. Usually, one bus is selected as reference (voltage phase at this bus denoted as zero).

The weighted-least square (WLS) method is a very well know method utilized for state estimation. Here the state variables such as voltage and phase angles are calculated through the minimization of the square of the error for all measurements. According to [7] the measurement vector is defined as:

$$z = h(x) + e \tag{1}$$

where z is the measurement vector, h is the matrix with nonlinear power flow equations, x represents the state variables and e is the error vector. The WLS method seeks for the minimization of the sum of the squares of the weighted difference between the measured and true value.

2. Methodology

2.1 Methodology for the Design of the MOOC

The content of the MOOC will utilize several technological tools for the development of examples and practical problems associated with the study of Cybersecurity, State Estimation and Optimization for microgrids. The course will represent next generation MOOC centered on artificial intelligence tools for simulations. The following tools and methodologies are utilized as part of the course:

- Python: this is an object-oriented programming language [13]. Thousands of applications in Engineering are based on Python, with the purpose of data analysis and building websites.
- Machine learning: it is based on the use of data and algorithms to imitate human behaviour [14].
- Deep learning: it is focused on techniques for teaching computers to learn by example [15].
- Jupyter Notebook: web application for creating and sharing computational documents [16].
- Data Analytics: science centered on data analysis to make conclusions about given information [17].
- MATLAB: software used in the engineering field for calculations and simulations [4].

The content related to the MOOC comprehends three main items. The first component is represented by the syllabus, the second item is linked to the course content and the third element covers the simulation results by using Python and MATLAB. For the syllabus it is relevant to include the following information:

- Course Title- Cybersecurity, State Estimation and Optimization in Electrical Microgrids.
- Course Modality- online MOOC
- Course description- the course covers the general analysis and some software applications associated with electrical microgrids Cybersecurity, State Estimation and Optimization. Simulations using MATLAB and Python will be studied as part of the MOOC.
- Content (Introduction to Electrical Microgrids, Cybersecurity, State Estimation, Optimization and Community Microgrids).

The MOOC it's been developed during two years timeline. The main motivation lies in the recent opportunity provided by the National Science Foundation through the e-fellows program [18]. Additionally, one of the authors of this paper participated as part of the NSF CyberTraining Project focused on Data Centric Security and Resilience of Cyber-Physical Energy Infrastructures (2021-2022) [19]. The author encountered the necessity of continuing with the development of interactive tools for the evaluation of microgrids. The first year of the MOOC design process was devoted to training in programming in Python and PHP, data analytics (DA) and machine learning (ML), deep learning (DL), refining training in MATLAB, and literature review in State Estimation, Optimization and Cybersecurity issues in Microgrids. Furthermore, the identification of datasets has been part of the design process. Research will continue the second year with a focus on the design of the MOOC. The free access Massively Open Online Courses (MOOC) will be taken by students who manifest interest in the study of microgrid operation and the role that these microgrids play for secure and optimal performance of energy grids.

Next the methodology for the design of the laboratories or simulations in MATLAB for Cybersecurity, State Estimation and Optimization are presented.

2.2 Methodology for Cybersecurity Simulations

The algorithm associated with cybersecurity has been implemented using the MATLAB tools and libraries for Artificial Intelligence (AI). Most AI areas use Machine Learning and Deep Learning. Deep Learning is an area that incorporates Machine Learning, where several layers are implemented in a network in order to process information and infer patterns. The Machine Learning (ML) philosophy is based on providing to the ML algorithm the test data and the answers and once trained the algorithm will decipher the rules that relate the data and the corresponding results. Real datasets associated with the operation of the electrical power system in Dominican Republic were used for the simulations in cybersecurity. Some data points were modified to model an attack condition in the electrical system. MATLAB classification learner tool was utilized to run the simulation. The classifier will train the network. The predictors are the electrical line current for each phase (A, B, C), the electrical line voltage for each phase (A, B, C) and the energy consumption in kWh. The network is a classification tree type. At the end the MATLAB tool classify test data into one of two scenarios defined as attack and normal operation. The step-by-step process of data processing is presented in the appendix A of this paper.

2.3 Methodology for Optimization Simulations

The algorithm for microgrid optimization using the Q-learning [8] reinforcement learning technique was developed in MATLAB for the purpose of simulating the electrical microgrid optimal performance. The goal is to optimize the power flow in the network using the Q-learning technique. The microgrid configuration includes an islanded mode of operation, with a photovoltaic array as a renewable power source and a diesel generator as the conventional power supplier. The battery storage is available as well as a dumping load. Cost per kW, battery capacity, size of diesel generator, learning rate, among others can be mentioned as the parameters that might be modified to test the algorithm. Real datasets associated with solar radiation [9] and electrical demand [10] where utilized. The analysis was developed for a time window of 1 hour, for a total of 24 hours per day. Some of the content of the algorithm in MATLAB includes the following aspects and settings of initial values:

- Definition of battery initial state of charge (50%) and minimum and maximum battery and diesel generator capacities (50%, 2kW and 4kW respectively).

- Definition of discount factor and learning rate (0.8). The optimization method was based on exploitation of action 1 (using the renewable source as a main mechanism for providing energy to the electrical load) and action 2 (using diesel generator to cover renewable energy deficit).
- State of the system was defined by the value of renewable energy generation, load demand, maximum and minimum capacities of batteries and maximum power that the diesel generator was able to provide to the system.
- Creation of the for-loops for the different scenarios or actions. The calculation of cost in the system's operation was introduced as part of these loops. The cost takes into consideration several variables such as power provided by photovoltaic subsystem, power provided by batteries, amount of dumped load, amount of failed load and unitary cost indexes, among others.
- Calculation of Q-values for 200 different iterations.
- Decision making process to compare Q values related to action 1 and action 2 selecting the larger Q value to determine the power scheduled to be delivered by the different sources in the microgrid.

The cost of power produced by the diesel generator has been modified with respect to past simulations (three times the cost of renewable power) [11]. Other parameters that students are able to modify are learning rate (changed to 0.8 instead of 0.9), maximum capacity of batteries (2 instead of 3) and discount factor (modified from 0.9 to 0.95).

2.4 Methodology for State Estimation Simulations

The goal of the simulation is to estimate the state variables, where the least square function method is utilized for traditional state estimation. The microgrid system includes two buses, bus1 with generation and bus 2 where electrical load is connected. The magnitude voltage value at bus 1 is defined as *V1magnitude*, the magnitude of voltage value at bus 2 is defined as *V2magnitude*, the value of susceptance for distribution line between bus1and bus 2 is defined as *B21*, the active power flowing between the buses is defined as *P21* and the reactive power flowing between the buses is defined as *Q21*. The phase angle for bus 1 and 2 are defined as *thetha1* and *theta2* respectively. Applying the least square method with the function **lscov** from MATLAB it is possible to calculate the vector **p**, where **p** represents the vector of estimated values (*V1magnitude*; *V2magnitude*; *theta2*).

$$z_1 = |V_1| \tag{2}$$

$$z_2 = |V_2| \tag{3}$$

$$z_3 = P_{21} = |V_2||V_1|(-B_{21})\sin\ \theta_2 \tag{4}$$

$$z_4 = Q_{21} = |V_2{}^2|(B_{21}) + |V_2||V_1|\cos\ \theta_2 \tag{5}$$

$$x = [|V_1|_,|V_2|,\theta_2]^T \tag{6}$$

$$H = \begin{bmatrix} \frac{\partial z_1}{\partial |V_1|} & \frac{\partial z_1}{\partial |V_2|} & \frac{\partial z_1}{\partial \theta_2} \\ \vdots & \vdots & \vdots \\ \frac{\partial z_4}{\partial |V_1|} & \frac{\partial z_4}{\partial |V_2|} & \frac{\partial z_4}{\partial \theta_2} \end{bmatrix} \quad (7)$$

In equations (2) to (7): *z1* is the first element for the measurements vector **z**, *z2* is the second element for the measurements vector **z**, *z3* is the third element for the measurements vector **z**, *z4* is the fourth element for the measurements vector **z**, *P21* is the power flowing between the bus 1 and 2, *B21* represents the susceptance for the distribution line between buses 1 and 2, *θ2* is the phase angle for the voltage at bus 2, x is the state variable vector, *V1* is the voltage at bus 1, *V2* is the voltage at bus 2, *H* is the Jacobian matrix. The jacobian matrix in equation (7) is defined in terms of each one of the partial derivatives for all the variables. Fig. 1 shows the configuration for the microgrid where PMU1 and PMU2 are the phasor measurement units dedicated to take the measurements. Generator G1 is connected to the Bus 1 while the load is connected to Bus 2.

Fig. 1. Microgrid structure for state estimation simulation

3. Simulation Results

3.1 Results for Cybersecurity Simulations

In the area of cybersecurity the MATLAB classifier has been employed. Fig. 2 includes the classification learner results when currents in phase C and phase A from the Dominican Republic electrical power system are used as predictors. The program immediately recognizes the two categories: attack and non-attack to the network. A total of 191 sets of variables were used for training.

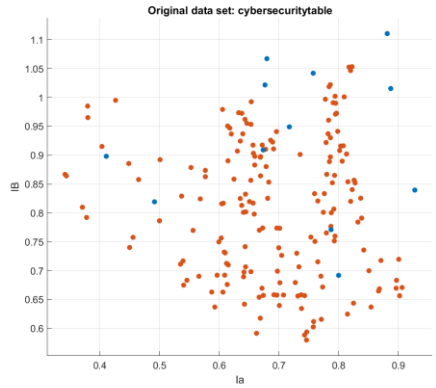

Fig. 2. Classification of attack (in blue), non-attack (in red) conditions.

A total of 20 scenarios were defined for the testing phase. Some sets of data were modified by applying a 5% or 10% difference in comparison with the original data (voltage decreased by 5% or 10%, current increased by 5% or 10%), with the aim of creating the attack condition. After the training phase, the MATLAB tool was fed with the test data and as a result, the classifier provides the output with the labels Attack and Normal Operation for the electrical system. According to the classifier the scenarios number 2, 6, 10 and 16 correspond to a cyber-attack condition for the network. Test data table is shown in Appendix A. Test results are shown below:

Table 1. Results for testing phase

Test number	Condition
1	{'Normal Operation'}
2	{'Attack' }
3	{'Normal Operation'}
4	{'Normal Operation'}
5	{'Normal Operation'}
6	{'Attack' }
7	{'Normal Operation'}
8	{'Normal Operation'}
9	{'Normal Operation'}
10	{'Normal Operation'}
11	{'Attack' }
12	{'Normal Operation'}
13	{'Normal Operation'}
14	{'Normal Operation'}
15	{'Normal Operation'}
16	{'Attack' }
17	{'Normal Operation'}
18	{'Normal Operation'}
19	{'Normal Operation'}
20	{'Normal Operation'}

For the purpose of recreating the simulation, MOOC students may be able to increase the total number of scenarios by using the real datasets available in the Open Science database [2]. The design and implementation of the simulation in MATLAB supports the learning outcomes and objectives identified in item 1.1: the ability to simulate, analyze and adapt algorithms related to Cybersecurity in Microgrids, by designing and writing MATLAB codes.

3.2 Results for Optimization Simulations

The goal for the simulation is to optimize the power flow in the microgrid using the Q-learning technique as mentioned in item 2.3. After running the simulation it can be noticed the difference from other results [11]. New results indicate that Q value decreases as the increase in cost of power produced by diesel generator and decrease in the learning rate. However, the convergence of the Q-value demonstrates success in the optimized operation of the microgrid, as displayed in Fig. 3.

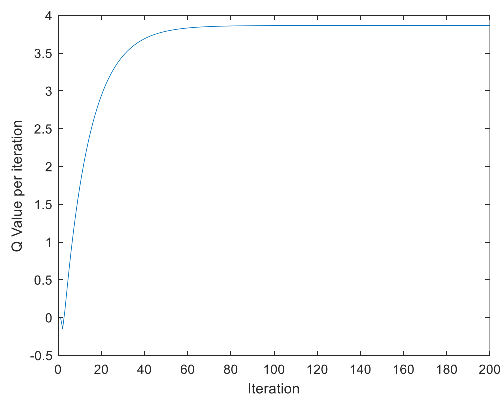

Fig. 3. Q-values for optimization problem

The design and implementation of the simulation in MATLAB supports the learning outcomes and objectives identified in item 1.1: the ability to simulate, analyze and adapt algorithms related to optimization in Microgrids, by designing and writing MATLAB codes.

3.3 Results for State Estimation Simulations

The goal of this simulation is to obtain the values for system voltage magnitude and phases. Results are produced in terms of voltages and phases in per unit. Voltage in buses 1 and 2 and phase in bus 2 are calculated. An example of the results for the standard error for the voltage at bus 2 is shown (Fig. 4), where the standard error is small, indicating a good estimation for the electrical system.

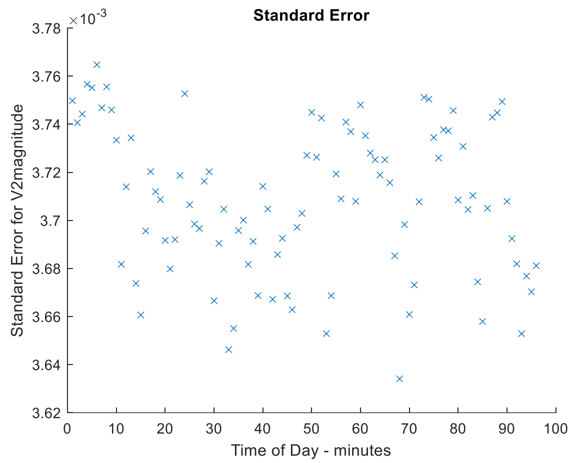

Fig. 4. Standard error for voltage at bus 2

Value for the voltages and the phase in per unit are shown (Fig. 5) for time stamps 17 and 18 as an example of the results produced by MATLAB after the application of the least square error function. The values presented in this figure represent the voltages in bus 1, bus 2 and phase in bus 2, respectively. The obtention of these values show the success in the simulation as the values create the foundation for the making decision process for those actions to be carried away over the microgrid hourly operation.

```
val(:,:,17) =

    1.0037
    0.9138
    0.0593


val(:,:,18) =

    1.0037
    0.9825
    0.0511
```

Fig. 5. Results for state estimation

The design and implementation of the simulation in MATLAB supports the learning outcomes and objectives identified in item 1.1: the ability to simulate, analyze and adapt algorithms related to state estimation in Microgrids, by designing and writing MATLAB codes.

4. Conclusions

In the post-pandemic times, it is of extreme relevance to count with online educational tools or MOOCs available to students to analyze concepts and applications on electrical microgrids. The evolving field of microgrid operation requires the creation of free online MOOCs that present the foremost aspects on Cybersecurity, State Estimation and Optimization for electrical microgrids. These MOOCs must employ real data for simulation purposes, using machine learning, deep learning and in general artificial intelligence methods. Moreover, there is an urgency in pursuing additional simulations linked to microgrid cyber secure and optimal performance. This paper presented the main features for the design of the MOOC and the invitation is open to students and professionals that would like to collaborate with this project. This paper also described the importance of cybersecurity, optimization and state estimation areas to study for microgrids, covering simulations in MATLAB that will be utilized by course participants in order to improve critical thinking and technical skills. The authors procured real datasets and are making access available for free using an Open Science system provided by the non-profit Latin American and Caribbean Consortium of Engineering Institutions. Cybersecurity code is done using MATLAB classification learner to detect potential threats to the electrical network. On the other hand, optimization based on Q-learning technique and real data for solar radiation and electrical load can be implemented in the exploration of operating a microgrid establishing best practices both technically and economically. Finally, state estimation method is very powerful at times of calculating the state of the system in terms of voltages and phases for making decision process.

5. Future work

Several aspects can be pointed as a future work. First, it is imperative that additional real datasets be obtained and place it in an Open Science database so it will be accessible by everyone who uses the MOOC. Also, creating other algorithms to detect cyber-attacks using other machine learning tools, such as Google Colaboratory (Tensorflow) [12], will be done in the near future.

6. Acknowledgments

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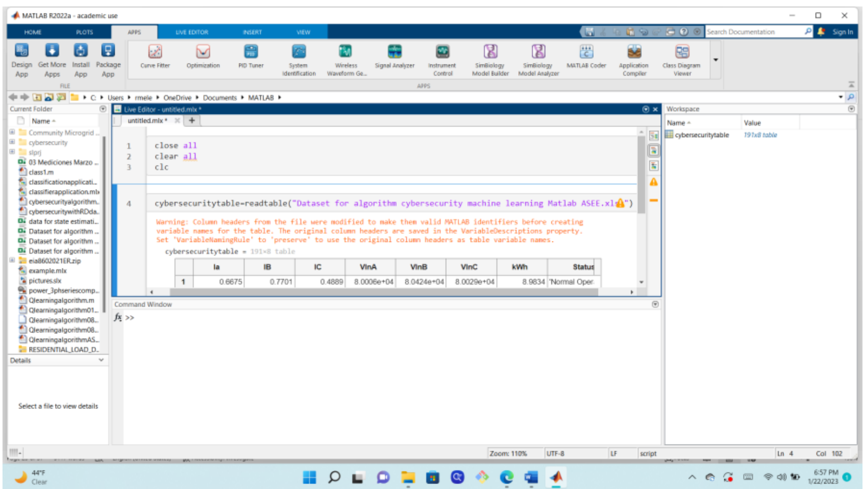
Appendix A

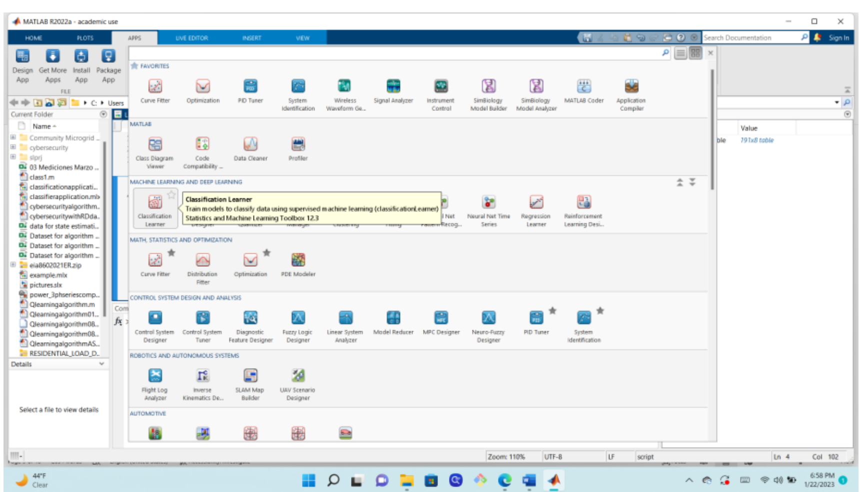
As part of the cybersecurity algorithm using MATLAB classification learner tool, the following steps should be considered in order to implement the tool for cyber-attack identification in an electrical microgrid.

Data source: Ing. Eduardo Sagredo, Dominican Republic electrical power system, Punta Catalina substation. Data available at [2].

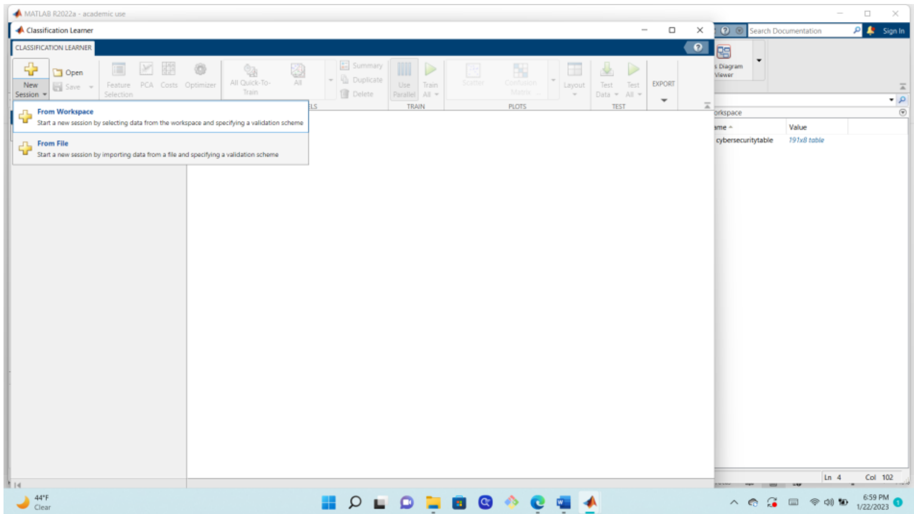
The first step consists of reading the dataset with the electrical variables, in the MATLAB Live Editor. The electrical variables are represented by the current for lines A, B and C, plus values of line voltages and electrical demand in kWh. A table with the variables has been created, with normal condition of the microgrid and inserting some attack data points at different time stamps. MATLAB can read the table:



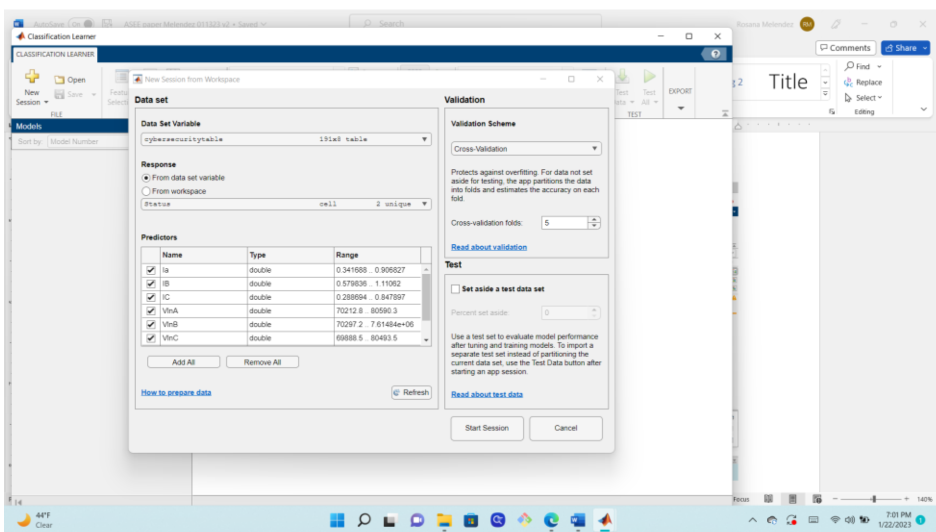
Next the APPS tab is selected, then launching the Classification Learner option from MATLAB software:



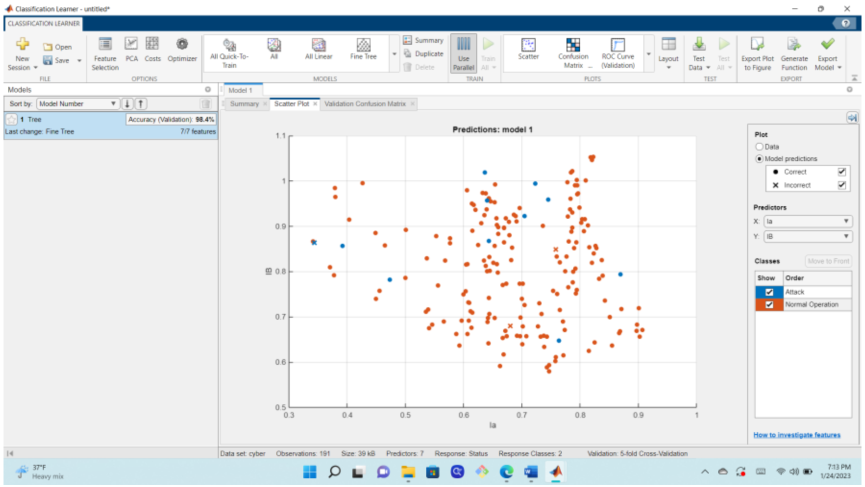
After launching the classification tool the user must open a new section from workspace:



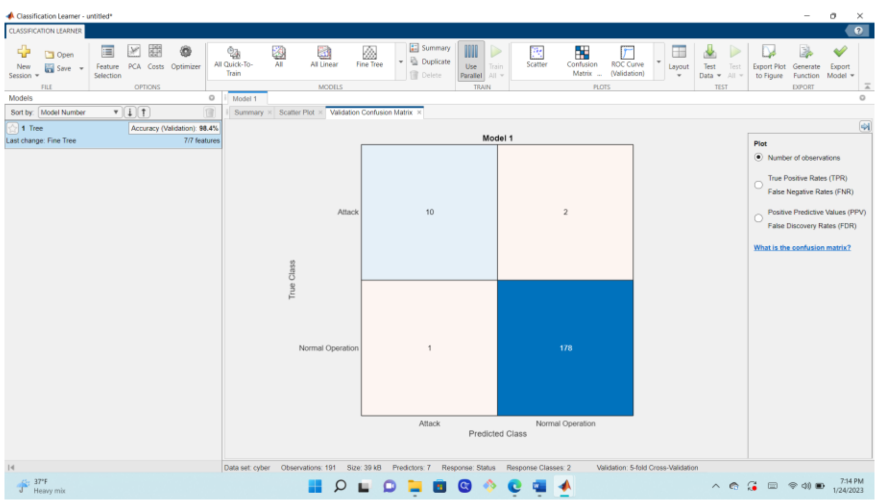
The program immediately recognizes the variables or features (line currents, line voltages and electrical demand) and the two classes (attack and non attack):



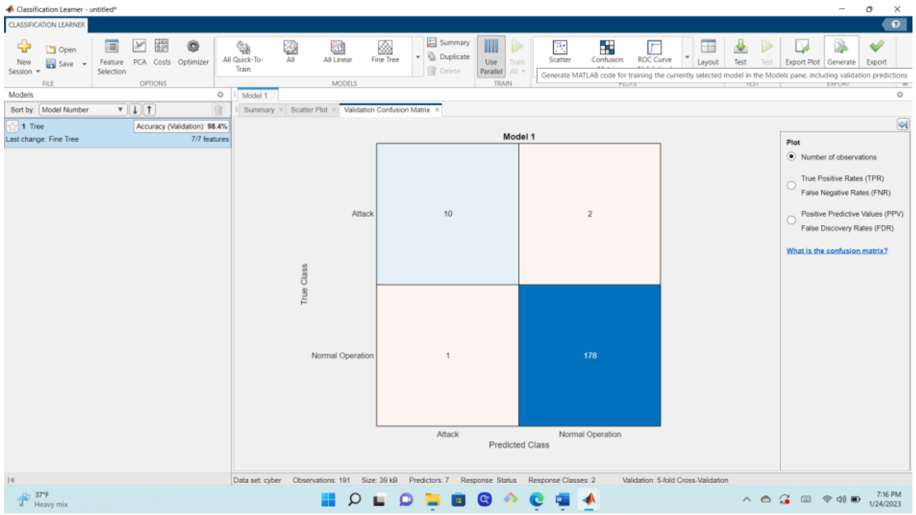
Next, the user must click on Start Session option and the plot with different combinations of variables (features, which are the line voltages, line current and demand in kWh) will be generated:



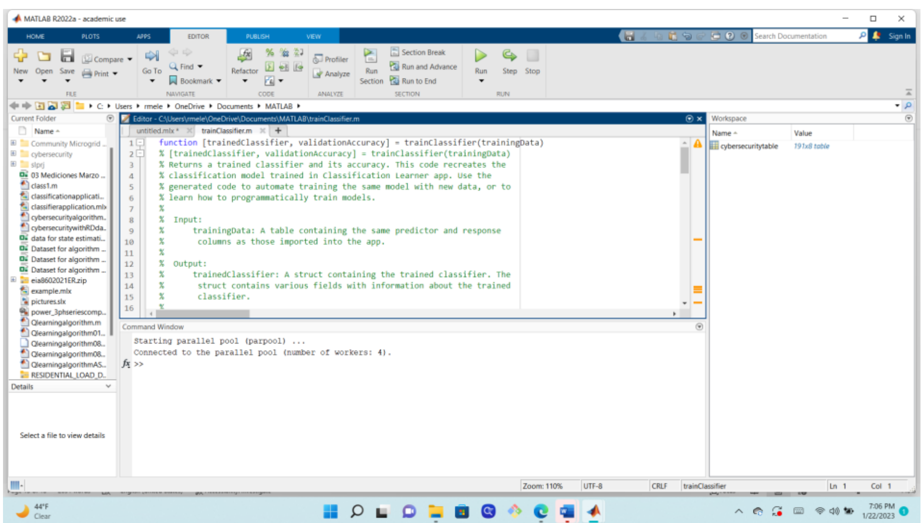
Users must then click on Train All command and the classifier will train the network and as a result a validation confusion matrix is created, showing the true positives, true negatives, false positives and false negatives results from the training phase:



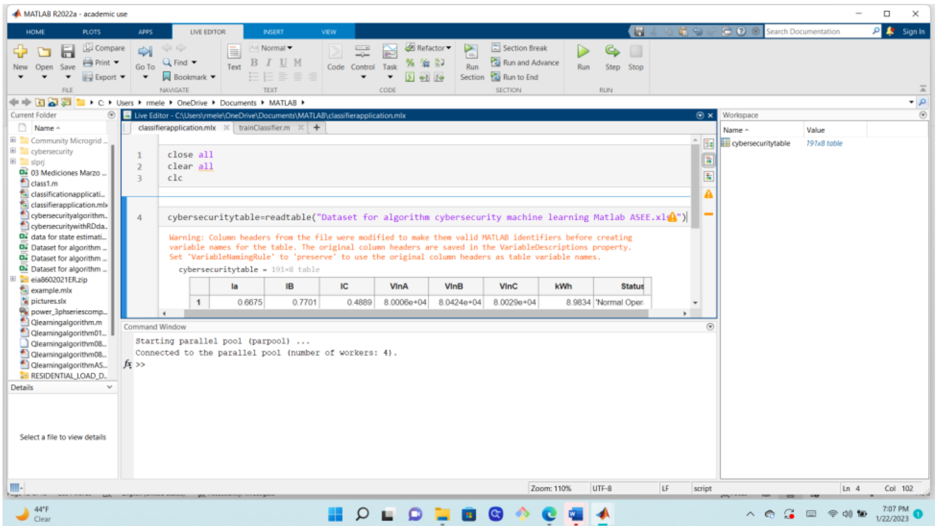
After this step users must click on Export option and select Generate Function, which will generate the machine learning algorithm:



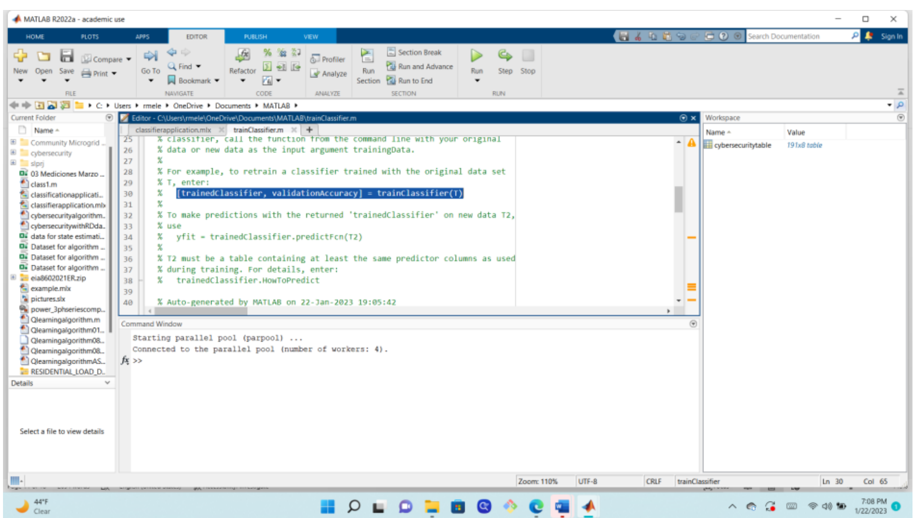
Then users must go back to the Live Editor and save the application with the same name of the function generated by the MATLAB software:



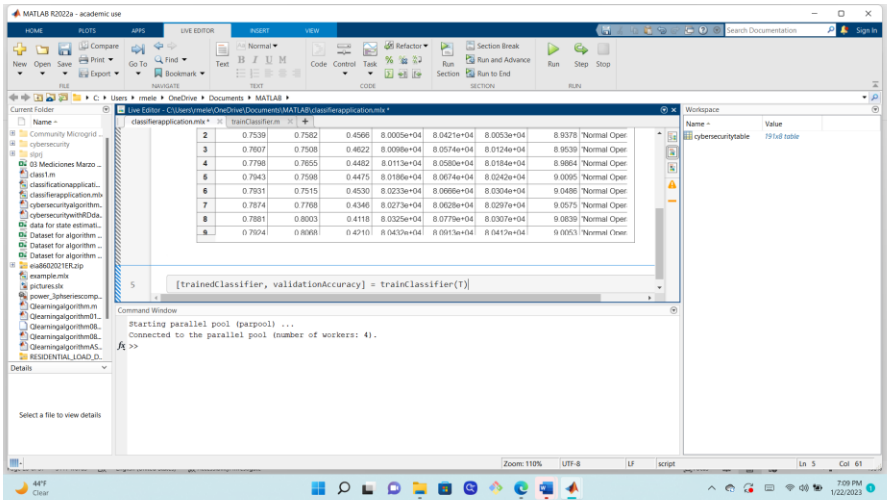
Next, users should go back to the Live Editor and save the file as mlx file:



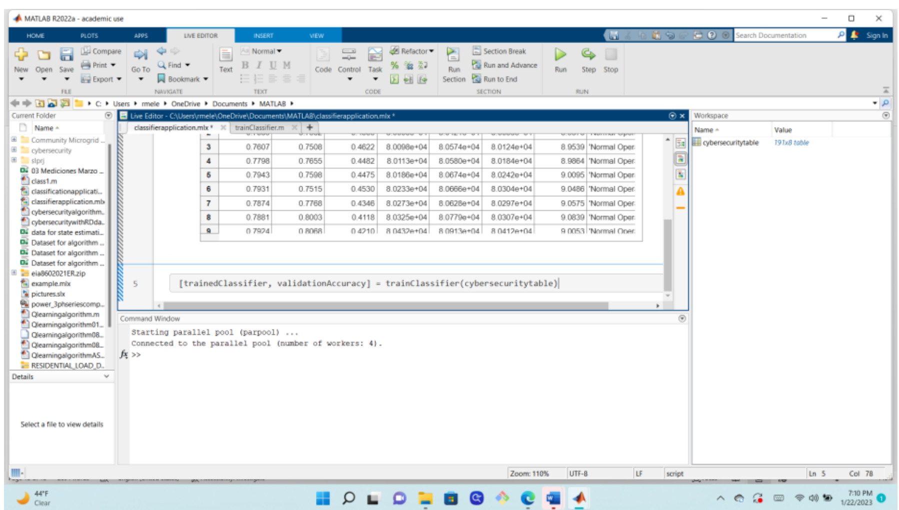
Next, users must create another line of code in the Live Editor file. Go to the generated function file for the classifier and copy the line of command that will allow to retrain of the classifier:



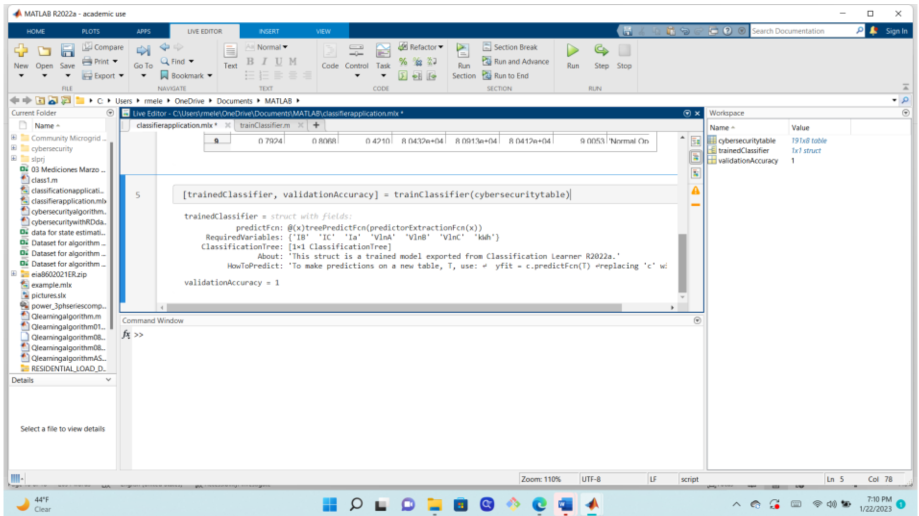
Users must generate a new line in the Live Script file and paste the line command copied from the classifier function:



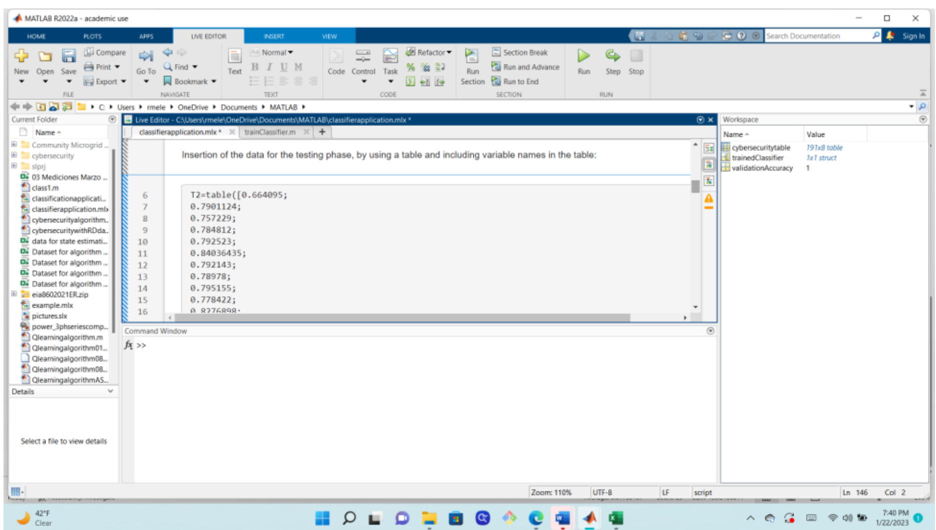
The next step is to modify the name of the table in the new line command to match the name of the table originally used in the script:



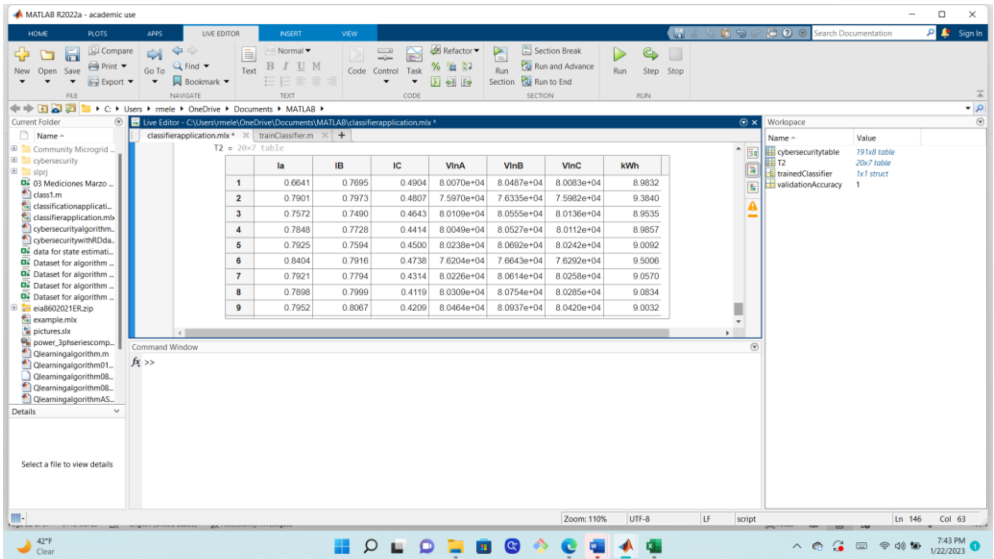
Click on Run Section and obtain the results for the retraining:



Next, user must create the table and call the variables for testing. At this stage the data for the testing phase must be used (see table A1):



From the trainClassifier file copy the command line for prediction. Finally click on Run in order to run the entire code, to obtain the results of the testing phase:



Finally the algorithm will classify now the test data into attack or non-attack:

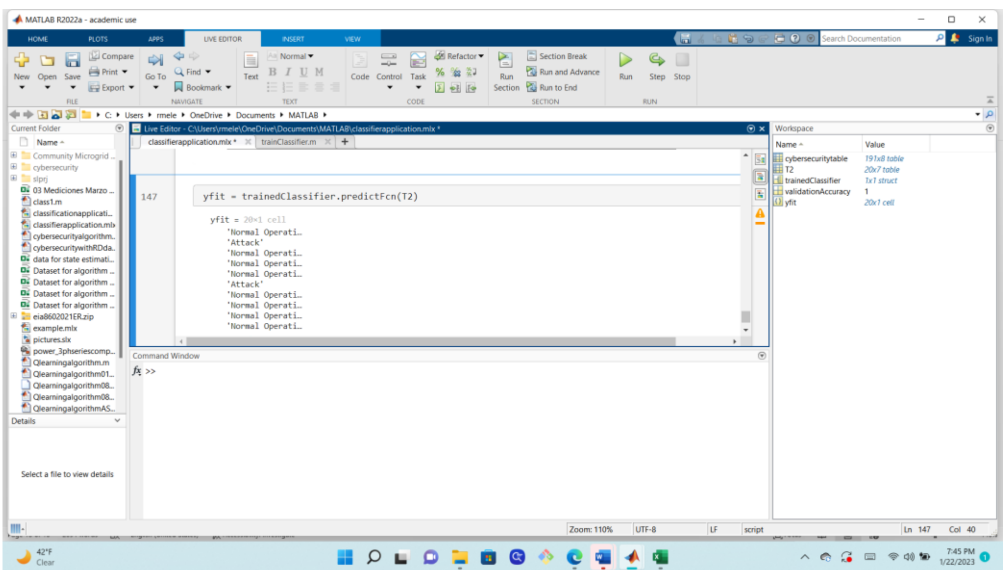


Table A1. Example of test dataset for twenty scenarios

Ia	I b	I c	Vln a	Vln b	Vln c	kWh
0.664095	0.769457	0.490378	80069.55	80487.44	80082.7	8.983215
0.790112	0.797326	0.480704	75969.53	76334.63	75981.62	9.384
0.757229	0.749047	0.464307	80109.41	80555.16	80136.25	8.953472
0.784812	0.772785	0.441386	80049.02	80527.39	80112.27	8.985739
0.792523	0.759356	0.449977	80237.96	80691.84	80241.57	9.009178
0.840364	0.791552	0.473831	76203.69	76642.57	76292.09	9.500601
0.792143	0.779356	0.431422	80226.29	80613.55	80257.73	9.057018
0.78978	0.799863	0.411896	80309.03	80754.37	80285.31	9.083426
0.795155	0.806659	0.420888	80463.57	80936.75	80420.14	9.003153
0.778422	0.874763	0.376406	80356.39	80784.41	80288.81	8.898657
0.82769	0.9743	0.361075	76271.39	76563.72	76163.73	9.248516
0.783655	0.926391	0.341842	80400.06	80746.3	80201.23	8.850492
0.782655	0.944904	0.334403	80335.95	80702.92	80129.73	8.898609
0.785707	0.964606	0.331583	80337.54	80632.36	80113.2	8.825017
0.797204	1.007252	0.313251	80179.2	80487.85	79946.94	8.752991
0.876483	1.076582	0.348599	72339.69	72607.42	72159.08	9.661599
0.793295	0.945236	0.329911	80486.54	80773.26	80271.88	8.897264
0.79877	0.976561	0.318676	80369.04	80675.7	80122.39	8.855816
0.808881	1.002373	0.310289	80259.47	80547.6	80076.67	8.778576
0.821099	1.051593	0.295176	80078.39	80385.23	79768.75	8.719343