AUTOMATED FRAMEWORK FOR GENERATING CYBER-PHYSICAL RANGE FOR SMART GRID

USER MANUAL FOR SMART GRID CYBER RANGE

ADSC, NUS

June 20, 2023

Contents

1 Introduction

This document provides a guide to generate a Smart Grid Cyber Range (SGCR) based on user-defined models. The setup is to be made on a Linux operating system. In this example, Ubuntu 20.04 LTS is used.

1.1 OS and Python dependencies required

The following are the tools, utilities and libraries that will be used. Details on the installation can be found in the respective sections of each SGCR component. Refer to requirements.txt for the specific versions of Python dependencies.

OS dependencies

(1) gcc
(2) python3
(3) python3-pip
(4) mysql-server
(5) libiec61850
(6) xmllint
(7) nlohmann-json3-dev
(8) libmysql++-dev
(9) openjdk-8-jdk
(10) mininet
(11) openvswitch-testcontroller
(12) xterm
(13) jq
(14) openPLC61850
(15) ScadaBR
(16) rapid-xml
(17) wireshark (optional)

Python dependencies

(1) pandapower
(2) pymysql
(3) matplotlib
(4) python-igraph
(5) xmltodict
(6) lxml

2 Database

This is a one-time setup.

2.1 Dependencies required

Install MySQL (either on localhost or in another host) by referring to the official manual.

2.2 Steps to set up the database

(1) Create an empty database

(2) Restore the pandapower database structure (i.e. tables with no data) with the given pandapower_db_structure.sql file
sudo mysql -u [user] -p [database] < pandapower_db_structure.sql

(3) Modify files <dir>/IED/db_config.txt and <dir>/Panda-db/DBTransmitter.py with the right **Username**, **Password** and **Database**

3 Virtual IED

3.1 Dependencies required

(1) libiec61850
run **make** in <dir>/IED/02_build/libs/libiec61850

(2) xmltodict
pip install xmltodict

(3) xmllint
sudo apt install libxml2-utils

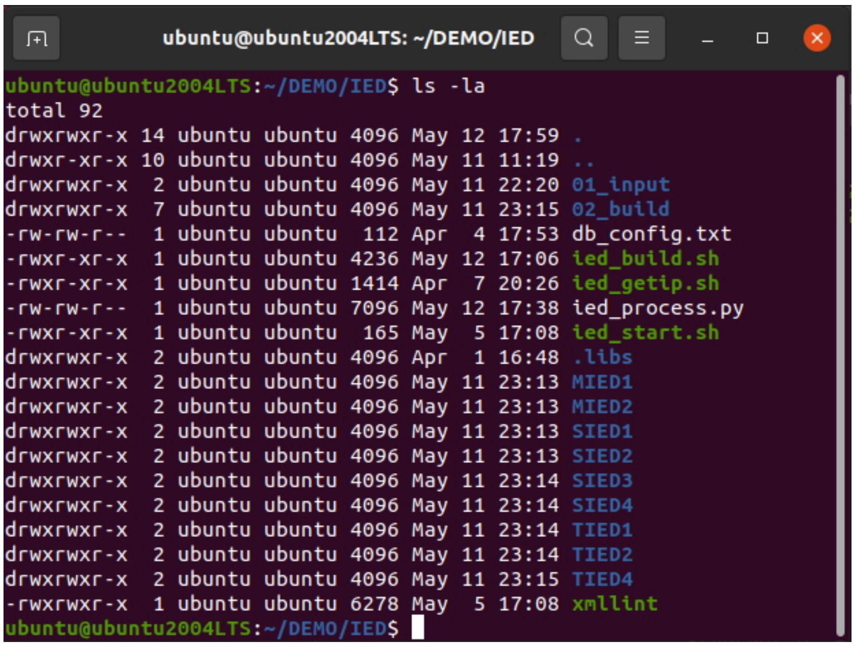
(4) nlohmann-json3-dev
sudo apt install nlohmann-json3-dev

(5) libmysql++-dev
sudo apt install libmysql++-dev

(6) openjdk-8-jdk
sudo apt install openjdk-8-jdk

3.2 Folder contents

ICD files, CPMapping.xml, Thresholds.xml, db_config.txt, ied_build.sh, ied_getip.sh, ied_start.sh, xmllint and .libs, and folders 01_input, 02_build as listed in Fig. 1.



```
ubuntu@ubuntu2004LTS:~/DEMO/IED$ ls -la
total 92
drwxrwxr-x 14 ubuntu ubuntu 4096 May 12 17:59 .
drwxr-xr-x 10 ubuntu ubuntu 4096 May 11 11:19 ..
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 22:20 01_input
drwxrwxr-x  7 ubuntu ubuntu 4096 May 11 23:15 02_build
-rw-rw-r--  1 ubuntu ubuntu  112 Apr  4 17:53 db_config.txt
-rwxr-xr-x  1 ubuntu ubuntu 4236 May 12 17:06 ied_build.sh
-rwxr-xr-x  1 ubuntu ubuntu 1414 Apr  7 20:26 ied_getip.sh
-rw-rw-r--  1 ubuntu ubuntu 7096 May 12 17:38 ied_process.py
-rwxr-xr-x  1 ubuntu ubuntu  165 May  5 17:08 ied_start.sh
drwxrwxr-x  2 ubuntu ubuntu 4096 Apr  1 16:48 .libs
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:13 MIED1
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:13 MIED2
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:13 SIED1
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:13 SIED2
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:14 SIED3
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:14 SIED4
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:14 TIED1
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:14 TIED2
drwxrwxr-x  2 ubuntu ubuntu 4096 May 11 23:15 TIED4
-rwxrwxr-x  1 ubuntu ubuntu 6278 May  5 17:08 xmllint
ubuntu@ubuntu2004LTS:~/DEMO/IED$
```

Figure 1

3.3 Building Virtual IEDs:

This is a one-time setup and will only be required to be repeated if there are changes in the CPMapping, Thresholds or ICD files.

(1) Required user input files below are placed in “01_input” folder:

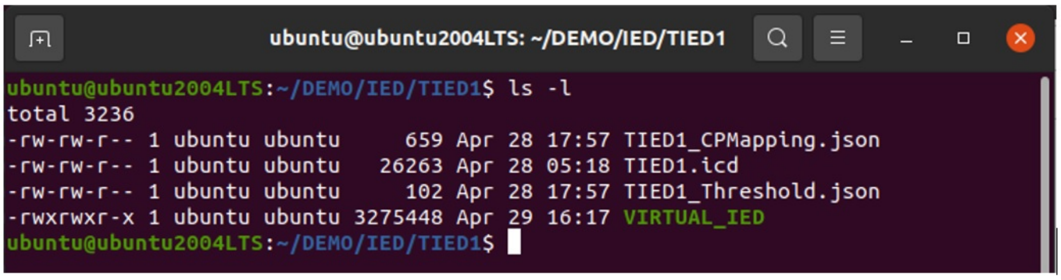
- CPMapping.xml
- Thresholds.xml
- ICD files (<IED_name>.icd)

(2) Command to build:

```
cd <dir>/IED
./ied_build.sh
```

(3) The build will perform the following for each IED:

- Convert CPMapping.xml to <IED_name>_CPMapping.json
- Convert Thresholds.xml to <IED_name>_Threshold.json
- Build VIRTUAL_IED
- Place the respective files into folder <IED_name>, as shown in the example in Fig. 2.



```
ubuntu@ubuntu2004LTS:~/DEMO/IED/TIED1$ ls -l
total 3236
-rw-rw-r-- 1 ubuntu ubuntu     659 Apr 28 17:57 TIED1_CPMapping.json
-rw-rw-r-- 1 ubuntu ubuntu   26263 Apr 28 05:18 TIED1.icd
-rw-rw-r-- 1 ubuntu ubuntu     102 Apr 28 17:57 TIED1_Threshold.json
-rwxrwxr-x 1 ubuntu ubuntu 3275448 Apr 29 16:17 VIRTUAL_IED
ubuntu@ubuntu2004LTS:~/DEMO/IED/TIED1$
```

Figure 2

4 Cyber Network Simulation

4.1 Dependencies required

(1) Mininet
The installation instruction can be found in http://mininet.org/download/

(2) OpenVSwitch Testcontroller
sudo apt install openvswitch-testcontroller
sudo ln -s /usr/bin/ovs-testcontroller /usr/bin/controller

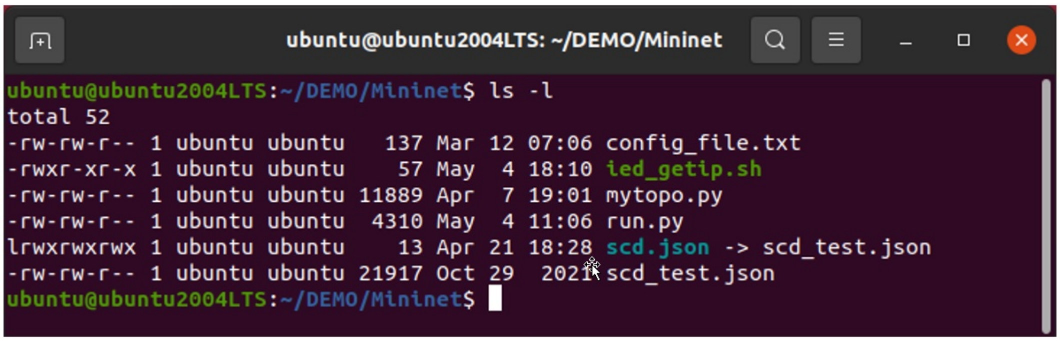
(3) xterm
sudo apt install xterm

(4) jq
sudo apt install jq

4.2 Commands to start cyber network simulation

Ensure the database and virtual IEDs are set up before this step.

(1) cd <dir>/Mininet

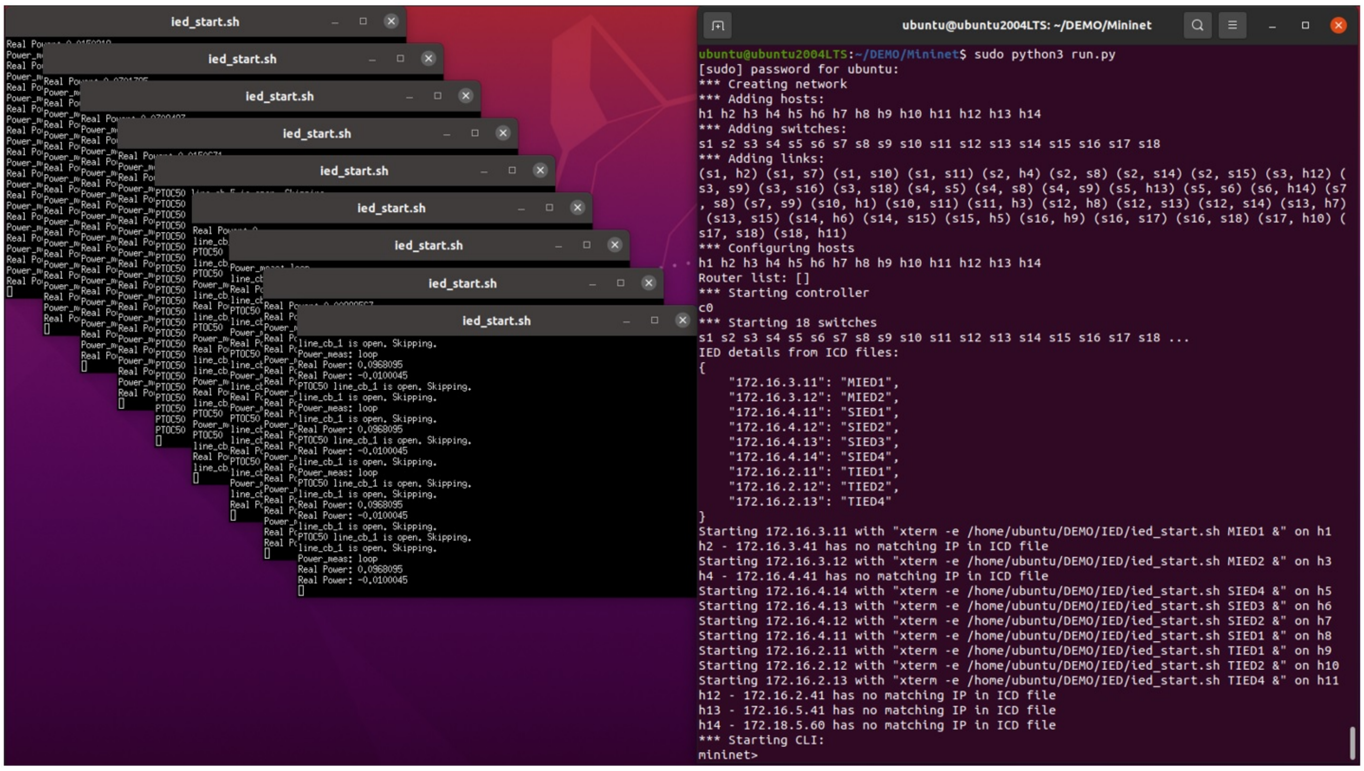


```
ubuntu@ubuntu2004LTS:~/DEMO/Mininet$ ls -l
total 52
-rw-rw-r-- 1 ubuntu ubuntu   137 Mar 12 07:06 config_file.txt
-rwxr-xr-x 1 ubuntu ubuntu    57 May  4 18:10 ied_getip.sh
-rw-rw-r-- 1 ubuntu ubuntu 11889 Apr  7 19:01 mytopo.py
-rw-rw-r-- 1 ubuntu ubuntu  4310 May  4 11:06 run.py
lrwxrwxrwx 1 ubuntu ubuntu    13 Apr 21 18:28 scd.json -> scd_test.json
-rw-rw-r-- 1 ubuntu ubuntu 21917 Oct 29  2021 scd_test.json
ubuntu@ubuntu2004LTS:~/DEMO/Mininet$ 
```

Figure 3

(2) Run command:
sudo python3 run.py

Output:



```
line_cb_1 is open. Skipping.
Power_meas: loop
Real Power: 0.0968095
Real Power: -0.0100045
PTOC50 line_cb_1 is open. Skipping.
line_cb_1 is open. Skipping.
Power_meas: loop
line_cb_1 is open. Skipping.
Real Power: 0.0968095
PTOC50 line_cb_1 is open. Skipping.
Real Power: -0.0100045
line_cb_1 is open. Skipping.
Power_meas: loop
PTOC50 line_cb_1 is open. Skipping.
line_cb_1 is open. Skipping.
Real Power: 0.0968095
Real Power: -0.0100045
line_cb_1 is open. Skipping.
PTOC50 line_cb_1 is open. Skipping.
line_cb_1 is open. Skipping.
Power_meas: loop
Real Power: 0.0968095
Real Power: -0.0100045
```

```
ubuntu@ubuntu2004LTS:~/DEMO/Mininet$ sudo python3 run.py
[sudo] password for ubuntu:
*** Creating network
*** Adding hosts:
h1 h2 h3 h4 h5 h6 h7 h8 h9 h10 h11 h12 h13 h14
*** Adding switches:
s1 s2 s3 s4 s5 s6 s7 s8 s9 s10 s11 s12 s13 s14 s15 s16 s17 s18
*** Adding links:
(s1, h2) (s1, s7) (s1, s10) (s1, s11) (s2, h4) (s2, s8) (s2, s14) (s2, s15) (s3, h12) (
s3, s9) (s3, s16) (s3, s18) (s4, s5) (s4, s8) (s4, s9) (s5, h13) (s5, s6) (s6, h14) (s7
, s8) (s7, s9) (s10, h1) (s10, s11) (s11, h3) (s12, h8) (s12, s13) (s12, s14) (s13, h7)
 (s13, s15) (s14, h6) (s14, s15) (s15, h5) (s16, h9) (s16, s17) (s16, s18) (s17, h10) (
s17, s18) (s18, h11)
*** Configuring hosts
h1 h2 h3 h4 h5 h6 h7 h8 h9 h10 h11 h12 h13 h14
Router list: []
*** Starting controller
c0
*** Starting 18 switches
s1 s2 s3 s4 s5 s6 s7 s8 s9 s10 s11 s12 s13 s14 s15 s16 s17 s18 ...
IED details from ICD files:
{
    "172.16.3.11": "MIED1",
    "172.16.3.12": "MIED2",
    "172.16.4.11": "SIED1",
    "172.16.4.12": "SIED2",
    "172.16.4.13": "SIED3",
    "172.16.4.14": "SIED4",
    "172.16.2.11": "TIED1",
    "172.16.2.12": "TIED2",
    "172.16.2.13": "TIED4"
}
Starting 172.16.3.11 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh MIED1 &" on h1
h2 - 172.16.3.41 has no matching IP in ICD file
Starting 172.16.3.12 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh MIED2 &" on h3
h4 - 172.16.4.41 has no matching IP in ICD file
Starting 172.16.4.14 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh SIED4 &" on h5
Starting 172.16.4.13 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh SIED3 &" on h6
Starting 172.16.4.12 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh SIED2 &" on h7
Starting 172.16.4.11 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh SIED1 &" on h8
Starting 172.16.2.11 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh TIED1 &" on h9
Starting 172.16.2.12 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh TIED2 &" on h10
Starting 172.16.2.13 with "xterm -e /home/ubuntu/DEMO/IED/ied_start.sh TIED4 &" on h11
h12 - 172.16.2.41 has no matching IP in ICD file
h13 - 172.16.5.41 has no matching IP in ICD file
h14 - 172.18.5.60 has no matching IP in ICD file
*** Starting CLI:
mininet>
```

Figure 4

5 PLC

5.1 Dependencies required

(1) Install OpenPLC61850, by downloading from GitHub repository:
git clone https://github.com/smartgridadsc/OpenPLC61850.git
cd OpenPLC61850 && sudo ./install.sh linux

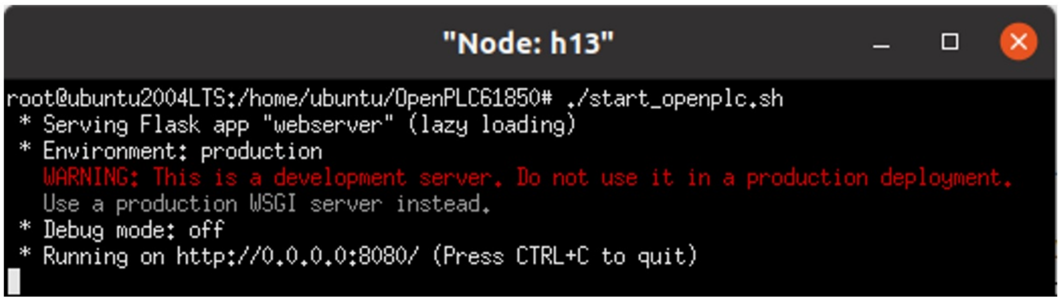
(2) Replace <dir>/OpenPLC61850/webserver/scl_client_files and scl_server_files with <dir>/examples/single_substation/OpenPLC61850/scl_client_files and scl_server_files respectively for the single substation example

5.2 Commands to start the OpenPLC:

(1) Open a mininet node

(2) From Mininet CLI, open a terminal in a PLC node, e.g. h13
mininet> xterm h13

(3) In the terminal, start OpenPLC:
cd <dir>/OpenPLC61850 && ./start_openplc.sh



```
root@ubuntu2004LTS:/home/ubuntu/OpenPLC61850# ./start_openplc.sh
 * Serving Flask app "webserver" (lazy loading)
 * Environment: production
   WARNING: This is a development server. Do not use it in a production deployment.
   Use a production WSGI server instead.
 * Debug mode: off
 * Running on http://0.0.0.0:8080/ (Press CTRL+C to quit)
```

Figure 5

(4) In the same terminal, launch Firefox or Chrome browser and access OpenPLC:
sudo -u <ubuntu_user> firefox & (or google-chrome if it is installed)
On browser, load http://localhost:8080 and log in as openplc/openplc

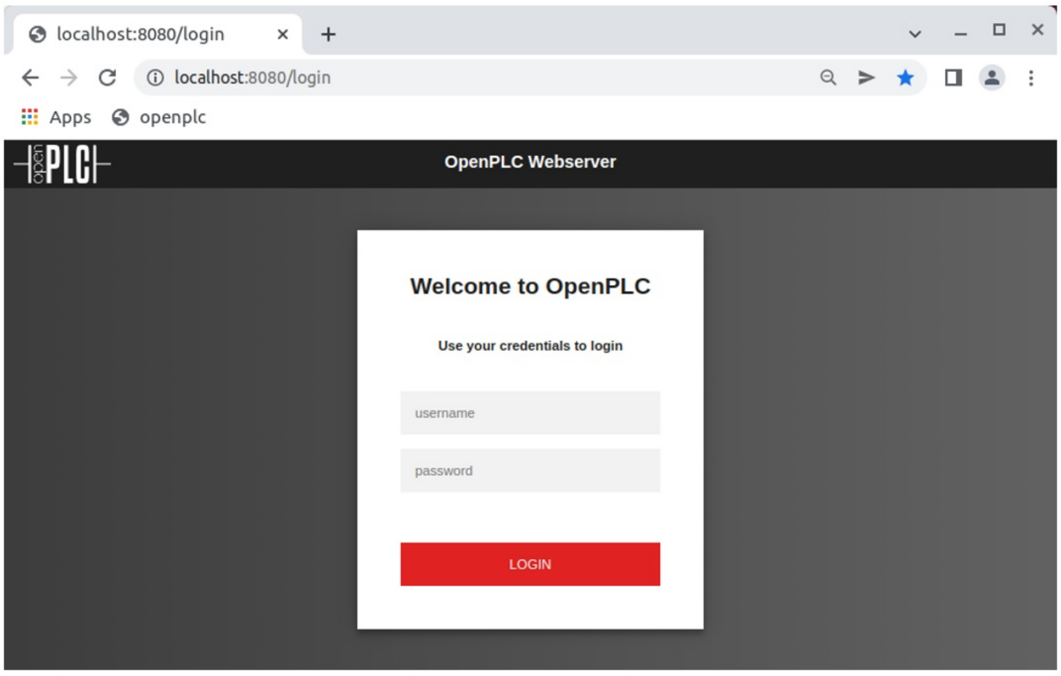
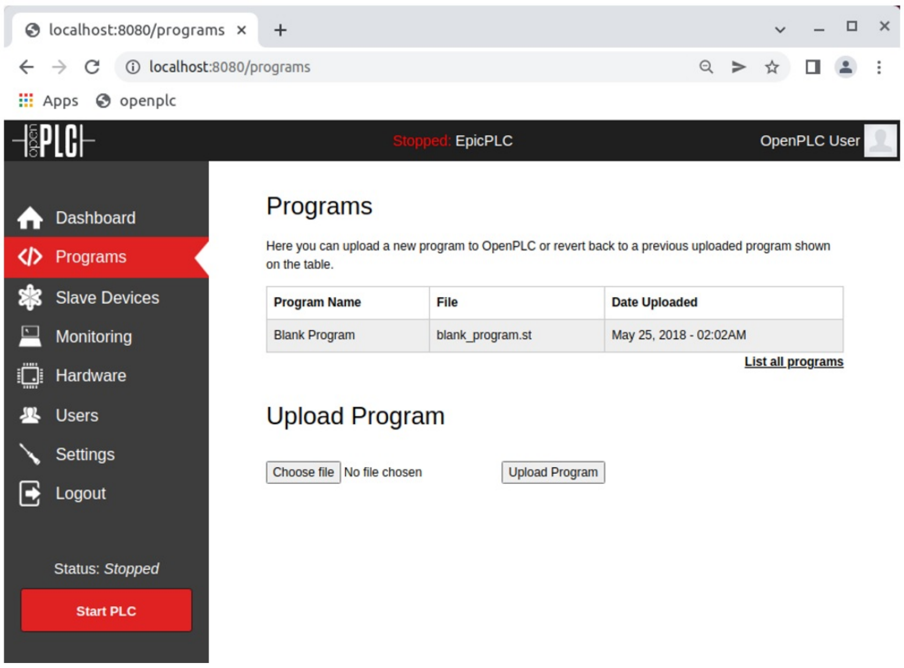

localhost:8080/login
Apps
openplc
OpenPLC Webserver
Welcome to OpenPLC
Use your credentials to login
username
password
LOGIN

Figure 6

(5) Go to Program -> Choose File -> select the given .st file -> Upload Program (one-time setup)

For the single substation example, use <dir>/examples/single_substation/OpenPLC61850/st_files/singlesub.st



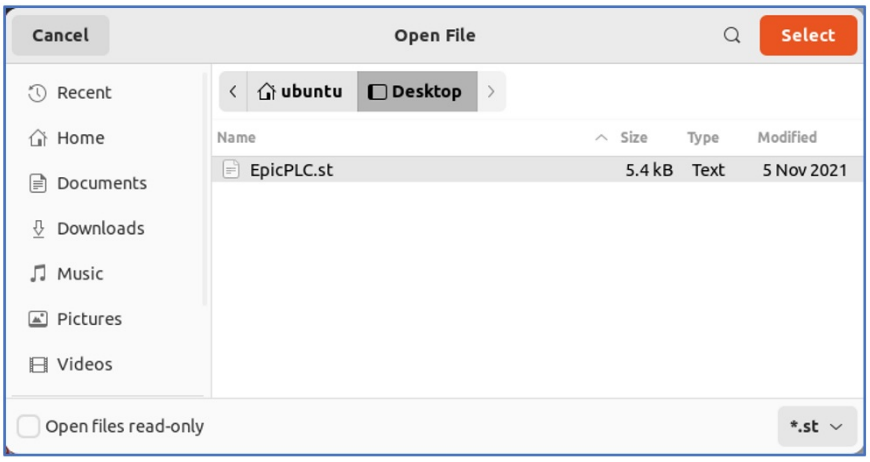
Programs

Here you can upload a new program to OpenPLC or revert back to a previous uploaded program shown on the table.

Program Name	File	Date Uploaded
Blank Program	blank_program.st	May 25, 2018 - 02:02AM

Upload Program

Figure 7



Name	Size	Type	Modified
EpicPLC.st	5.4 kB	Text	5 Nov 2021

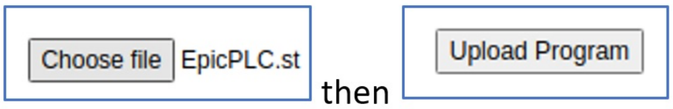
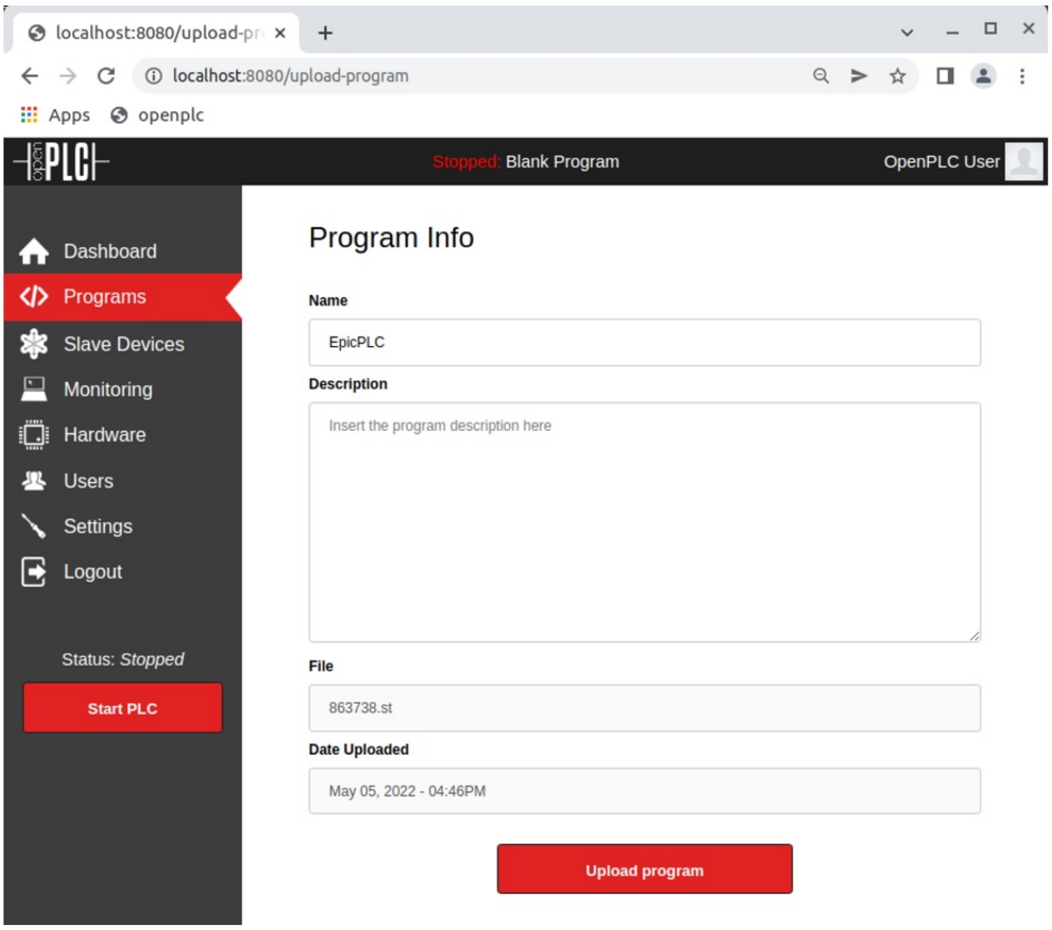


Figure 8



Program Info

Name
EpicPLC

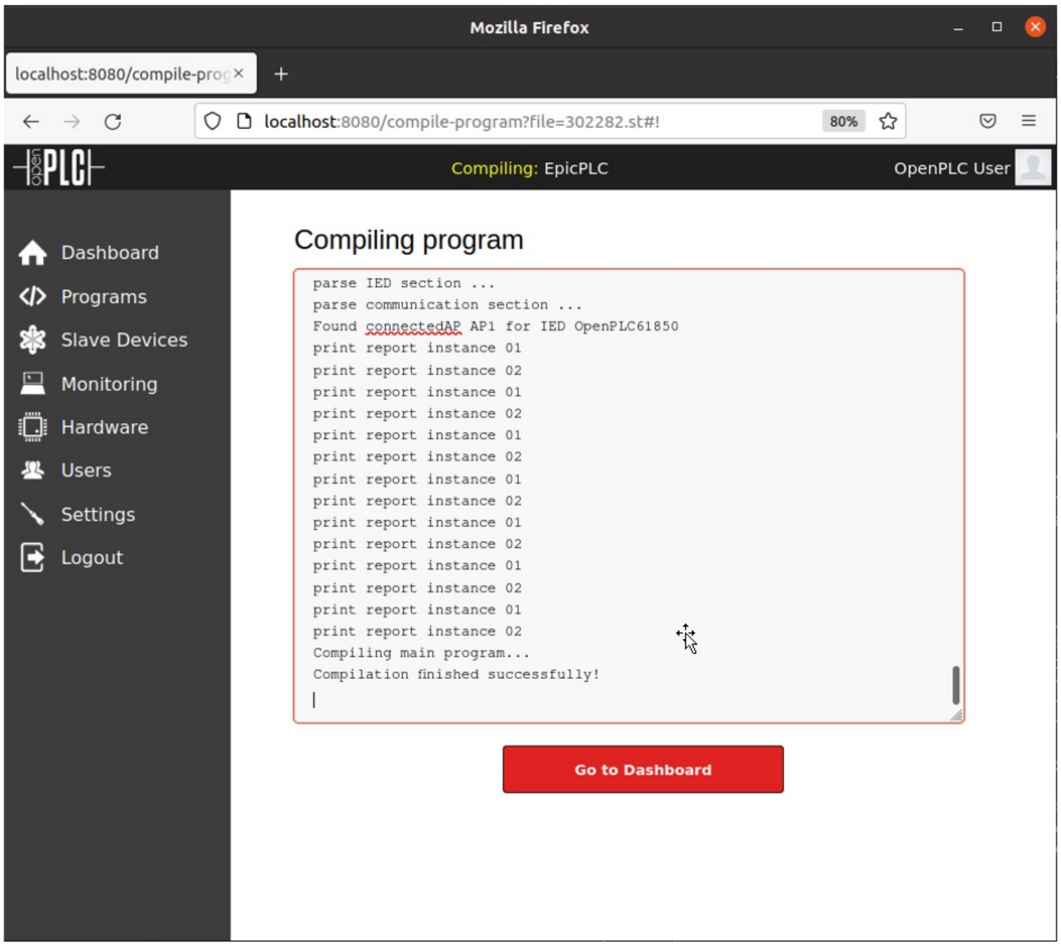
Description
Insert the program description here

File
863738.st

Date Uploaded
May 05, 2022 - 04:46PM

Figure 9

(6) In Program -> select the uploaded program -> Launch Program (to compile program)

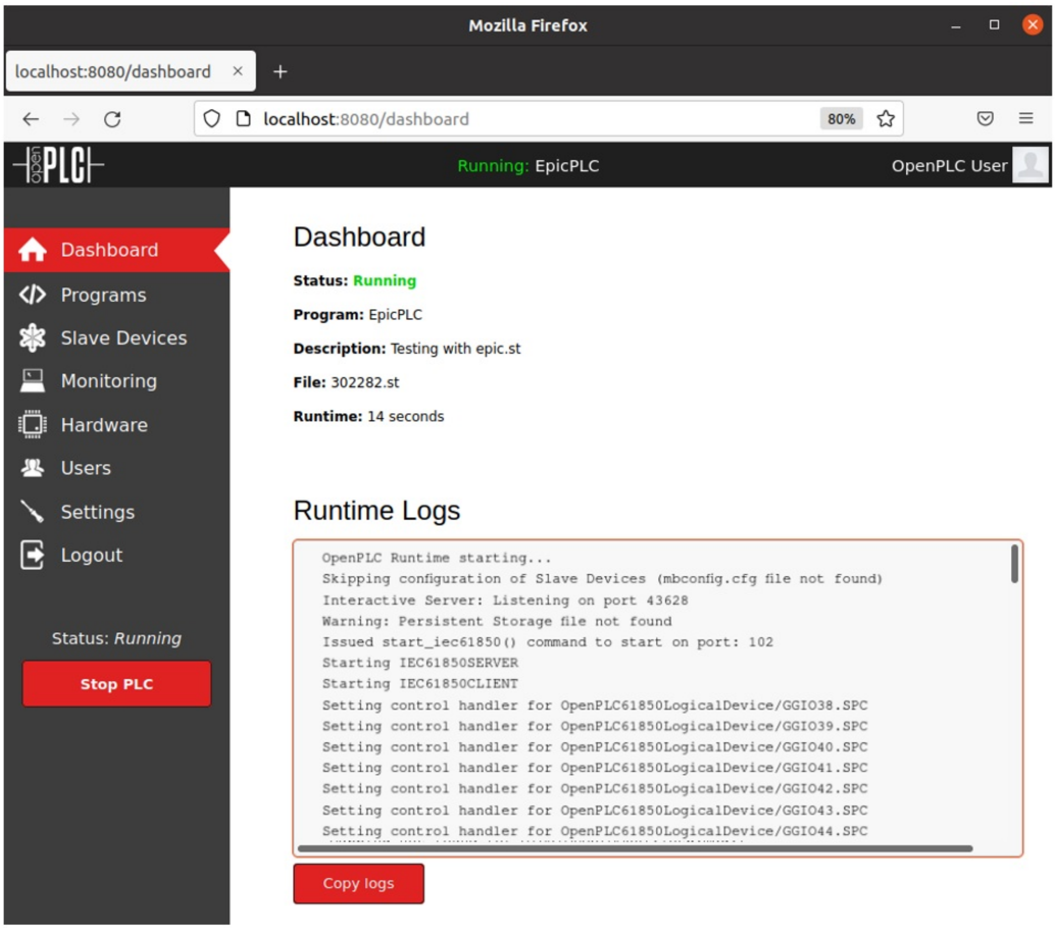


Compiling program

```
parse IED section ...
parse communication section ...
Found connectedAP AP1 for IED OpenPLC61850
print report instance 01
print report instance 02
print report instance 01
print report instance 02
print report instance 01
print report instance 02
print report instance 01
print report instance 02
print report instance 01
print report instance 02
print report instance 01
print report instance 02
print report instance 01
print report instance 02
Compiling main program...
Compilation finished successfully!
```

Figure 10

(7) Go to Dashboard -> Start PLC



Dashboard

Status: Running

Program: EpicPLC

Description: Testing with epic.st

File: 302282.st

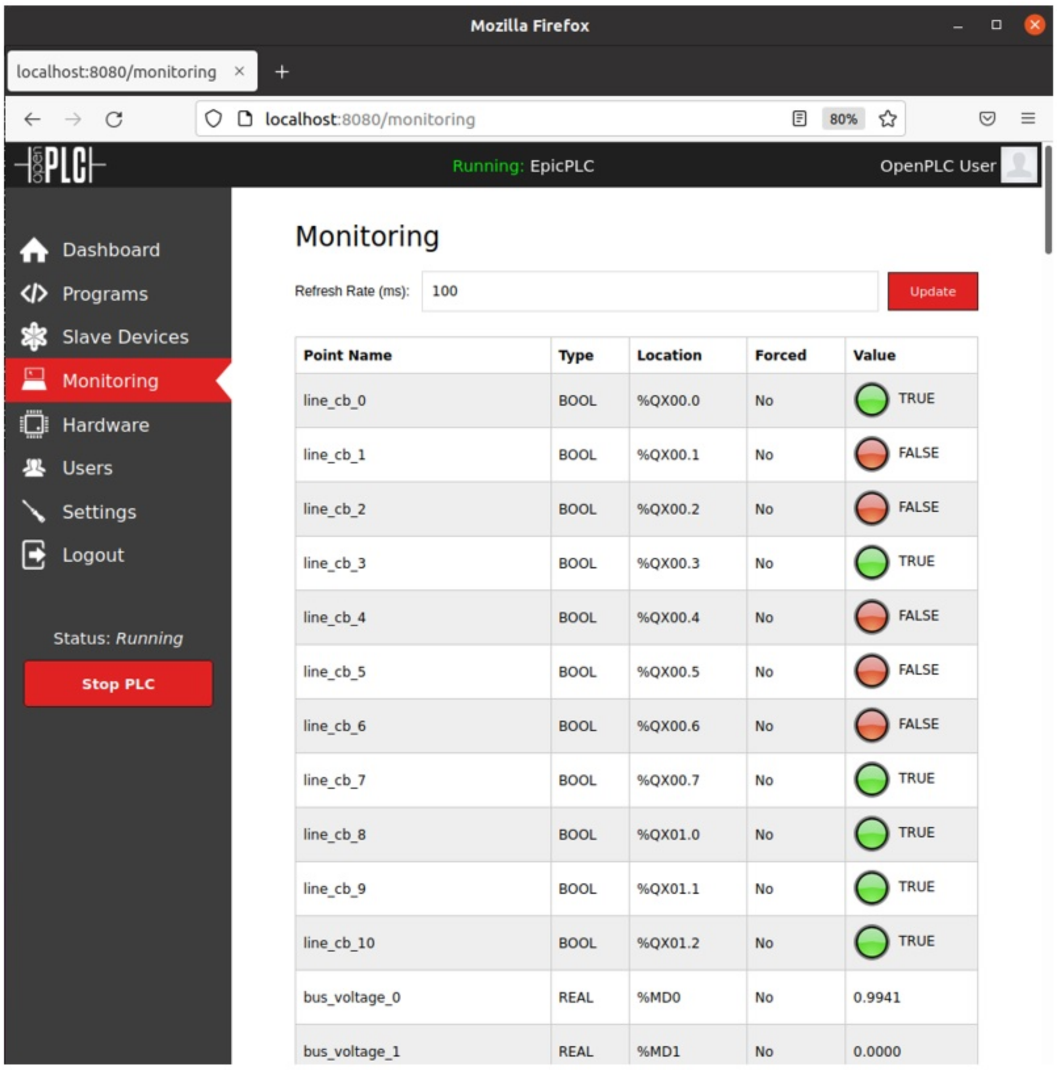
Runtime: 14 seconds

Runtime Logs

```
OpenPLC Runtime starting...
Skipping configuration of Slave Devices (mbconfig.cfg file not found)
Interactive Server: Listening on port 43628
Warning: Persistent Storage file not found
Issued start_iec61850() command to start on port: 102
Starting IEC61850SERVER
Starting IEC61850CLIENT
Setting control handler for OpenPLC61850LogicalDevice/GGIO38.SPC
Setting control handler for OpenPLC61850LogicalDevice/GGIO39.SPC
Setting control handler for OpenPLC61850LogicalDevice/GGIO40.SPC
Setting control handler for OpenPLC61850LogicalDevice/GGIO41.SPC
Setting control handler for OpenPLC61850LogicalDevice/GGIO42.SPC
Setting control handler for OpenPLC61850LogicalDevice/GGIO43.SPC
Setting control handler for OpenPLC61850LogicalDevice/GGIO44.SPC
```

Figure 11

(8) Go to Monitoring (if no data is shown here, click Stop PLC and Start PLC again)



Monitoring

Refresh Rate (ms): 100

Point Name	Type	Location	Forced	Value
line_cb_0	BOOL	%QX00.0	No	🟢 TRUE
line_cb_1	BOOL	%QX00.1	No	🔴 FALSE
line_cb_2	BOOL	%QX00.2	No	🔴 FALSE
line_cb_3	BOOL	%QX00.3	No	🟢 TRUE
line_cb_4	BOOL	%QX00.4	No	🔴 FALSE
line_cb_5	BOOL	%QX00.5	No	🔴 FALSE
line_cb_6	BOOL	%QX00.6	No	🔴 FALSE
line_cb_7	BOOL	%QX00.7	No	🟢 TRUE
line_cb_8	BOOL	%QX01.0	No	🟢 TRUE
line_cb_9	BOOL	%QX01.1	No	🟢 TRUE
line_cb_10	BOOL	%QX01.2	No	🟢 TRUE
bus_voltage_0	REAL	%MD0	No	0.9941
bus_voltage_1	REAL	%MD1	No	0.0000

Figure 12

6 SCADA

6.1 Dependencies required

(1) Python3

(2) Python modules (for ScadaBR_Config):

- lxml
  pip install lxml
- xmltodict
  pip install xmltodict

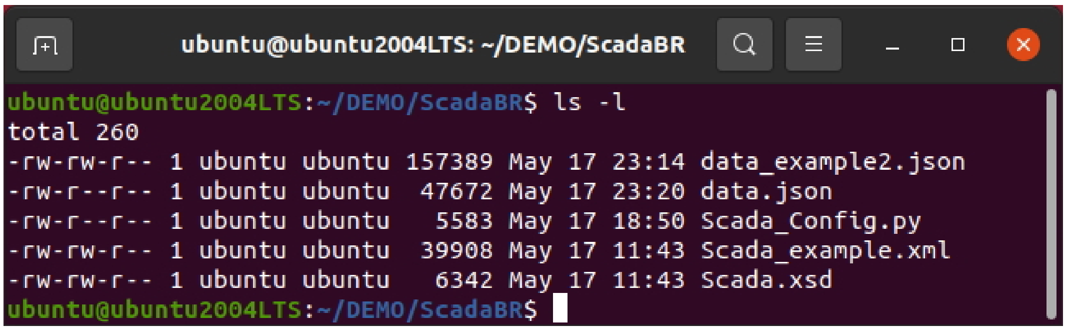
(3) Download ScadaBR_Config from GitHub repository
(https://github.com/smartgridadsc/CyberRange/tree/main/single_substation/ScadaBR)

(4) Install ScadaBR, by downloading from GitHub:
git clone https://github.com/thiagoralves/ScadaBR_Installer.git
cd ScadaBR_Installer && sudo ./install_scadabr.sh

(5) Initial pandapower data must exist in the database (run python3 Simulator.py for 1 cycle to populate then Ctrl-C)

6.2 ScadaBR configuration

This script converts the ScadaBR configuration in XML to JSON. This is a one-time setup.

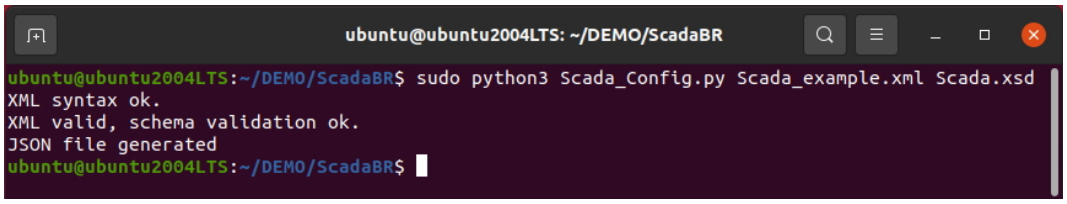


```
ubuntu@ubuntu2004LTS:~/DEMO/ScadaBR$ ls -l
total 260
-rw-rw-r-- 1 ubuntu ubuntu 157389 May 17 23:14 data_example2.json
-rw-r--r-- 1 ubuntu ubuntu  47672 May 17 23:20 data.json
-rw-r--r-- 1 ubuntu ubuntu   5583 May 17 18:50 Scada_Config.py
-rw-rw-r-- 1 ubuntu ubuntu  39908 May 17 11:43 Scada_example.xml
-rw-rw-r-- 1 ubuntu ubuntu   6342 May 17 11:43 Scada.xsd
ubuntu@ubuntu2004LTS:~/DEMO/ScadaBR$
```

Figure 13

Command to run:
sudo python3 Scada_Config.py Scada_example.xml Scada.xsd
where Scada_example.xml is the input file and data.json is the converted output file.

Output:



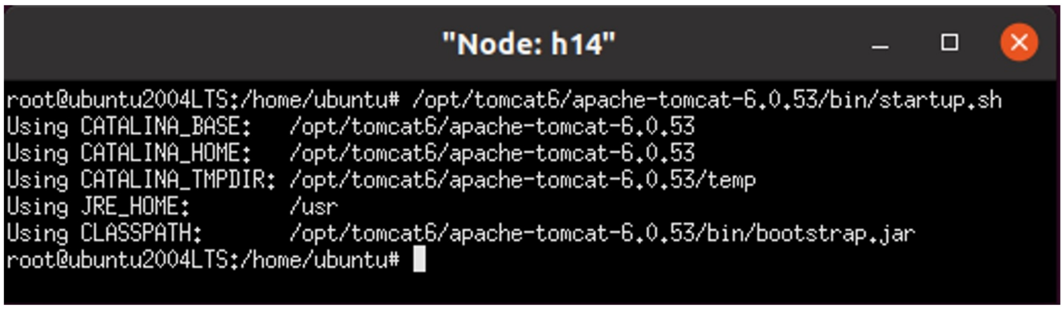
```
ubuntu@ubuntu2004LTS:~/DEMO/ScadaBR$ sudo python3 Scada_Config.py Scada_example.xml Scada.xsd
XML syntax ok.
XML valid, schema validation ok.
JSON file generated
ubuntu@ubuntu2004LTS:~/DEMO/ScadaBR$
```

Figure 14

6.3 Commands to start the ScadaBR

(1) Open a mininet node (e.g. xterm h14)

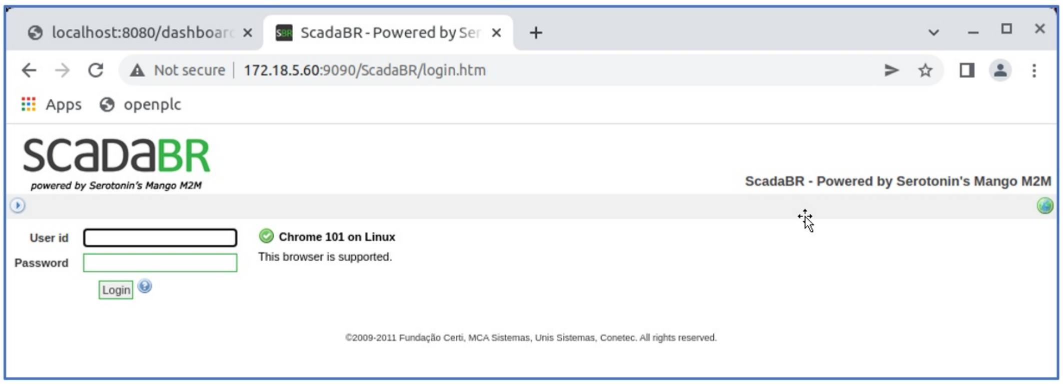
(2) In the terminal, start ScadaBR:
/opt/tomcat6/apache-tomcat-6.0.53/bin/startup.sh



```
root@ubuntu2004LTS:/home/ubuntu# /opt/tomcat6/apache-tomcat-6.0.53/bin/startup.sh
Using CATALINA_BASE:   /opt/tomcat6/apache-tomcat-6.0.53
Using CATALINA_HOME:   /opt/tomcat6/apache-tomcat-6.0.53
Using CATALINA_TMPDIR: /opt/tomcat6/apache-tomcat-6.0.53/temp
Using JRE_HOME:        /usr
Using CLASSPATH:       /opt/tomcat6/apache-tomcat-6.0.53/bin/bootstrap.jar
root@ubuntu2004LTS:/home/ubuntu#
```

Figure 15

(3) Access ScadaBR on the web browser:
http://<ip_of_mininet_node_running_scadabr>:9090/ScadaBR/login.htm
and log in as admin/admin



Not secure | 172.18.5.60:9090/ScadaBR/login.htm

ScadaBR - Powered by Serotonin's Mango M2M

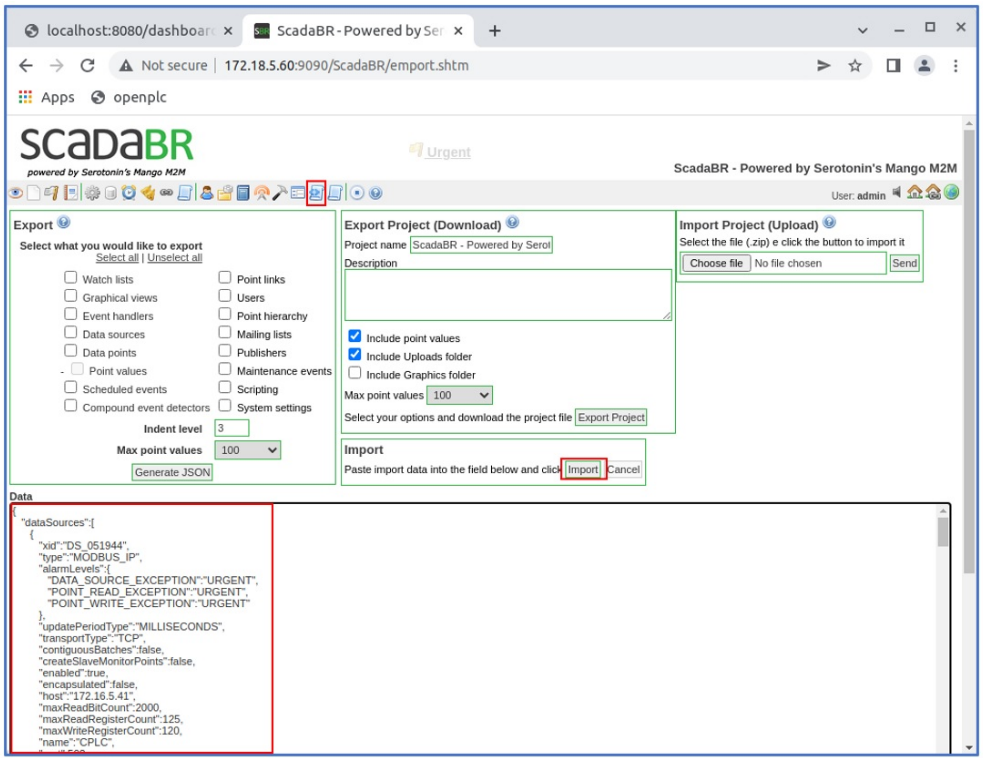
User id
Password
Login

Chrome 101 on Linux
This browser is supported.

©2009-2011 Fundação Certi, MCA Sistemas, Unis Sistemas, Conetec. All rights reserved.

Figure 16

(4) Import data (one-time setup):
Select Import/Export icon in ScadaBR after logging in
Paste content of data.json (converted by Scada_Config.py script) and click Import


localhost:8080/dashboard
ScadaBR - Powered by Ser
Not secure | 172.18.5.60:9090/ScadaBR/emport.shtm
Apps
openplc
scadaBR
powered by Serotonin's Mango M2M
Urgent
ScadaBR - Powered by Serotonin's Mango M2M
User: admin

Export
Select what you would like to export
Select all | Unselect all

- [ ] Watch lists
- [ ] Graphical views
- [ ] Event handlers
- [ ] Data sources
- [ ] Data points
- [ ] Point values
- [ ] Scheduled events
- [ ] Compound event detectors
- [ ] Point links
- [ ] Users
- [ ] Point hierarchy
- [ ] Mailing lists
- [ ] Publishers
- [ ] Maintenance events
- [ ] Scripting
- [ ] System settings

Indent level: 3
Max point values: 100
Generate JSON

Export Project (Download)
Project name: ScadaBR - Powered by Serot
Description

- [x] Include point values
- [x] Include Uploads folder
- [ ] Include Graphics folder

Max point values: 100
Select your options and download the project file Export Project

Import Project (Upload)
Select the file (.zip) e click the button to import it
Choose file No file chosen Send

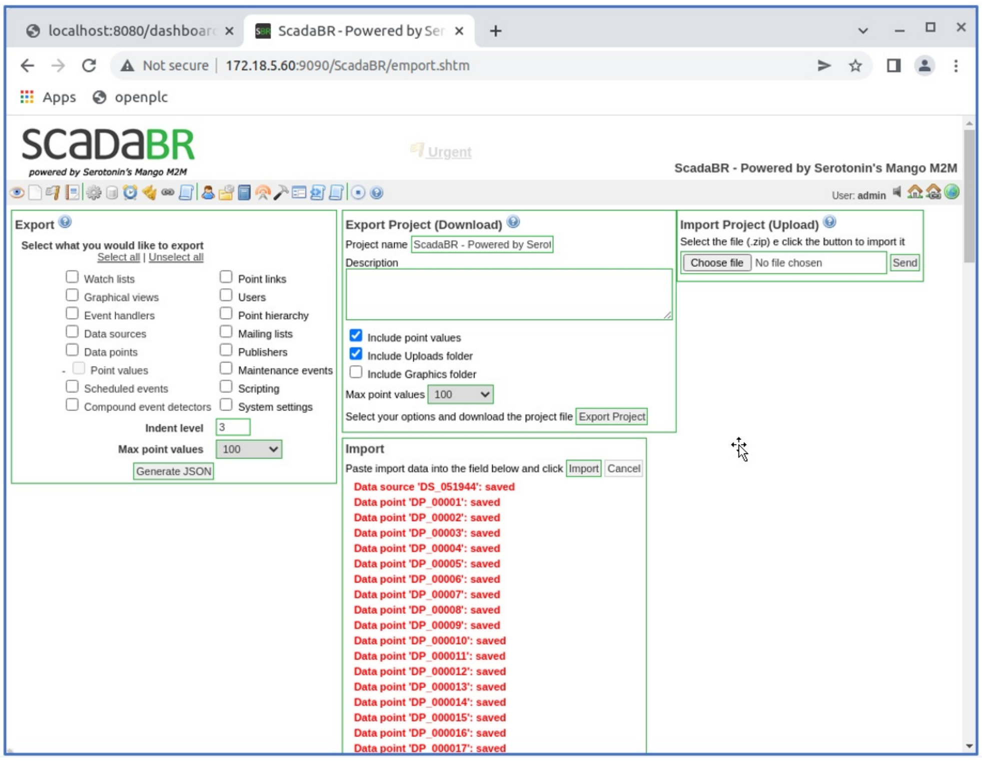
Import
Paste import data into the field below and click Import Cancel

Data

```
{
  "dataSources":[
    {
      "xid":"DS_051944",
      "type":"MODBUS_IP",
      "alarmLevels":{
        "DATA_SOURCE_EXCEPTION":"URGENT",
        "POINT_READ_EXCEPTION":"URGENT",
        "POINT_WRITE_EXCEPTION":"URGENT"
      },
      "updatePeriodType":"MILLISECONDS",
      "transportType":"TCP",
      "contiguousBatches":false,
      "createSlaveMonitorPoints":false,
      "enabled":true,
      "encapsulated":false,
      "host":"172.16.5.41",
      "maxReadBitCount":2000,
      "maxReadRegisterCount":125,
      "maxWriteRegisterCount":120,
      "name":"CPLC",
```

Figure 17

In ScadaBR, click Watch list icon to view the data metrics



localhost:8080/dashboar
ScadaBR - Powered by Ser
Not secure | 172.18.5.60:9090/ScadaBR/emport.shtm
Apps
openplc
scadaBR
powered by Serotonin's Mango M2M
Urgent
ScadaBR - Powered by Serotonin's Mango M2M
User: admin

Export

Select what you would like to export

Select all | Unselect all

- [ ] Watch lists
- [ ] Graphical views
- [ ] Event handlers
- [ ] Data sources
- [ ] Data points
- [ ] Point values
- [ ] Scheduled events
- [ ] Compound event detectors
- [ ] Point links
- [ ] Users
- [ ] Point hierarchy
- [ ] Mailing lists
- [ ] Publishers
- [ ] Maintenance events
- [ ] Scripting
- [ ] System settings

Indent level: 3

Max point values: 100

Generate JSON

Export Project (Download)

Project name: ScadaBR - Powered by Serot

Description:

- [✓] Include point values
- [✓] Include Uploads folder
- [ ] Include Graphics folder

Max point values: 100

Select your options and download the project file: Export Project

Import Project (Upload)

Select the file (.zip) e click the button to import it

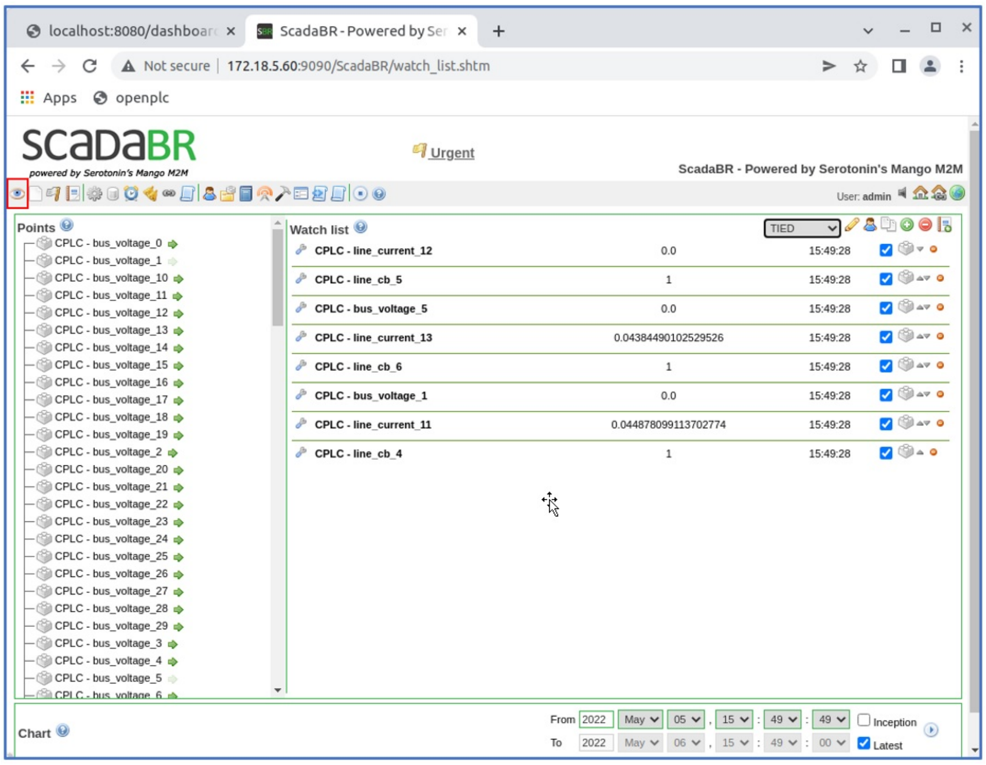
Choose file | No file chosen | Send

Import

Paste import data into the field below and click Import | Cancel

```
Data source 'DS_051944': saved
Data point 'DP_00001': saved
Data point 'DP_00002': saved
Data point 'DP_00003': saved
Data point 'DP_00004': saved
Data point 'DP_00005': saved
Data point 'DP_00006': saved
Data point 'DP_00007': saved
Data point 'DP_00008': saved
Data point 'DP_00009': saved
Data point 'DP_000010': saved
Data point 'DP_000011': saved
Data point 'DP_000012': saved
Data point 'DP_000013': saved
Data point 'DP_000014': saved
Data point 'DP_000015': saved
Data point 'DP_000016': saved
Data point 'DP_000017': saved
```

Figure 18



localhost:8080/dashboar
ScadaBR - Powered by Ser
Not secure | 172.18.5.60:9090/ScadaBR/watch_list.shtm
Apps
openplc
scadaBR
powered by Serotonin's Mango M2M
Urgent
ScadaBR - Powered by Serotonin's Mango M2M
User: admin

Points

```
CPLC - bus_voltage_0
CPLC - bus_voltage_1
CPLC - bus_voltage_10
CPLC - bus_voltage_11
CPLC - bus_voltage_12
CPLC - bus_voltage_13
CPLC - bus_voltage_14
CPLC - bus_voltage_15
CPLC - bus_voltage_16
CPLC - bus_voltage_17
CPLC - bus_voltage_18
CPLC - bus_voltage_19
CPLC - bus_voltage_2
CPLC - bus_voltage_20
CPLC - bus_voltage_21
CPLC - bus_voltage_22
CPLC - bus_voltage_23
CPLC - bus_voltage_24
CPLC - bus_voltage_25
CPLC - bus_voltage_26
CPLC - bus_voltage_27
CPLC - bus_voltage_28
CPLC - bus_voltage_29
CPLC - bus_voltage_3
CPLC - bus_voltage_4
CPLC - bus_voltage_5
CPLC - bus_voltage_6
```

Watch list TIED

CPLC - line_current_12	0.0	15:49:28	✓
CPLC - line_cb_5	1	15:49:28	✓
CPLC - bus_voltage_5	0.0	15:49:28	✓
CPLC - line_current_13	0.04384490102529526	15:49:28	✓
CPLC - line_cb_6	1	15:49:28	✓
CPLC - bus_voltage_1	0.0	15:49:28	✓
CPLC - line_current_11	0.044878099113702774	15:49:28	✓
CPLC - line_cb_4	1	15:49:28	✓

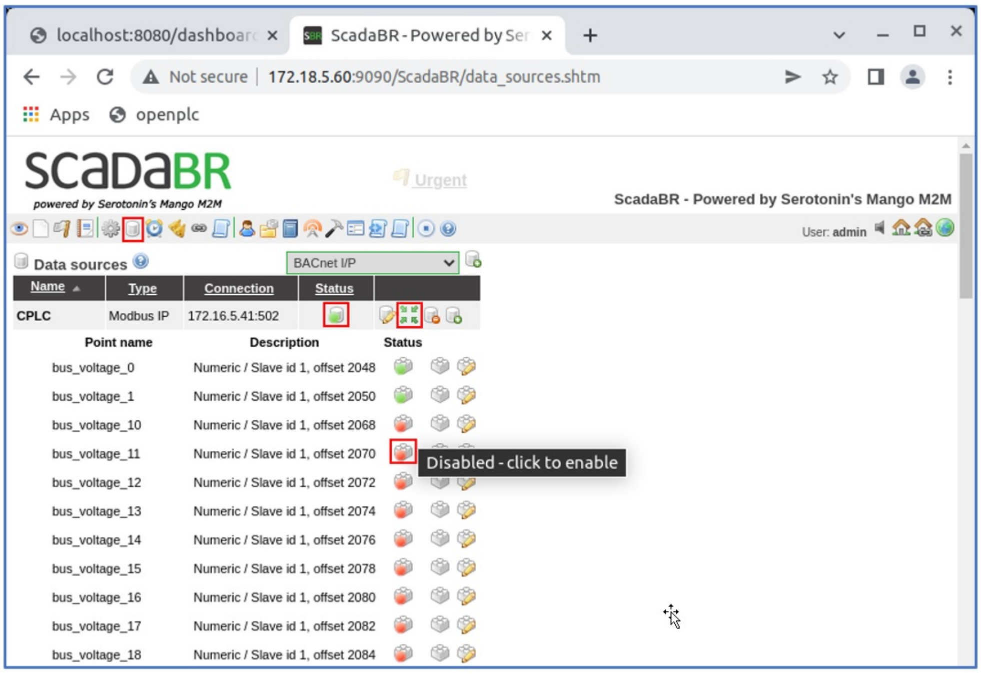
Chart

From 2022 May 05 , 15 : 49 : 49 [ ] Inception

To 2022 May 06 , 15 : 49 : 00 [✓] Latest

Figure 19

If required, click Data sources icon to enable/disable the data source and data points


localhost:8080/dashboarc
ScadaBR - Powered by Ser
Not secure | 172.18.5.60:9090/ScadaBR/data_sources.shtm
Apps
openplc
scadaBR
powered by Serotonin's Mango M2M
Urgent
ScadaBR - Powered by Serotonin's Mango M2M
User: admin
Data sources
BACnet I/P
Disabled - click to enable

Name	Type	Connection	Status
CPLC	Modbus IP	172.16.5.41:502	

Point name	Description	Status
bus_voltage_0	Numeric / Slave id 1, offset 2048	
bus_voltage_1	Numeric / Slave id 1, offset 2050	
bus_voltage_10	Numeric / Slave id 1, offset 2068	
bus_voltage_11	Numeric / Slave id 1, offset 2070	
bus_voltage_12	Numeric / Slave id 1, offset 2072	
bus_voltage_13	Numeric / Slave id 1, offset 2074	
bus_voltage_14	Numeric / Slave id 1, offset 2076	
bus_voltage_15	Numeric / Slave id 1, offset 2078	
bus_voltage_16	Numeric / Slave id 1, offset 2080	
bus_voltage_17	Numeric / Slave id 1, offset 2082	
bus_voltage_18	Numeric / Slave id 1, offset 2084	

Figure 20

7 Pandapower Simulation

SSD file is input to create the SLD of the electrical system. The parameter specification detail are provided by extra configuration XML files.

7.1 Dependencies required

(1) Install pandapower, by running the command:
pip install pandapower
(http://www.pandapower.org/start/#install)

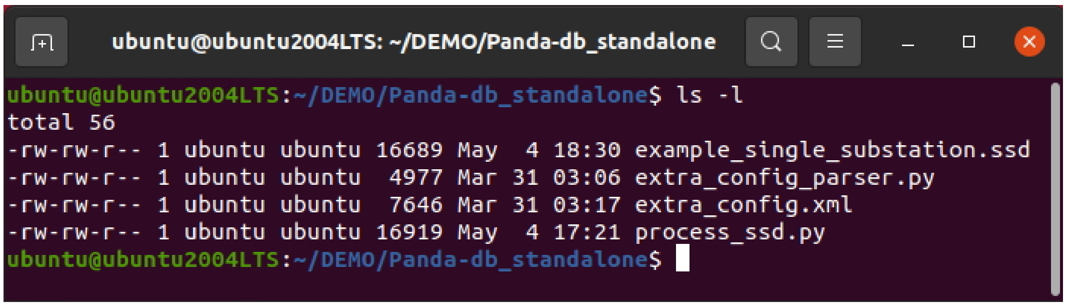
(2) Python3

(3) Python modules:

- pymysql
  pip install pymysql
- matplotlib
  pip install matplotlib
- python-igraph
  pip install python-igraph

7.2 Folder contents

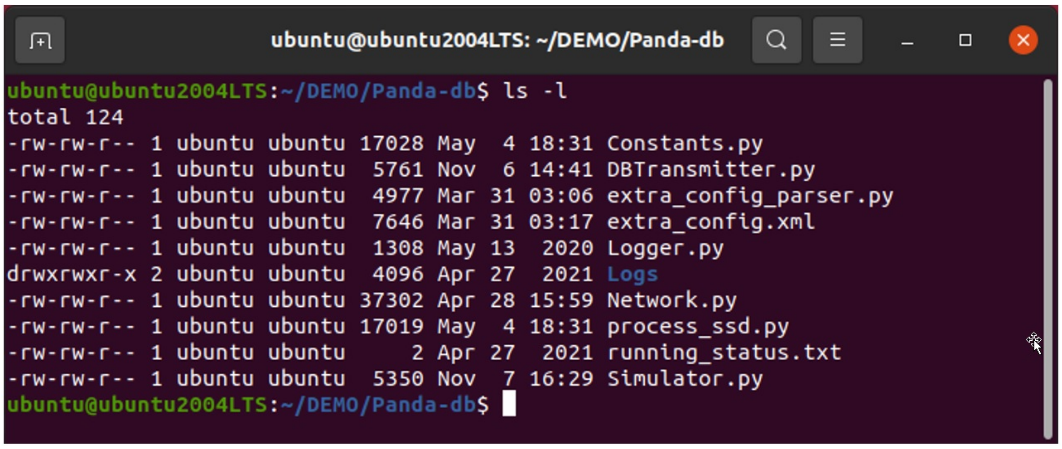
(1) Standalone system
SSD file, extra_config.xml, extra_config_parser.py, process_ssd.py as listed in Fig. 21.



```
ubuntu@ubuntu2004LTS:~/DEMO/Panda-db_standalone$ ls -l
total 56
-rw-rw-r-- 1 ubuntu ubuntu 16689 May  4 18:30 example_single_substation.ssd
-rw-rw-r-- 1 ubuntu ubuntu  4977 Mar 31 03:06 extra_config_parser.py
-rw-rw-r-- 1 ubuntu ubuntu  7646 Mar 31 03:17 extra_config.xml
-rw-rw-r-- 1 ubuntu ubuntu 16919 May  4 17:21 process_ssd.py
ubuntu@ubuntu2004LTS:~/DEMO/Panda-db_standalone$ 
```

Figure 21

(2) Dynamic system (cyber network simulation with virtual IEDs, PLC and SCADA)
SSD file, extra_config.xml, extra_config_parser.py, process_ssd.py, Simulator.py, Constants.py, DBTransmitter.py, Logger.py, Network.py, running_status.txt and Logs folder as listed in Fig. 22.



```
ubuntu@ubuntu2004LTS:~/DEMO/Panda-db$ ls -l
total 124
-rw-rw-r-- 1 ubuntu ubuntu 17028 May  4 18:31 Constants.py
-rw-rw-r-- 1 ubuntu ubuntu  5761 Nov  6 14:41 DBTransmitter.py
-rw-rw-r-- 1 ubuntu ubuntu  4977 Mar 31 03:06 extra_config_parser.py
-rw-rw-r-- 1 ubuntu ubuntu  7646 Mar 31 03:17 extra_config.xml
-rw-rw-r-- 1 ubuntu ubuntu  1308 May 13  2020 Logger.py
drwxrwxr-x 2 ubuntu ubuntu  4096 Apr 27  2021 Logs
-rw-rw-r-- 1 ubuntu ubuntu 37302 Apr 28 15:59 Network.py
-rw-rw-r-- 1 ubuntu ubuntu 17019 May  4 18:31 process_ssd.py
-rw-rw-r-- 1 ubuntu ubuntu     2 Apr 27  2021 running_status.txt
-rw-rw-r-- 1 ubuntu ubuntu  5350 Nov  7 16:29 Simulator.py
ubuntu@ubuntu2004LTS:~/DEMO/Panda-db$
```

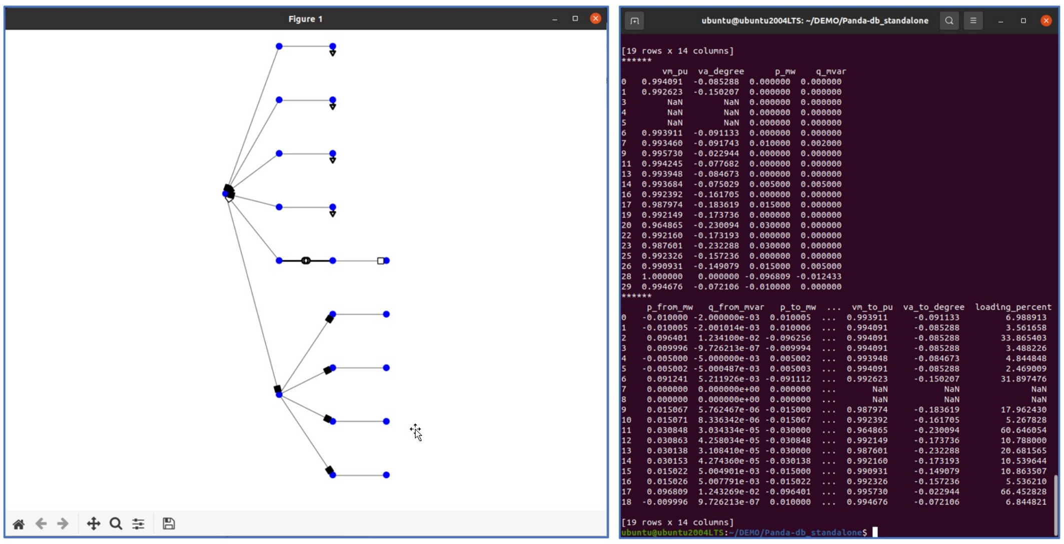
Figure 22

7.3 Commands to run the Pandapower simulation

(1) Standalone system

python3 process_ssd.py

Output:



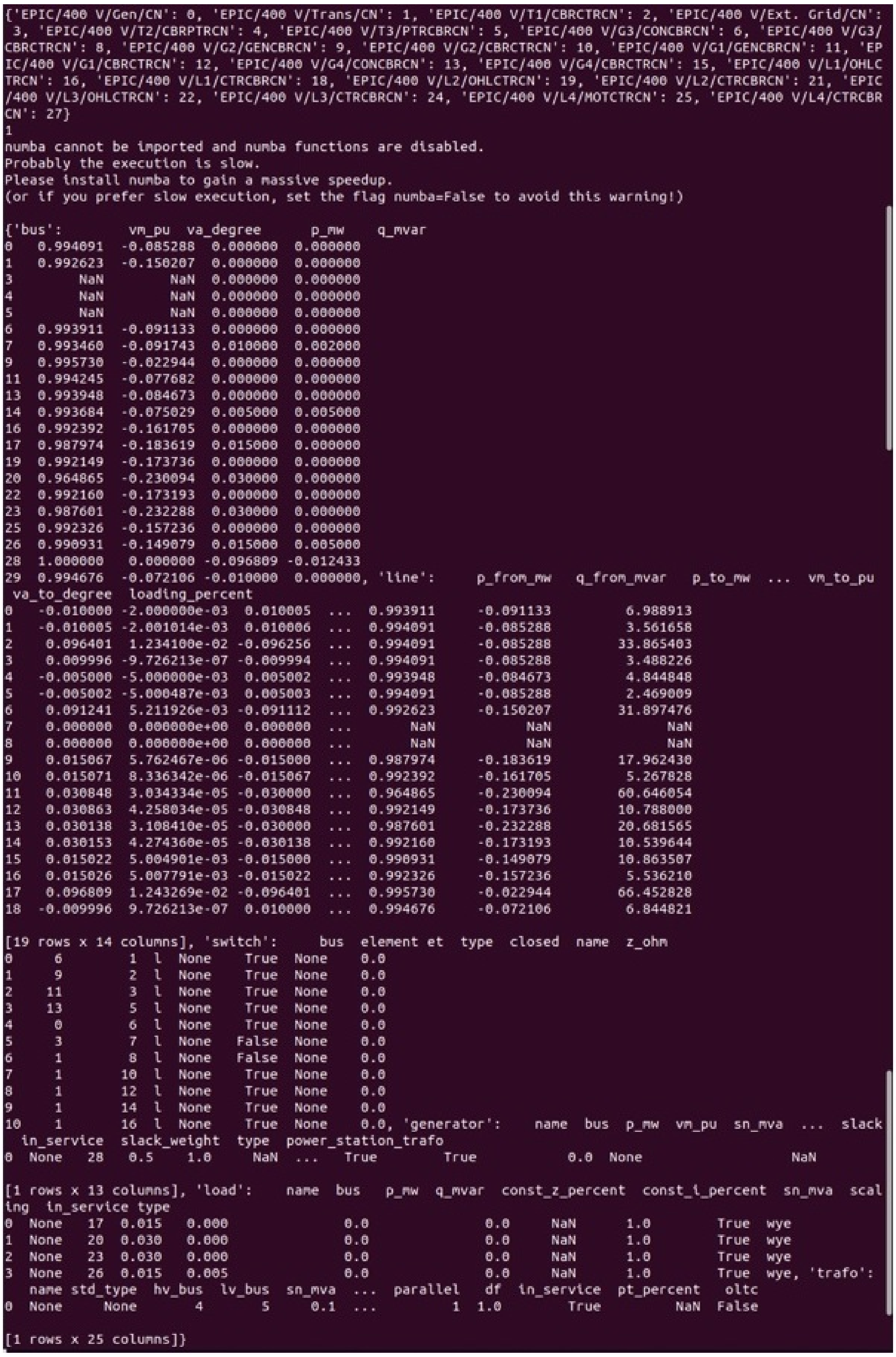
```
[19 rows x 14 columns]
******
      vm_pu  va_degree      p_mw    q_mvar
0   0.994091  -0.085288  0.000000  0.000000
1   0.992623  -0.150207  0.000000  0.000000
3        NaN        NaN  0.000000  0.000000
4        NaN        NaN  0.000000  0.000000
5        NaN        NaN  0.000000  0.000000
6   0.993911  -0.091133  0.000000  0.000000
7   0.993460  -0.091743  0.010000  0.002000
9   0.995730  -0.022944  0.000000  0.000000
11  0.994245  -0.077682  0.000000  0.000000
13  0.993948  -0.084673  0.000000  0.000000
14  0.993684  -0.075029  0.005000  0.005000
16  0.992392  -0.161705  0.000000  0.000000
17  0.987974  -0.183619  0.015000  0.000000
19  0.992149  -0.173736  0.000000  0.000000
20  0.964865  -0.230094  0.030000  0.000000
22  0.992160  -0.173193  0.000000  0.000000
23  0.987601  -0.232288  0.030000  0.000000
25  0.992326  -0.157236  0.000000  0.000000
26  0.990931  -0.149079  0.015000  0.005000
28  1.000000   0.000000 -0.096809 -0.012433
29  0.994676  -0.072106 -0.010000  0.000000
******
    p_from_mw   q_from_mvar   p_to_mw  ...  vm_to_pu  va_to_degree  loading_percent
0   -0.010000 -2.000000e-03  0.010005  ...  0.993911     -0.091133         6.988913
1   -0.010005 -2.001014e-03  0.010006  ...  0.994091     -0.085288         3.561658
2    0.096401  1.234100e-02 -0.096256  ...  0.994091     -0.085288        33.865403
3    0.009996 -9.726213e-07 -0.009994  ...  0.994091     -0.085288         3.488226
4   -0.005000 -5.000000e-03  0.005002  ...  0.993948     -0.084673         4.844848
5   -0.005002 -5.000487e-03  0.005003  ...  0.994091     -0.085288         2.469009
6    0.091241  5.211926e-03 -0.091112  ...  0.992623     -0.150207        31.897476
7    0.000000  0.000000e+00  0.000000  ...       NaN           NaN              NaN
8    0.000000  0.000000e+00  0.000000  ...       NaN           NaN              NaN
9    0.015067  5.762467e-06 -0.015000  ...  0.987974     -0.183619        17.962430
10   0.015071  8.336342e-06 -0.015067  ...  0.992392     -0.161705         5.267828
11   0.030848  3.034334e-05 -0.030000  ...  0.964865     -0.230094        60.646054
12   0.030863  4.258034e-05 -0.030848  ...  0.992149     -0.173736        10.788000
13   0.030138  3.108410e-05 -0.030000  ...  0.987601     -0.232288        20.681565
14   0.030153  4.274360e-05 -0.030138  ...  0.992160     -0.173193        10.539644
15   0.015022  5.004901e-03 -0.015000  ...  0.990931     -0.149079        10.863507
16   0.015026  5.007791e-03 -0.015022  ...  0.992326     -0.157236         5.536210
17   0.096809  1.243269e-02 -0.096401  ...  0.995730     -0.022944        66.452828
18  -0.009996  9.726213e-07  0.010000  ...  0.994676     -0.072106         6.844821

[19 rows x 14 columns]
ubuntu@ubuntu2004LTS:~/DEMO/Panda-db_standalone$
```

Figure 23

(2) Dynamic system

python3 Simulator.py

Output:



```
{'EPIC/400 V/Gen/CN': 0, 'EPIC/400 V/Trans/CN': 1, 'EPIC/400 V/T1/CBRCTRCN': 2, 'EPIC/400 V/Ext. Grid/CN':
 3, 'EPIC/400 V/T2/CBRPTRCN': 4, 'EPIC/400 V/T3/PTRCBRCN': 5, 'EPIC/400 V/G3/CONCBRCN': 6, 'EPIC/400 V/G3/
CBRCTRCN': 8, 'EPIC/400 V/G2/GENCBRCN': 9, 'EPIC/400 V/G2/CBRCTRCN': 10, 'EPIC/400 V/G1/GENCBRCN': 11, 'EP
IC/400 V/G1/CBRCTRCN': 12, 'EPIC/400 V/G4/CONCBRCN': 13, 'EPIC/400 V/G4/CBRCTRCN': 15, 'EPIC/400 V/L1/OHLC
TRCN': 16, 'EPIC/400 V/L1/CTRCBRCN': 18, 'EPIC/400 V/L2/OHLCTRCN': 19, 'EPIC/400 V/L2/CTRCBRCN': 21, 'EPIC
/400 V/L3/OHLCTRCN': 22, 'EPIC/400 V/L3/CTRCBRCN': 24, 'EPIC/400 V/L4/MOTCTRCN': 25, 'EPIC/400 V/L4/CTRCBR
CN': 27}
1
numba cannot be imported and numba functions are disabled.
Probably the execution is slow.
Please install numba to gain a massive speedup.
(or if you prefer slow execution, set the flag numba=False to avoid this warning!)

{'bus':         vm_pu  va_degree      p_mw    q_mvar
0   0.994091  -0.085288  0.000000  0.000000
1   0.992623  -0.150207  0.000000  0.000000
3        NaN        NaN  0.000000  0.000000
4        NaN        NaN  0.000000  0.000000
5        NaN        NaN  0.000000  0.000000
6   0.993911  -0.091133  0.000000  0.000000
7   0.993460  -0.091743  0.010000  0.002000
9   0.995730  -0.022944  0.000000  0.000000
11  0.994245  -0.077682  0.000000  0.000000
13  0.993948  -0.084673  0.000000  0.000000
14  0.993684  -0.075029  0.005000  0.005000
16  0.992392  -0.161705  0.000000  0.000000
17  0.987974  -0.183619  0.015000  0.000000
19  0.992149  -0.173736  0.000000  0.000000
20  0.964865  -0.230094  0.030000  0.000000
22  0.992160  -0.173193  0.000000  0.000000
23  0.987601  -0.232288  0.030000  0.000000
25  0.992326  -0.157236  0.000000  0.000000
26  0.990931  -0.149079  0.015000  0.005000
28  1.000000   0.000000 -0.096809 -0.012433
29  0.994676  -0.072106 -0.010000  0.000000, 'line':     p_from_mw   q_from_mvar   p_to_mw  ...  vm_to_pu
 va_to_degree  loading_percent
0   -0.010000 -2.000000e-03  0.010005  ...  0.993911     -0.091133        6.988913
1   -0.010005 -2.001014e-03  0.010006  ...  0.994091     -0.085288        3.561658
2    0.096401  1.234100e-02 -0.096256  ...  0.994091     -0.085288       33.865403
3    0.009996 -9.726213e-07 -0.009994  ...  0.994091     -0.085288        3.488226
4   -0.005000 -5.000000e-03  0.005002  ...  0.993948     -0.084673        4.844848
5   -0.005002 -5.000487e-03  0.005003  ...  0.994091     -0.085288        2.469009
6    0.091241  5.211926e-03 -0.091112  ...  0.992623     -0.150207       31.897476
7    0.000000  0.000000e+00  0.000000  ...       NaN           NaN             NaN
8    0.000000  0.000000e+00  0.000000  ...       NaN           NaN             NaN
9    0.015067  5.762467e-06 -0.015000  ...  0.987974     -0.183619       17.962430
10   0.015071  8.336342e-06 -0.015067  ...  0.992392     -0.161705        5.267828
11   0.030848  3.034334e-05 -0.030000  ...  0.964865     -0.230094       60.646054
12   0.030863  4.258034e-05 -0.030848  ...  0.992149     -0.173736       10.788000
13   0.030138  3.108410e-05 -0.030000  ...  0.987601     -0.232288       20.681565
14   0.030153  4.274360e-05 -0.030138  ...  0.992160     -0.173193       10.539644
15   0.015022  5.004901e-03 -0.015000  ...  0.990931     -0.149079       10.863507
16   0.015026  5.007791e-03 -0.015022  ...  0.992326     -0.157236        5.536210
17   0.096809  1.243269e-02 -0.096401  ...  0.995730     -0.022944       66.452828
18  -0.009996  9.726213e-07  0.010000  ...  0.994676     -0.072106        6.844821

[19 rows x 14 columns], 'switch':     bus  element et  type  closed  name  z_ohm
0     6        1  l  None    True  None    0.0
1     9        2  l  None    True  None    0.0
2    11        3  l  None    True  None    0.0
3    13        5  l  None    True  None    0.0
4     0        6  l  None    True  None    0.0
5     3        7  l  None   False  None    0.0
6     1        8  l  None   False  None    0.0
7     1       10  l  None    True  None    0.0
8     1       12  l  None    True  None    0.0
9     1       14  l  None    True  None    0.0
10    1       16  l  None    True  None    0.0, 'generator':    name  bus  p_mw  vm_pu  sn_mva  ...  slack
  in_service  slack_weight  type  power_station_trafo
0  None   28   0.5    1.0     NaN  ...   True        True          0.0  None                 NaN

[1 rows x 13 columns], 'load':    name  bus   p_mw  q_mvar  const_z_percent  const_i_percent  sn_mva  scal
ing  in_service type
0  None   17  0.015   0.000              0.0              0.0     NaN      1.0        True  wye
1  None   20  0.030   0.000              0.0              0.0     NaN      1.0        True  wye
2  None   23  0.030   0.000              0.0              0.0     NaN      1.0        True  wye
3  None   26  0.015   0.005              0.0              0.0     NaN      1.0        True  wye, 'trafo':
   name std_type  hv_bus  lv_bus  sn_mva  ...  parallel   df  in_service  pt_percent   oltc
0  None     None       4       5     0.1  ...         1  1.0        True         NaN  False

[1 rows x 25 columns]}
```

Figure 24

8 Larger Scale Model

The following utilities can be used to create the artifacts required for larger scale models.

8.1 SSD Merger

This utility merges multiple single-substation SSD files into one multi-substations SSD file given the SED files.
To use:

(1) Place single-substation SSD files and respective SED files in ssd_sed_input_files folder

(2) Run:
python3 merge_ssd.py

(3) The merged SSD file will be created in the ssd_output_file folder

8.2 SCD Merger

This utility merges mulitple single-substation SCD files into one multi-substations SCD file.
To use:

(1) Place single-substation SCD files in scd_input_files folder

(2) Run:
python3 merge_scd.py

(3) The merged SCD file will be created in scd_output_files folder

Edit merge_scd.py to point to input and output SCD files of your choice.

8.3 SCD Parser

This utility converts an SCD file to JSON format, which can then be used as an input file for Mininet.
To run:

- python3 parse.py

Edit parse.py to point to the SCD and JSON files of your choice.

8.4 Thresholds

The file Thresholds.xml contains the threshold values for all IEDs. It can be created manually or with the script below to help create one using a threshold template.
Input files required from user to be placed in working_folder:

- <IED_name>.icd for every IED (can be placed under sub-folders)

To run:

- python3 create_thresholds.py

The following file will be generated in working_folder:

- Thresholds.xml

9 Acknowledgement

This work is supported by the National Research Foundation, Singapore, Singapore University of Technology and Design under its National Satellite of Excellence in Design Science and Technology for Secure Critical Infrastructure Grant (NSoE_DeST-SCI2019-0005).