

## Virtual Lab Description

The Virtual Lab is an online educational simulation tool that mimics the operation of the actual laboratory microgrid of ICCS-NTUA. A mathematical model of the laboratory microgrid has been developed along with a friendly Graphical User Interface (GUI). The tool is web-based which eliminates the need for downloading software, while it allows the simultaneous use by several users. The user can access the web platform with a simple sign up process. Once the user has logged-in, he can observe several variables (e.g. voltage, active power, reactive power etc) and perform several actions (e.g. change the power factor of the inverter). The simulation tool includes two different laboratory setups and corresponding experiments which are described below, along with some theoretic background:

- Voltage control
- Microgrid operation

In parallel, a Remote Lab has been developed where the user gains access to the SCADA of the actual laboratory microgrid of ICCS-NTUA and can monitor and control remotely hardware equipment (see corresponding section of the ERIGrid website). The GUI and the laboratory setups used are exactly the same with the Virtual Lab.

### 1) Voltage control

The main objectives of this experiment are to demonstrate the voltage rise issue that can occur in distribution networks, due to the high production of Distributed Generation (DG) (mainly Photovoltaics), but also the ancillary services that modern DG inverters offer in order to mitigate the aforementioned voltage rise.

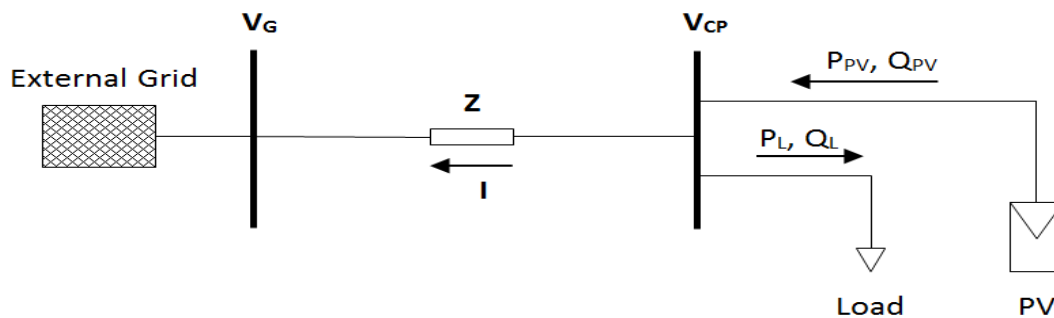


Figure 1: Two bus system

According to power system theory, the voltage drop or rise along a line ( $R, X$ ) where at the end a load and/or PV is connected (Figure 1), can be approximated with the following equation:

$$\Delta V \approx \frac{(P_{pv} - P_{Load}) \cdot R + (Q_{pv} - Q_{load}) \cdot X}{V_G}$$

Therefore, if  $P_{pv} * R > (P_{load} * R + Q_{load} * X)$  and  $Q_{pv} = 0$ , the voltage of the coupling point ( $V_{CP}$ ) will be higher than the grid voltage ( $V_G$ ). The impact of active and reactive power on the voltage depends on the resistance ( $R$ ) and inductance ( $X$ ) of the line (e.g. in low voltage networks where  $R$  is higher than  $X$ , the impact of the active power is stronger than the reactive power). The voltage rise can be mitigated if the PV inverter absorbs reactive power ( $Q_{pv}$ ), according to the above equation.

The laboratory setup that is simulated for this experiment can be seen in Figure 2. It should be noted that at the Remote Lab application the below laboratory setup is actually implemented in the hardware laboratory (i.e. a hardware R-L line module is connected between the utility grid and a hardware PV inverter). In order to better demonstrate the voltage rise problem there is no load connected at the end of the line. Therefore, if the reactive power of the inverter is also zero, there will always be a voltage rise due to the PV production.

The GUI for this experiment is presented in Figure 3 and Figure 4. As shown in Figure 3, the user can monitor the voltage, active power, reactive power and power factor of both the PV inverter and the main grid. From the control panel on the left side of the screen, the user can perform three main actions:

- Adjust the operating power factor of the inverter (available values are 0.8, 0.85, 0.9, 0.95 and 1, according to the capabilities of the inverter). All power factor values that are less than unity represent absorption of reactive power.
- Adjust the active power set-point of the inverter (i.e. in order to curtail active power). If the set-point is set above the Maximum Power Point ( $P_{mpp}$ ) value, the inverter will operate at  $P_{mpp}$  instead.
- Activate or deactivate the Voltage-Reactive Power Q(V) droop control. Activating the Q(V) droop control, disables the power factor set-point that the user has set on the 1<sup>st</sup> input field.

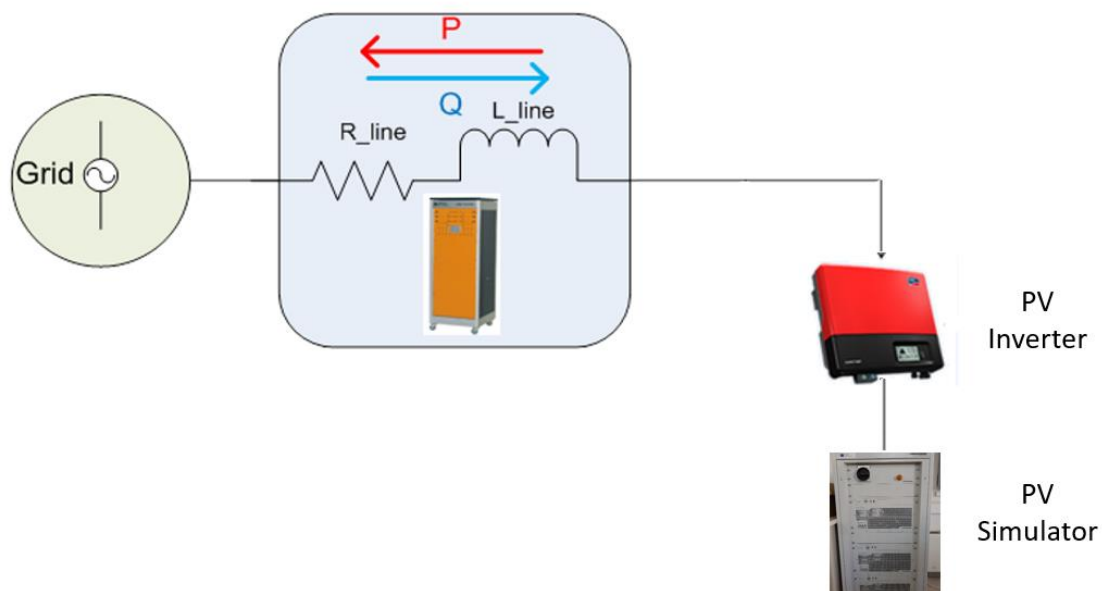


Figure 2: Setup of the voltage rise experiment

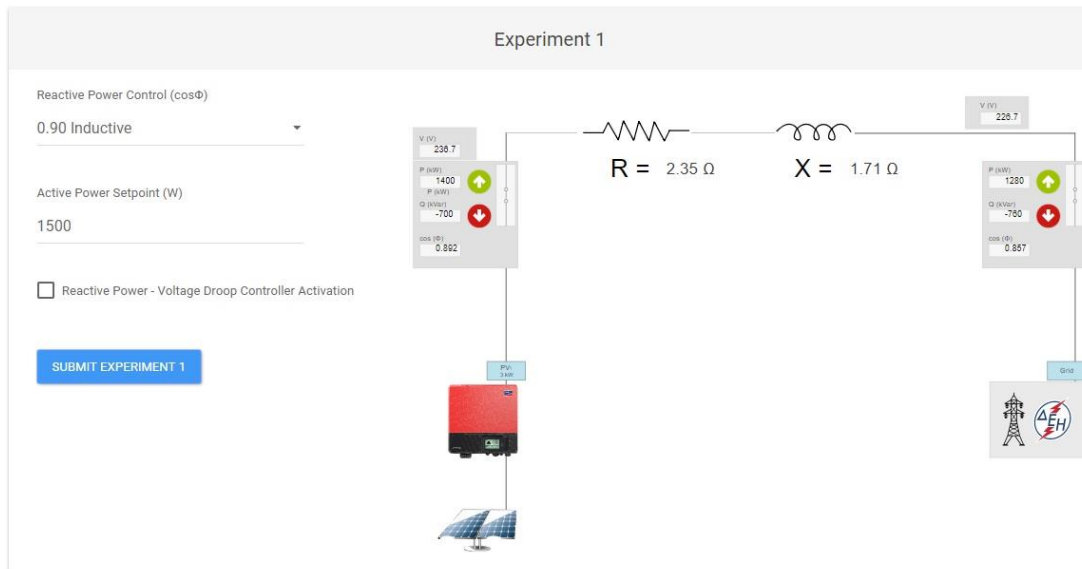


Figure 3: Graphical User Interface of the voltage control experiment

Below this part of the GUI, the user is presented with four line charts displaying the voltage, active power, reactive power and power factor of the PV inverter respectively. The X-axis of the charts displays the UTC time. A new data point is added on the charts every 5 seconds. At the Virtual Lab the presented values are results of the mathematical model. At the Remote Lab application, the data points are imported from the SCADA system's database. Figure 4 shows the four line charts of the experiment during a change of the power factor of the inverter from unity (1) to 0.85 inductive (e.g. according to a command by the distribution system operator). The change occurs at 08:59:35 UTC, as seen on the charts. It is shown that when the power factor is set to 0.85 inductive, the PV inverter starts absorbing reactive power (850 VAR) in order to mitigate the voltage rise (the voltage is reduced from 245.5 V to 238 V).



Figure 4: Voltage, active power, reactive power and power factor of the inverter via the GUI of the Virtual Lab

## 2) Microgrid operation

The objective of the second experiment is to familiarize the user with the concept of microgrids in both grid-connected and islanded operating modes. The single phase microgrid of the laboratory of ICCS-NTUA is mathematically modelled. Access is provided from the same web platform as the previous experiment. The online GUI can be seen in Figure 5 and Figure 6. Figure 5 displays the main part of the GUI, where the user can monitor the state of all the units that comprise the microgrid, which are (from left to right): a wind turbine with its inverter, a lead-acid battery bank with its inverter, PV panels with their inverter, resistive and inductive loads and the utility grid. The active power, reactive power and power factor is monitored for each unit, as well as the voltage and frequency of the AC bus where all the units are connected on. On the left side of this part of the GUI, the user can select different values for the microgrid's resistive loads. The available values are: 250 W, 750 W, 1250 W, 1750 W and 2250 W according to the capabilities of the laboratory.

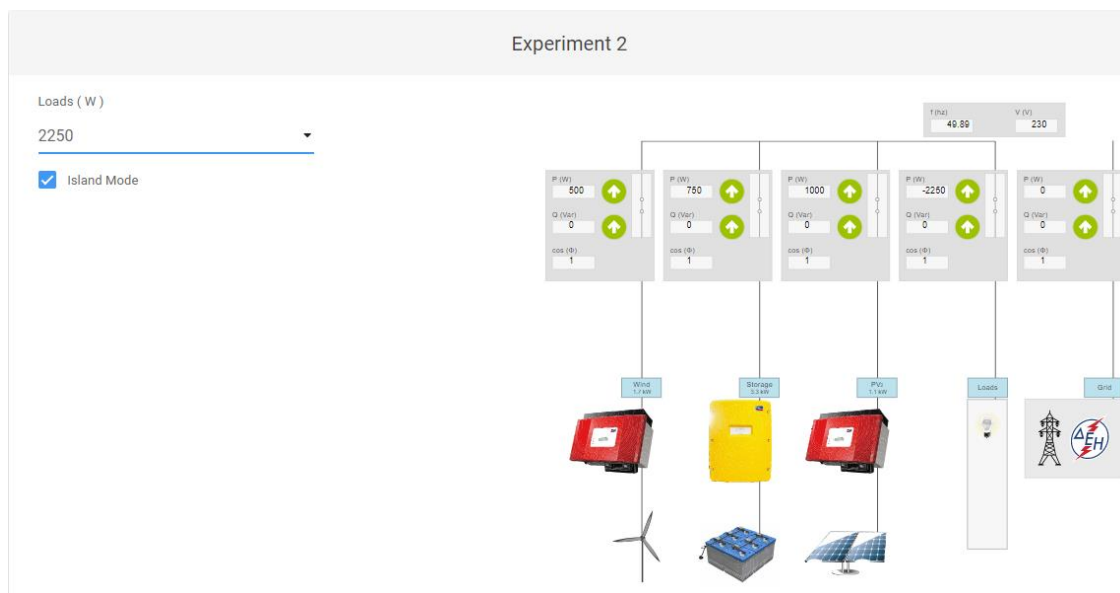


Figure 5: Graphical User Interface of the microgrid operation experiment

Figure 6 depicts two charts. The top chart represents the microgrid active power balancing, showing the active power of all the microgrid's units and the utility grid. The user can select or deselect a specific unit's graph line by using the legend on the bottom side of the chart, which allows an efficient visual representation. The bottom chart displays the microgrid's AC bus frequency.

It must be noted that at the Remote Lab application, the active power of all the microgrid's units and the utility grid are imported from the SCADA system's database and added on the chart every 5 seconds, while control of the loads is also performed via the SCADA.



*Figure 6: Active power balance and frequency of the microgrid*

The experiment starts with the microgrid in grid-connected mode, where the user observes that the utility grid is responsible for the power balancing of the microgrid's units when changes in the loads and production occur, while the battery inverter is in idle state, acting according to its Battery Management System (BMS).

Next, the microgrid is switched to islanded mode. In this state, the user again performs changes in the loads and monitors the response of the battery inverter, which is now responsible for the power balancing, since the utility grid is disconnected. The frequency of the microgrid is also monitored which depends on the  $f(P)$  droop characteristic of the battery inverter (similar to synchronous generators). Figure 6 shows that at the transition to islanded mode the frequency rises, because the RES production exceeds the load and the battery inverter absorbs active power. Next, the load is increased leading to a reduction of the frequency.