USER MANUAL

Photovoltaic Hosting Capacity (PVHC) estimator plugin for PowerFactory

2018 edition

With the open-source PVHC estimator tool, accurately and rapidly compute the hosting capacity of your electrical network under specific solar configurations and user-defined control algorithms. Include battery systems, redefine PVHC thresholds and tailor your simulation according to your project's needs. This tool is freely available as a PowerFactory plugin (PowerFactory license not included).

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About this manual

This manual is designed to help acquaint you with the fundamentals of PVHC. This manual provides information on how to setup PVHC with PowerFactory, the methodology used to compute the PV hosting capacity and the usage of PVHC with detailed description of user inputs. This manual ends with a case example to showcase the capabilities of PVHC. Furthermore, this manual is designed with hyperlinks scattered throughout the document in order to help with navigation.

PVHC is intended for users with technical know-how in the field of power engineering and electrical network simulation with PowerFactory. An operational network modelled in PowerFactory is required, basic knowledge of coding in Python is recommended and Python scripting with PowerFactory is optional.

This manual does not serve as a Python documentation nor does it replace the user manual and all technical references of PowerFactory. In addition, this manual does not serve as a troubleshooter for simulation issues in PowerFactory nor does it interpret the results and outcomes of PVHC. Finally, PVHC will not account for real life decision making and declines all related responsibilities.

What's new in 2018

Main new features and developments have been introduced in PVHC 2018, namely:

- It is now possible to compute the PV hosting capacity with PV systems modelled under **Active Power Input**. Until now, PVHC was only compatible with **Solar Calculation** models. Only PV systems with identical modelling can be part of a same PVHC computation.
- Objects are now class-based, namely PowerFactory objects created within PVHC. The code is therefore more readable compared to a dictionary-based approach.
- Results are output in .txt files, as opposed to Excel files of the previous PVHC version.
- Once a PVHC is executed, more information is shown, namely:
    - A figure depicting the evolution of the number of panels incremented for each PV system (only available for **Solar Calculation** models).
    - A logging of the algorithm is displayed, making it easier to identify the steps taken by PVHC.

Contents

1 Preface

With the rise of concerns for the environment and advances in technology for renewable energies, the number of distributed energy resources (DER) on the distribution network is increasing, namely that of photovoltaic (PV) power stations. The transmission system of today was conceived to allow bulk power to be transported from centralized power plants to end-users and did not anticipate the large deployment of competitive-priced solar power at distribution level. Thus, utility companies are experiencing an increasing number of interconnection requests [1] on their networks. Combining this with known power quality issues, such as voltage rise and reverse power flow, related to high penetration of PV generation makes the task of distribution system operators (DSO) more difficult. As a result, the DSO must go through strenuous impact studies to assess the potential adverse effects on their grid [2] before proceeding to the installation of such PV systems. Most utility companies avoid these procedures and choose to undersize their installations which leads to a very conservative deployment of PV production. As a result, the share of renewable energy sources (RES) becomes suboptimal and the grid electrical capabilities are not fully exploited.

To address this difficulty, PVHC was developed for utility companies to rapidly evaluate the current state of their grid in terms of power quality under chosen PV configurations and to estimate the total PV hosting capacity of their network. The latter is defined as "the amount of PV that can be accommodated under existing control and infrastructure configurations" [3]. PVHC takes advantage of PowerFactory to encompass the spatial and time domain of the impact of PV while considering the fully detailed model of the gird to provide an exact estimation of hosting capacity, locally and globally across the feeder.

Moreover, PVHC allows the implementation of user-defined control strategies in order to evaluate and compare their beneficial effects with respect to power quality and hosting capacity.

1.1 What is PVHC

PVHC is a tool that allows you to compute the PV hosting capacity of a radial low-voltage distribution network rapidly and accurately with a high level of customization according to your project's needs. Indeed, you may redefine the thresholds for your hosting capacity, involve battery systems and include or not grid elements into the algorithm.

PVHC is programmed in Python and runs in parallel with PowerFactory. The functionalities of PowerFactory are provided in Python through a dynamic module which interfaces with the PowerFactory API thus providing Python scripts with access to a comprehensive range of data in the host application. Conversely, integrating the Python scripting language in PowerFactory allows the automation of tasks and the creation of user-defined calculation commands and methods.

When launched from within PowerFactory, PVHC takes your project's current set-up of the grid modelled in PowerFactory and allows the configuration of various settings through a user-friendly interface, offering a seamless integration with PowerFactory.

PVHC is highly expandable and portable in a way that with proper knowledge of Python scripting with PowerFactory, PVHC's source code can easily be modified to suit any project's needs.

1.2 What PVHC is not

PVHC is not an electrical power system simulation software nor does it replace PowerFactory or any of its functionalities. Furthermore, PVHC is not a standalone program and requires an operational grid modelled in PowerFactory.

2 Installation

2.1 System requirements

PVHC requires an installation of PowerFactory with a working license containing at least the modules *Quasi-Dynamic Simulation* and *Scripting and Automation*. System requirements follow the same as PowerFactory installed on your computer.

2.2 Setting up PVHC

This subsection describes a step-by-step procedure for setting up and running PVHC. Before proceeding, it is highly recommended to install WinPython (`http://winpython.github.io/`) since it contains all necessary tools (Python, 3rd party Python packages, PyQt, Qt Designer, and a coding IDE called Spyder) needed for the setup below. Installing WinPython is not mandatory and the procedure described below offers alternatives for setting up PVHC, although they do not guarantee that the plugin will execute properly.

2.2.1 Python interpreter

Before anything else, an installation of a Python interpreter is required (`https://www.python.org/downloads`) and its architecture (32- or 64-bit) should match that of your version of PowerFactory. Python 3.4 is recommended since it was used when developing PVHC. Moreover, this setting is also to be configured within PowerFactory (`TOOLS → External Applications → Python → Version`).

The used editor setting should also be entered in PowerFactory (`TOOLS → External Applications → Python → Used editor`), unless `system default` is selected. An example of editor, which was downloaded along with WinPython:

```
C:\Program Files\WinPython-64bit-3.4.4.6Qt5\Spyder.exe
```

Finally, additional Python packages imported for successfully running PVHC should normally be included in a basic Python installation.

2.2.2 Path appending

This next step involves modifying a few lines of code inside `main.py` by opening the script with your recently downloaded Python editor. First, you should append the directory of the Python module for PowerFactory to your Python path. The module should correspond to the version of Python you have setup beforehand. An example used at the beginning in `main.py,` which should be modified according to your system's setup:

```
sys.path.append('C:\\Program Files\\DIgSILENT\\PowerFactory 2018 SP3)
```

```
sys.path.append('C:\\Program Files\\DIgSILENT\\PowerFactory 2018 SP3\\Python\\3.4')
```

Optionally, you can also append the directory of additional packages to your Python path. An example used inside `main.py,` which should be modified according to you system's setup:

```
sys.path.append('C:\\Program Files\\WinPython-64bit-3.4.4.6Qt5\\python-3.4.4.amd64\\Lib\\site-
packages')
```

2.2.3 Installing PyQt5

PVHC was developed using Qt Designer, a visual tool for making graphical user interfaces (GUI) and included in a WinPython installation. In order for Qt Designer to work, it uses a package called PyQt, which also comes along with WinPython. If you are not using WinPython, you do not need to install Qt itself, PyQt contains the Qt Designer executable and all necessary Python packages and can be downloaded here: `https://riverbankcomputing.com/software/pyqt/download5`.

With WinPython, Qt Designer and PyQt are included and you should automatically have a directory called PyQt5 inside Python's site-packages directory. An example that could be different according to your system's setup:

```
C:\Program Files\WinPython-64bit-3.4.4.6Qt5\pyhon-3.4.4.amd64\Lib\site-packages\PyQt5
```

2.2.4 Creating a Python command

A Python command object must be created in order to run PVHC from PowerFactory. To create a new Python command in PowerFactory, open the Data-Manager and create a new object via the `New Object` icon in the toolbar. Select `DPL Command and more` and then `Python Script (ComPython)` from the `Element` drop-down list. Creating a `ComPython` object will open up a new window allowing you to modify the recently created object. You may choose a different name for your Python command but you must link `main.py` to it. To do so, go to `Script → Script file` from the `ComPython` window then find and select `main.py` from the directory where PVHC is installed. You may then close the window or execute the script (see sub-section below).

For more information on integrating the Python scripting language in PowerFactory, refer to the user manual of PowerFactory.

2.3 Running PVHC

In order to run PVHC, you can either:

- Open the recently created Python command object via the Data-Manager and click on the `Execute` button.
- Right-click on the recently created Python command in the Data-Manager and click `Execute`.

If successful, the GUI of PVHC should appear. Otherwise, an error message will show up in the PowerFactory output window describing the cause of the failure.

3 Methodology

This section describes the methodology used to compute the PV hosting capacity in PVHC from the basic principles behind the algorithm to how user-defined control strategies are deployed.

3.1 Basic principles

The approach consists in simultaneously incrementing the installed power of all PV systems in the loop of the studied distribution grid, executing a **quasi-dynamic simulation** and a short-circuit analysis in PowerFactory, and freezing the PV systems who led to the violation of predefined thresholds of **power system criteria**. The overall power is increased until all PV systems are frozen or until a specific amount of installed power for each system is reached, in which case the PV hosting capacity is computed.

3.1.1 Increment power

Since the rated power of an installation is highly dependent on the number of installed panels, the power incremented for a PV system is equivalent to that of the peak power of one panel multiplied by the **step size** (in number of panels) defined by the user. This means that it is possible to study the PV hosting capacity with systems of different technologies for which the installed power will not necessarily increase at the same rate (see Figure 1). Furthermore, you can begin incrementing the power from a **starting point** in order to decrease the computation time of the hosting capacity. Incrementing power this way is available for PV systems set to **Solar Calculation**.

As of 2018, it is possible to compute the PV hosting capacity by scaling the nominal power of PV systems uniformly. The approach is the same as incrementing the number of panels. The power incremented for a PV is equivalent to that of the nominal power multiplied by the **step size** (in terms of scaling factor) defined by the user. Finally, a **starting point** can be selected in order to decrease the computation time of the hosting capacity. Incrementing power this way is available for PV systems set to **Active Power Input**.

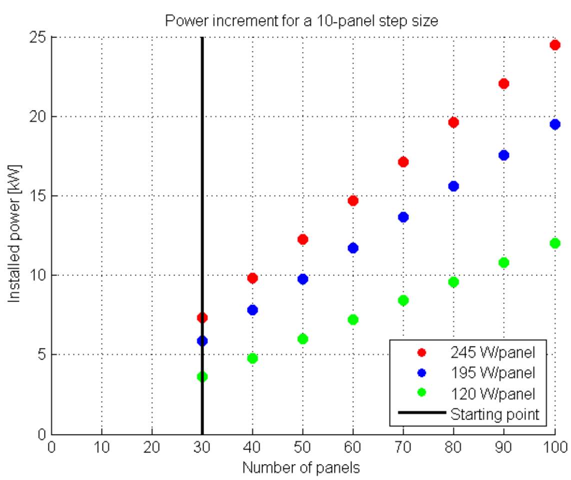

Figure 1 How installed power is incremented (Solar Calculation)

In the example above, three different technologies of PV panels have been installed for three distinct PV systems. After the number of panels is incremented, the resulting powers of each PV system will not necessarily be the same. In order to quantify the hosting capacity purely with respect to installed power, the same panel technology may be set to every PV system.

3.1.2 Customizing PV installations

The computation of a hosting capacity is designed to provide a high level of customization of PV systems. Due to possible installation constraints and depending on the model chosen for the PV plant, it is possible to adjust the **minimum** and

maximum number of installable panels for every PV system. When incrementing the overall power, these limits are covered even if they are not a multiple of the **step size**. The **starting point** is to be adjusted according to the lowest minimum number of panels among all considered PV systems (see Figure 2). PV systems are initially set to the power equivalent to the **minimum number of installable panels** if that number is greater than the **starting point**. This option is available for PV systems set to **Solar Calculation** model.

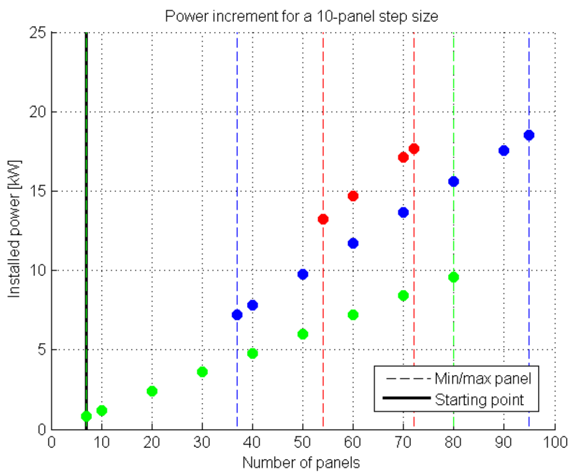

Figure 2 Customizable installations

In the example above, the power incremented will first include the green PV system alone, appending the blue then the red systems as soon at their respective minimum panels have been reached. Conversely, the power will stop incrementing for PV systems having reached their maximum panels, ending with the blue one. The blue and red PV systems are initially set to 37 and 54 panels respectively and are only incremented once the overall power reaches those values.

When computing the PV hosting capacity with PV systems set to **Active Power Input**, the power of every PV system is incremented regardless of maximum or minimum power preferences. This being said, the power of all PV systems start at a **scaling factor** and are incremented by a same **scaling factor** percentage.

3.2 Algorithm setup

Before incrementing the power, a few actions are carried out to prepare the algorithm and assess the feasibility of initial PV system configurations on power system criteria.

3.2.1 PV system ordering

When two or more PV systems are in the loop, their powers are not incremented simultaneously when a power system criteria is violated but rather one at a time. The PV systems are arranged in an **order** pre-defined by the user and calculated before the hosting capacity is performed. This procedure was chosen in order for PV systems which are the most susceptible of creating a particular failure (e.g. line overvoltage) to have their installed power incremented first.

3.2.2 Initial check

At the beginning of the algorithm and before the power is incremented from the **starting point**, all PV systems are set to their **minimum number of installable panels** (**Solar Calculation**) or at the **starting scaling factor** (**Active Power Input**). A quasi-dynamic simulation and a short-circuit analysis are then executed and PV systems causing a failure are turned off in the same order as previously mentioned. These PV systems will therefore not be included in the algorithm of PVHC. A workaround to this issue would be to adjust the minimum number of installable panels of faulty PV systems according to the detected failure before computing the hosting capacity or decrease the starting point for the scaling factor.

3.3 Failure detection and convergence

At each **panel step** or **scaling factor step**, a **quasi-dynamic simulation** and a short-circuit analysis are executed in order to assess the impact of increasing the power of PV systems on the quality of power and on grid reliability. A list of power system criteria [4], [5] considered in PVHC's algorithm is shown below with more details of thresholds **here**:

- Thermal limits of substations, primary, and secondary conductors.
- Power quality, quality of supply voltage.
- Impact on Load Tap Changers or OLTC.
- Fault/short-circuit currents of protection devices.

When a failure (i.e. surpassed threshold) is detected, the recently incremented PV system undergoes a bisection-like method to determine the exact installable power at a one-panel (**Solar Calculation**) or one-percentage scaling factor (**Active Power Input**) precision convergence. This procedure was chosen as a workaround to large **panel steps** or **scaling factor steps** that would have otherwise led to suboptimal solutions of hosting capacity. A flow chart illustrating this method is depicted in Figure 3.

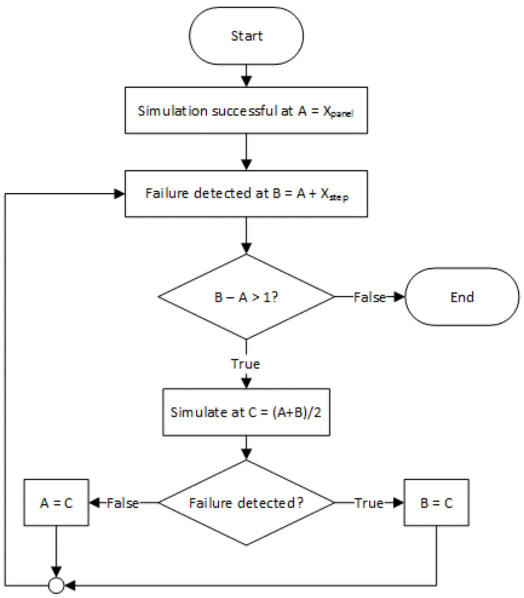

Figure 3 Bisection method to one-panel/one-percentage precision convergence

Once the bisection method is applied, the concerned PV system is frozen, meaning it will not see its power be increased anymore even though the **maximum number of installable panels** has not been reached. After this, the power continues to increase for the remaining PV systems still active in the loop.

3.4 Algorithm termination

The PV hosting capacity is computed when every PV system has either:

- Been turned off at the initial stage of the algorithm,
- Or is frozen after applying the bisection method when a failure is detected,
- Or has reached its maximum number of installable panels (**Solar Calculation**).

The PVHC algorithm is thereafter terminated (see Figure 4).

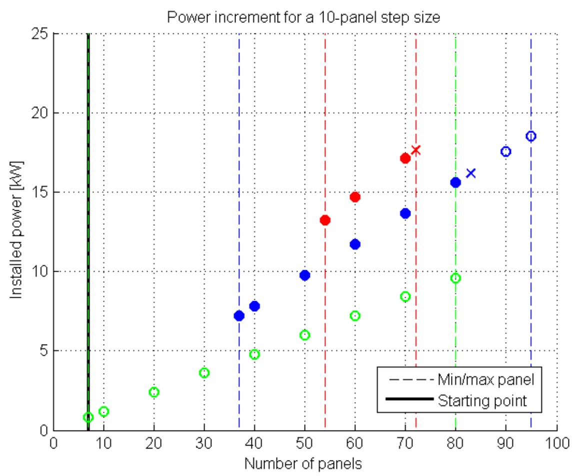

Figure 4 Example of algorithm outcome for Solar Calculation models of PV systems

In the example above, dots and circles represent steps of power that have and have not been examined respectively. Crosses indicate the maximum allowable power of PV systems. This means the green PV system has been turned off from the initial stage of the algorithm, the red system has reached its maximum number of installable panels and finally the blue system underwent the bisection method due to a threshold being reached.

Furthermore, **flags triggered** due to detected failures as well as initial conditions are reset at the end of the algorithm.

3.5 User-defined control strategies

You can implement your own **control strategy** in the form of a Python script that will be executed after the PV hosting capacity is computed. The goal of this feature is to test and compare various control methods in order to assess their ability to increase the hosting capacity. For this task, know-how on Python scripting in PowerFactory is required.

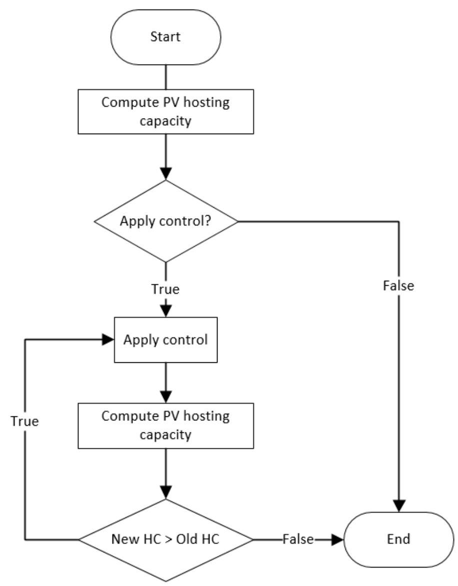

Figure 5 Applying user-defined control strategies with PVHC

In PVHC 2018, this option is not supported for PV systems set to **Active Power Input** model.

4 Overview of PVHC

This section describes the graphical user interface (GUI) of PVHC with a short description of each page and tab. Hyperlinks throughout this section are available after every screenshot and send you to a more detailed description of user inputs (**section 5**).

4.1 General usage

The GUI of PVHC consists of a single window of information divided into two main parts: (I) the **page selection list** on the left and (II) the corresponding set of **user inputs of the selected page** on the right. The GUI was created to offer a seamless integration with PowerFactory in mind.

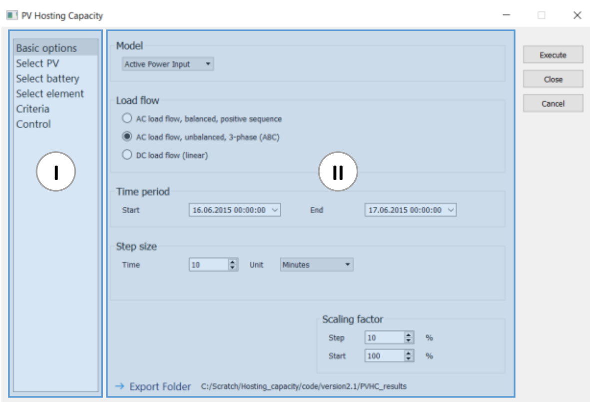

Figure 6 Main body of the graphical user interface of PVHC

4.2 Basic options

This page allows you to modify the type of **model for PV systems**, the **settings of the quasi-dynamic simulation** that are used for the computation of the PV hosting capacity, choose input **parameters for the algorithm**, and finally select the directory in which the simulation **results are exported**.

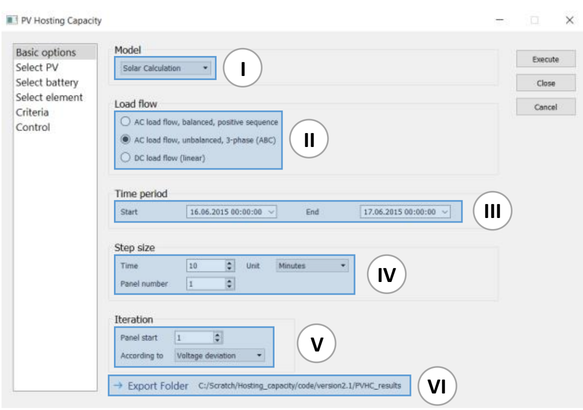

Figure 7 Basic options page

- **I.** **PV model**
- II. **Load flow**
- III. **Time period**
- IV. Step size: **time step size**, **panel step size**
- V. Iteration: **panel start**, **PV order**, **scaling factor step size**, **scaling factor start**
- VI. **Export folder**

4.3 Select PV

4.3.1 PV system tab

This page allows you to select (I) and unselect (II) PV systems to be considered or not in the PVHC algorithm. Only electrically connected PV systems will show up on this page.

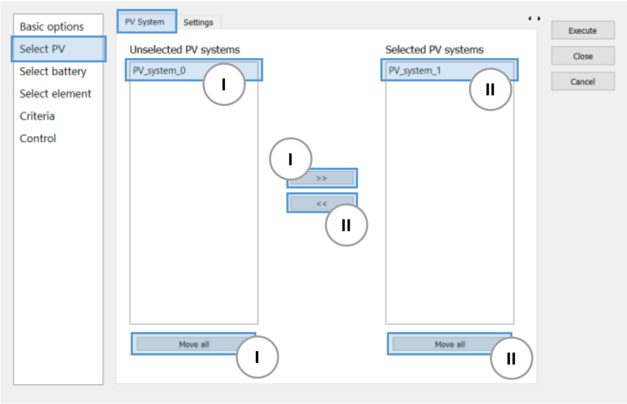

Figure 8 Select PV page, PV system tab

I. Selecting PV systems
II. Unselecting PV systems

4.3.2 Settings tab

This page allows you to configure the PV system selected **(I)**. Only selected PV systems from the PV system tab can be edited. Reconfiguring PV systems in PVHC does not modify their counterpart objects in PowerFactory unless PVHC is executed.

The following settings can be set for PV systems set to **Solar Calculation** here:

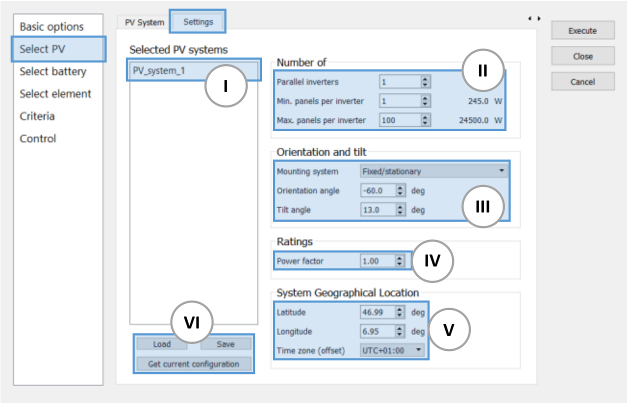

Figure 9 Select PV page, Settings tab, Solar calculation

I. Selected PV system
II. Number of: parallel inverters, minimum panels per inverter, maximum panels per inverter
III. Mounting system, orientation angle, tilt angle
IV. Power factor
V. System geographical location: latitude, longitude, time zone
VI. Save, load and get current PV system configurations

The following settings can be set for PV systems set to **Active Power Input** here:

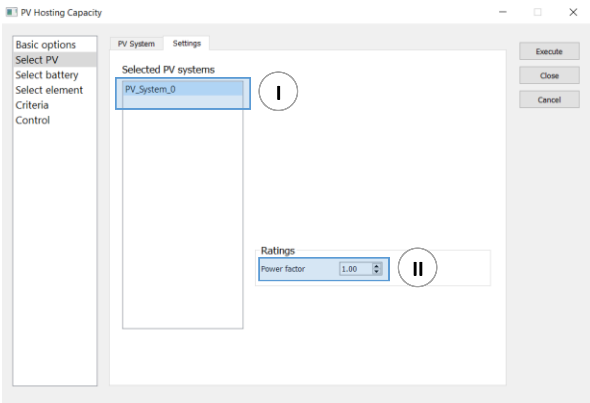

Figure 10 Select PV page, Settings tab, Active power input

I. **Selected PV system**
II. **Power factor**

4.4 Select Battery

4.4.1 Battery tab

This page allows you to **select (I) and unselect (II) battery systems** to be considered or not in the PVHC algorithm. Only electrically connected battery systems will show up on this page. In this version of PVHC, only quasi-dynamic simulation models (QDSL) of battery systems are supported and will appear on this page. Of course, you can create your own battery system model in PowerFactory and have it operate in parallel with PVHC like any other PowerFactory object. For more details on QDSL models, see the PowerFactory user manual.

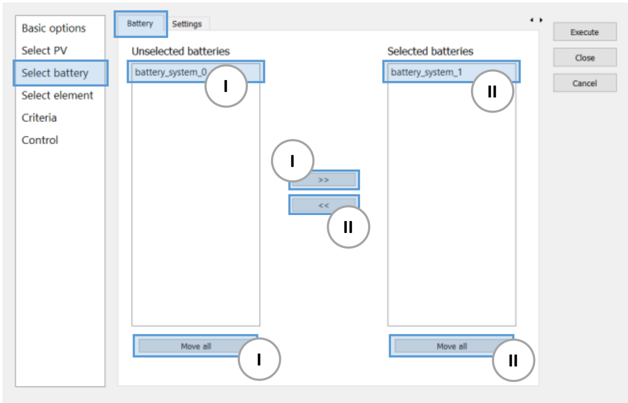

Figure 11 Select battery page, Battery tab

I. **Selecting battery systems**
II. **Unselecting battery systems**

4.4.2 Settings tab

This page allows you to **configure the battery system selected** **(I)**. Only selected battery systems from the **Battery tab** can be edited. Reconfiguring battery systems in PVHC does not modify their counterpart objects in PowerFactory unless PVHC is executed.

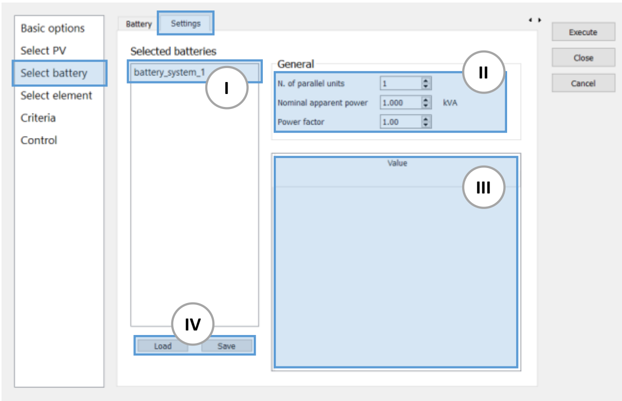

Figure 12 Select battery page, Settings tab

I. **[Selected battery system]**
II. General parameters: **[number of parallel units]**, **[nominal apparent power]**, **[power factor]**
III. **[QDSL battery system parameters]**
IV. **[Save]** and **[load]** battery system configurations

4.5 Select element

This page allows you to **select (I) and unselect (II) PowerFactory elements** (cables/lines, substations, fuses) that will respectively be included and dismissed in the PVHC process. Verification of **power system criteria** will be done for **selected elements** whereas **unselected elements** will be dismissed.

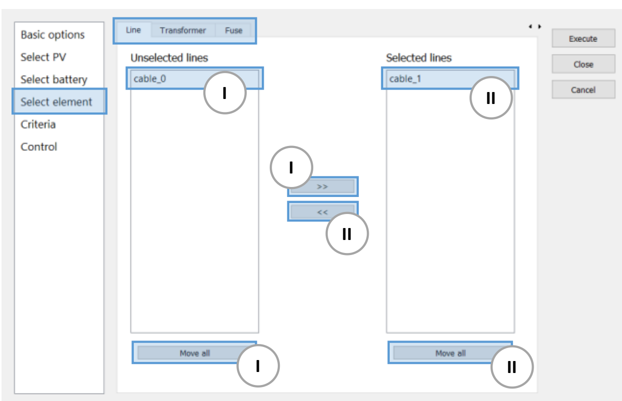

Figure 13 Select element page

I. **Selecting elements**
II. **Unselecting elements**

4.6 Criteria

This pages allows you to **adjust various power system criteria** that are verified for the **selected elements** during the computation of the PV hosting capacity. **Power system criteria** for **unselected elements** are dismissed.

4.6.1 Cables/lines

This page allows you to modify the **power system criteria** that are verified for the **selected cables/lines** during the computation of the PV hosting capacity.

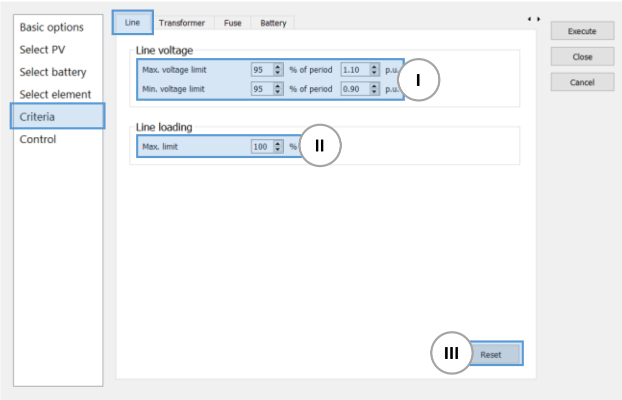

Figure 14 Criteria page, Line tab

I. **Cable/line voltage** criteria
II. **Cable/line loading** criteria
III. **Reset** to default values

4.6.2 Substations

This page allows you to modify the **power system criteria** that are verified for the **selected substations** during the computation of the PV hosting capacity.

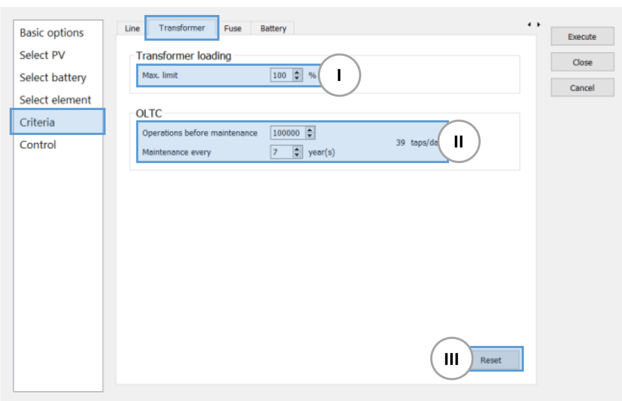

Figure 15 Criteria page, Transformer tab

I. **Substation loading** criteria
II. **Substation OLTC operation** criteria
III. **Reset** to default values

4.6.3 Fuses

This page allows you to modify the **power system criteria** that are verified for the **selected fuses** during the computation of the PV hosting capacity.

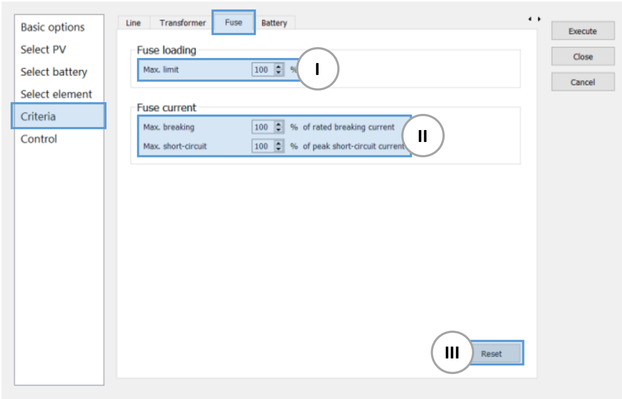

Figure 16 Criteria page, Fuse tab

I. **Fuse loading** criteria
II. **Fuse current** criteria
III. **Reset** to default values

4.6.4 Battery systems

This page allows you to modify the **power system criteria** that are verified for the **selected battery systems** during the computation of the PV hosting capacity.

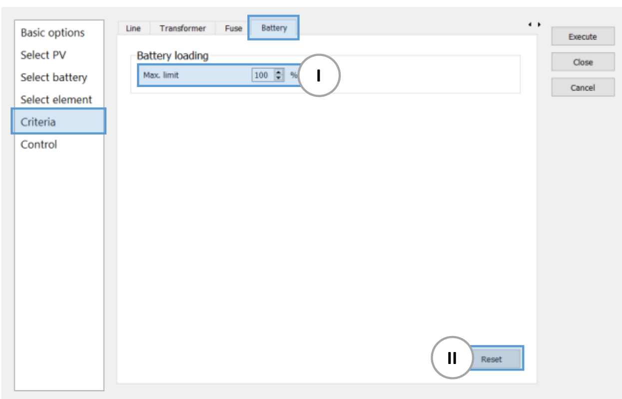

Figure 17 Criteria page, Battery tab

I. **Battery system loading** criteria
II. **Reset** to default values

4.7 Control

On the Control page you have the possibility to include your own Python-scripted control strategy that will be executed at the end of every consecutive PV hosting capacity. For more details on the PVHC algorithm combined with user-defined control, see **also**.

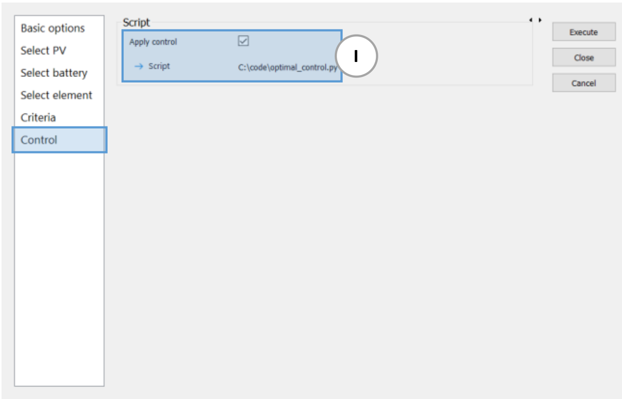

Figure 18 Control page

I. **Apply control**, **select control script**

4.8 Miscellaneous

On every page, PVHC can be executed or closed via the buttons below.

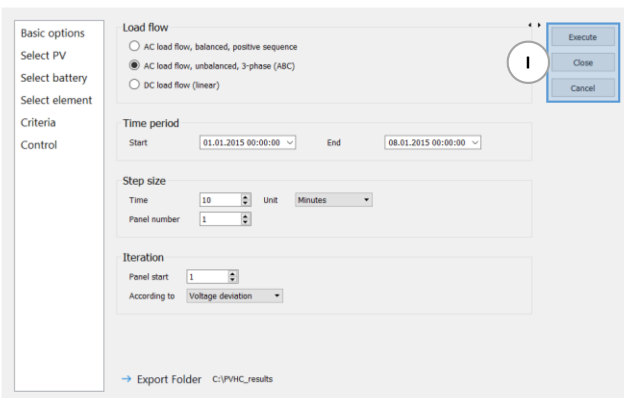

Figure 19 Miscellaneous buttons

I. **Execute**, **close**, and **cancel**

5 Using PVHC

This section describes all user inputs available via the GUI of PVHC. Hyperlinks for every parameter and variable described below are available throughout this section and send you to the appropriate screenshot of where these inputs can be entered in the plugin (**section 4**).

5.1 Changing the quasi-dynamic simulation settings

You have the possibility to change the settings of the quasi-dynamic simulation that is used for the computation of the PV hosting capacity of your study case in PowerFactory.

5.1.1 PV model

Just like in PowerFactory, you have the possibility to select the model for PV systems. Available models are:

- **Active Power Input:** the active power value can be specified directly. The power for this type of model is incremented by increasing the scaling factor.
- **Solar Calculation Mode:** the active power is calculated according to meteorological data, plant positioning, and time. See the technical reference for more details. The power for this type of model is incremented by increasing the number of panels of the PV system.

This setting can be change **here**.

5.1.2 Load flow

A quasi-dynamic simulation consists of a sequence of **load flow** calculations solved at every time step from the start to the end of the simulation period. The calculation methods currently available are:

- **AC Load Flow, balanced, positive sequence:** for single-phase positive sequence network representations, valid for balanced symmetrical networks. The simulation time with this type of method is relatively fast.
- **AC Load Flow, unbalanced, 3 Phase (ABC):** for multi-phase network representations, valid for analyzing unbalanced 3-phase systems, e.g. introduced by unbalance loads. The simulation time with this type of method is the slowest.
- **DC Load Flow (linear):** calculation method based on a set of linear equations, where the voltage angles of the buses are strongly related to the active power flow through cables and lines. The simulation time with this type of method is the fastest.

When PVHC is launched, the default calculation method is automatically set to **AC Load Flow, unbalance, 3 Phase (ABC)**, regardless of the method used for your study case in PowerFactory. Thus, closing PVHC will not save the **load flow** setting for latter sessions. You are free to select the desired calculation method, which will then be applied for the estimation of the hosting capacity. **DC Load Flow (linear)** is currently not supported in PVHC. For more details on **power flow** calculation methods, see the PowerFactory user manual.

This setting can be changed **here**.

5.1.3 Time period

Just like in PowerFactory, you have the possibility to modify the **start** and **end** period for your quasi-dynamic simulations. PVHC does not check if the entered timeframe of simulation is covered by that of your project nor does it align itself with the Time Characteristics of your project. For more details on time dependent quantities, see the PowerFactory user manual.

When PVHC is launched, the **start** and **end** period are taken directly from the last quasi-dynamic simulation executed in PowerFactory. A shorter period will result in shorter simulation times and vice versa.

This setting can be changed **here**.

5.1.4 Time step size

The **step size** for quasi-dynamic simulations can be redefined. When PVHC is launched, a 10-minute resolution is selected by default to comply with some of EN 50160 criteria. A larger step size will result in shorter simulation times and vice versa.

This setting can be changed **here**.

5.2 Changing the PVHC algorithm settings

The algorithm behind the computation of the PV hosting capacity accepts input variables that may improve total simulation time or alter final results in terms of installed solar power.

5.2.1 Panel step size

You can modify the **incremented number of panels** for PV systems at each iteration of the algorithm. For more details on this parameter, see **also**. The default value for the **panel step size** is 1. Preferably, you should increase this value to speed up execution time. This option is only available for **PV models** set to **Solar Calculation Mode**.

This setting can be changed **here**.

5.2.2 Panel start

The algorithm of PVHC starts incrementing the number of panels installed for PV systems at **panel start**. For more details on this parameter, see **also**. The default value for **panel start** is 1 but should be increased depending on how familiar you are with your grid in order to decrease execution time. For example, if you know from previous simulations the lowest minimum number of panels for your PV systems, then **panel start** may be set to that value. Furthermore, setting **panel start** too low may trigger under-voltages measured on cables/lines and thus terminate PVHC prematurely. This scenario typically occurs when high loads and low distributed generation are installed along the feeder of your distribution grid. This option is only available for **PV models** set to **Solar Calculation Mode**.

This setting can be changed **here**.

5.2.3 Order of PV systems

The increment of panels is iteratively done for one PV system at a time. The order in which these PV systems are incremented is arranged according to your selection of **order of PV systems**:

- **Voltage deviation**: PV systems are arranged in decreasing order of the measured maximum over-voltage at their PCC. PV systems creating the highest over-voltage are thus placed in first position of iteration.
- **Distance from substation**: PV systems are arranged in decreasing order of their distance from the feeding substation. PV systems located the furthest from the substation are thus placed in first position of iteration.
- **Maximum loading**: PV systems are arranged in decreasing order of the measured maximum loading of the cable/line connecting the PCC to the rest of the network. PV systems creating the highest maximum cable/line loading are thus placed in first position of iteration.
- **Random**: PV systems are arranged in random order.

Prior knowledge of the main weakness of your network may influence the **order of PV systems**. A judicious choice of this parameter may potentially give best results in terms of PV hosting capacity. The default value for the **order of PV systems** is set to **voltage deviation.** For more details on this parameter, see **also**. This option is only available for **PV models** set to **Solar Calculation Mode**.

This setting can be changed **here**.

5.2.4 Scaling factor step size

You can modify the **incremented scaling factor (%)** for PV systems at each iteration of the algorithm. For more details on this parameters, see **also**. The default value for the **scaling factor step size** is 10%. Preferable, you should increase this value to speed up execution time. This option is only available for **PV models** set to **Active Power Input**.

This setting can be changed **here**.

5.2.5 Scaling factor start

The algorithm of PVHC starts incrementing the scaling factor of PV systems at **scaling factor start**. For more details on this parameter, see **also**. The default value for **scaling factor start** is 100%, but should be increase depending on how familiar you are with your grid in order to decrease execution time. For example, if you know from previous simulations the lowest minimum scaling factor for your PV systems, then **scaling factor start** may be set to that value. Furthermore, setting **scaling factor start** too low may trigger under-voltages measured on cables/lines and thus terminate PVHC prematurely. This scenarios typically occurs when high loads and low distribution generation are installed along the feeder of your distribution grid. This option is only available for **PV models** set to **Active Power Input**.

This setting can be change **here**.

5.3 Choosing the directory to export results

All results of PVHC are exported in a folder located in the directory chosen in **export folder**. You are free to choose any existing directory on your system but the default value is set to one directory above that of the PVHC executable files in a folder named **PVHC_results**. Inside the latter, another folder is created every time PVHC is executed with the name made up of the **date and time** of execution and of the **project and study case name**. Finally, this folder stores the PVHC results (in *.csv* format).

This setting can be changed **here**.

5.4 Selecting PV systems to consider in the PVHC algorithm

Selected PV systems will be considered in the PVHC algorithm whereas **unselected PV systems** will automatically be turned off (thus generating zero power) after executing PVHC. If you need a PV system to be operational but not processed in the algorithm, you can either:

- Set the **minimum number of panels** equal to the **maximum number of panels**.
- Get the **current PV system configuration** directly from PowerFactory.

Selecting and unselecting PV systems can be done by either double-clicking the name of the PV system in the appropriate lists or using the buttons available **here**.

Only PV systems operating under the model chosen in the **basic options** can be selected for the computation of the PV hosting capacity.

5.5 Modifying PV system configurations

You may **modify the configuration of PV systems** before computing the PV hosting capacity. Do to so, **select a PV system in the appropriate list** and the set of **configurable parameters** will show up for that PV system. For more details on these parameters, see the PowerFactory technical reference for PV systems.

For PV systems set to **Active Power Input**, only the **power factor** can be configured.

5.5.1 Number of parallel inverters

The first time PVHC is launched, the **number of parallel inverters** displayed for the selected PV system is taken from the counterpart object in PowerFactory.

This parameter can be configured **here**.

5.5.2 Minimum number of panels per inverter

The default value for the **minimum number of panels** for the selected PV system is 1. For more details on this parameter, see **also**. Once edited, the equivalent minimum power of the PV system is displayed and is computed as follows:

$$P_{min}^{PV} = N_{min}^{panel} * P^{panel} \; [W] \qquad (1)$$

This parameter can be configured here.

5.5.3 Maximum number of panels per inverter

The default value for the **maximum number of panels** for the selected PV system is 100. For more details on this parameter, see also. Once edited, the equivalent maximum power of the PV system is displayed and is computed as follows:

$$P_{max}^{PV} = N_{max}^{panel} * P^{panel} \; [W] \qquad (2)$$

This parameter can be configured here.

5.5.4 Mounting system

The first time PVHC is launched, the **mounting system** displayed for the selected PV system is taken from the counterpart object in PowerFactory. The following **mounting systems** can be selected in PVHC and correspond to those in PowerFactory:

- **Fixed/Stationary**: you must specify the orientation and tilt angles.
- **Dual Axis Tracking System**: the orientation and tilt angles will follow the solar altitude and azimuth angles accordingly.
- **Horizontal Single Axis Tracking System**: you must specify the orientation angle. The tile angle will follow the solar altitude angle accordingly.
- **Vertical Single Axis Tracking System**: you must specify the tilt angle. The orientation angle will follow the azimuth angle accordingly.

This parameter can be configured here.

5.5.5 Orientation angle

The first time PVHC is launched, the **orientation angle** displayed for the selected PV system is taken from the counterpart object in PowerFactory.

This parameter can be configured here.

5.5.6 Tilt angle

The first time PVHC is launched, the **tilt angle** displayed for the selected PV system is taken from the counterpart object in PowerFactory.

This parameter can be configured here.

5.5.7 Power factor

The first time PVHC is launched, the **power factor** displayed for the selected PV system is taken from the counterpart object in PowerFactory.

This parameter can be configured here.

5.5.8 Latitude

The first time PVHC is launched, the **latitude** displayed for the selected PV system is taken from the terminal at which the counterpart PV system is connected in PowerFactory.

This parameter can be configured here.

5.5.9 Longitude

The first time PVHC is launched, the **longitude** displayed for the selected PV system is taken from the terminal at which the counterpart PV system is connected in PowerFactory.

This parameter can be configured **here**.

5.5.10 Time zone

The first time PVHC is launched, the **time zone** displayed for the selected PV system is taken from the counterpart object in PowerFactory.

This parameter can be configured **here**.

5.6 Saving and loading PV system configurations

You can conveniently **save** and **load** PV systems to save time when experimenting with different configurations or when a PV system configuration is needed in another project or study case. All parameters are saved or loaded except for the **minimum** and **maximum** number of panels, which are considered more as algorithm parameters than PV system configurable variables. By default, configuration files are stored in the same directory as the PVHC executable files in a folder named *settings_pv*. Finally, the type of these configuration files are *.xml* format.

Moreover, it is possible to **get the current configuration** of the selected PV system directly from the counterpart object in PowerFactory. In addition, this function replaces the **minimum** and **maximum** number of panels of the selected PV system by the number of panels per inverter of the counterpart object in PowerFactory.

These functions are only available for PV systems set to **Solar Calculation** mode.

These functions are accessible **here**.

5.7 Selecting battery systems to consider in the PVHC algorithm

Selected battery systems will be considered in the PVHC algorithm whereas **unselected battery systems** will automatically be turned off (thus providing no storage functions) after executing PVHC. This also means that power system criteria for **selected battery systems** are verified and conversely dismissed for **unselected battery systems**.

Selecting and unselecting battery systems can be done by either double-clicking the name of the battery system in the appropriate lists or using the buttons available **here**.

5.8 Modifying battery system configurations

You may **modify the configuration of battery systems** before computing the PV hosting capacity. Do to so, **select a battery system in the appropriate list** and the set of **configurable parameters** will show up for that battery system. **Configurable parameters** specific to QDSL modeled battery systems will also appear. For more details on these parameters, see the PowerFactory user manual.

5.8.1 Number of parallel units

The first time PVHC is launched, the **number of parallel units** displayed for the selected battery system is taken from the counterpart object in PowerFactory.

This parameter can be configured **here**.

5.8.2 Nominal apparent power

The first time PVHC is launched, the **nominal apparent power** displayed for the selected battery system is taken from the counterpart object in PowerFactory.

This parameter can be configured **here**.

5.8.3 Power factor

The first time PVHC is launched, the **power factor** displayed for the selected battery system is taken from the counterpart object in PowerFactory.

This parameter can be configured **here**.

5.8.4 QDSL battery system parameters

QDSL battery system parameters displayed for the selected battery system are imported directly from the counterpart object in PowerFactory, regardless of the values edited in a previous PVHC session (unless PVHC is executed, in which case the parameters will be modified inside PowerFactory).

These parameters can be configured **here**.

5.9 Saving and loading battery system configurations

You can conveniently **save** and **load** battery systems to save time when experimenting with different configurations or when a battery system configuration is needed in another project or study case. By default, configuration files are stored in the same directory as the PVHC executable files in a folder named *settings_batt*. Finally, the type of these configuration files are *.xml* format. An error message box appears if PVHC failed to load a battery system configuration (e.g., if the loaded QDSL model does not match that of the selected battery system).

These functions are accessible **here**.

5.10 Selecting elements for power system criteria verification

Selected elements will be subject to the verification of power system criteria while computing the PV hosting capacity whereas **unselected elements** will be dismissed (but not turned off as opposed to PV and battery systems).

Selecting and unselecting elements can be done by either double-clicking the name of the elements in the appropriate lists or using the buttons available **here**.

5.11 Adjusting power system criteria

The selected elements will be subject to the verification of their corresponding power system criteria whenever a quasi-dynamic simulation or a short-circuit analysis is executed. Each criterion holds a flag which triggers once its threshold is exceeded. The various criteria for each element as well as their default parameters are described below.

5.11.1 Cable/line voltage

Flags for cable/line voltage are triggered whenever:

- The over-voltage exceeds a certain maximum threshold (p.u.) for a defined period of time (%).
- The under-voltage is inferior to a certain minimum threshold (p.u.) for a defined period of time (%).

The default values for the maximum and minimum voltage limits are respectively:

- 1.10 p.u. for 95% of the simulation period.
- 0.90 p.u. for 95% of the simulation period.

These default thresholds correspond to those of 50160 standards, ensuring the quality of supply voltage in a distribution network. This parameter is triggered when performing a quasi-dynamic simulation.

These criteria can be adjusted **here**.

5.11.2 Cable/line loading

Flags for cable/line loading are triggered whenever the maximum loading exceeds a defined maximum threshold (%), which corresponds to the maximum ampacity limit. The default value for the maximum loading is 100%. This parameter is triggered when performing a quasi-dynamic simulation.

This criteria can be adjusted **here**.

5.11.3 Substation loading

Flags for substation loading are triggered whenever the maximum loading exceeds a defined maximum threshold (%), which corresponds to the maximum thermal limit. The default value for the maximum loading is 100%. This parameter is triggered when performing a quasi-dynamic simulation.

This criteria can be adjusted **here**.

5.11.4 Substation OLTC operation

Flags for substation OLTC operation are triggered whenever the number of OLTC tap changes per day exceeds a value equal to the number of operations before maintenance divided by the number of days until the next maintenance of the OLTC. The default values are 100’000 operations before maintenances every 7 years, which is equivalent to a maximum of 39 taps per day. This parameter is triggered when performing a quasi-dynamic simulation.

This criteria can be adjusted **here**.

5.11.5 Fuse loading

Flags for fuse loading are triggered whenever the maximum loading exceeds a defined maximum threshold (%), which corresponds to the maximum thermal limit. The default value for the maximum loading is 100%. This parameter is triggered when performing a short-circuit analysis.

This criteria can be adjusted **here**.

5.11.6 Fuse current

Flags for fuse current are triggered whenever the maximum breaking and short-circuit currents exceed their respective nominal ratings (%). The default value is 100%. This parameter is triggered when performing a short-circuit analysis.

These criteria can be adjusted **here**.

5.11.7 Battery loading

Flags for battery system loading are triggered whenever the maximum loading exceeds a defined maximum threshold (%), which corresponds to the maximum thermal limit. The default value for the maximum loading is 100%. This parameter is triggered when performing a quasi-dynamic simulation.

This criteria can be adjusted **here**.

5.12 Resetting default power system criteria

You can reset the default power system criteria individually for each type of element. This means that resetting the cable/line default criteria won’t reset those for substations.

This can be done by clicking the appropriate **Reset** button of the corresponding page **here**.

5.13 Applying user-defined control strategies

By ticking the control box **here**, a field box will appear for you to select you own Python script containing the **control strategy** you wish to implement. The function inside `main.py` **opens**, **reads**, and **executes** the control script with the input arguments contained inside a Python dictionary (Search for *open(control_options['script_path']).read()* in `main.py`). For more details on the **exec** function, see the Python documentation. Currently, the available input arguments are the following:

- **app**: corresponds to the PowerFactory application module created inside `main.py`.
- **`basic_options`**: contains the settings selected for your simulation and algorithm environment. These settings can be modified on this **page**.
- **`selected_pv`**: corresponds to a list containing the name of the PV systems selected **here**.
- **`selected_batt`**: corresponds to a list containing the name of battery systems selected **here**.
- **`selected_line`**: corresponds to a list containing the name of cables/lines selected **here**.
- **`selected_tran2`**: corresponds to a list containing the name of substations selected **here**.
- **`selected_fuse`**: corresponds to a list containing the name of the fuses selected **here**.
- **`criteria_line`**: contains the thresholds for the power system criteria regarding cables/lines. These parameters can be modified **here**.
- **`criteria_tran2`**: contains the thresholds for the power system criteria regarding substations. These parameters can be modified **here**.
- **`criteria_fuse`**: contains the thresholds for the power system criteria regarding fuses. These parameters can be modified **here**.
- **`criteria_batt`**: contains the thresholds for the power system criteria regarding battery systems. These parameters can be modified **here**.

Inside the Python script dedicated to your control strategy, input arguments of your main function should follow the same order as that of passed arguments in `main.py`. All functions and methods specific to the Python and PowerFactory environment obey and are executed as they would normally do in `main.py`.

5.14 Executing a PV hosting capacity estimation.

Executing a PV hosting capacity estimation via the button **here** will perform the actions in the following order:

I. Create a list containing the name of selected elements (PV systems, battery systems, cables/lines, substations, and fuses) for later use.
II. Save the **simulation and algorithm settings**, **power system criteria**, and **control options** in corresponding classes for later use.
III. Set up the PVHC algorithm, see **also.**
IV. Proceed to the computation of the PV hosting capacity, see **also**.
V. Export PVHC results and plot in PowerFactory.
VI. Execute the selected **control strategy,** if chosen to.
VII. Repeat steps IV-VI according to Figure 5, if the control option is enabled.
VIII. Reset initial conditions and flags.

Moreover, a dialogue box will appear displaying the status of the algorithm, the time elapsed, a figure detailing the evolution of panels incremented (only for **Solar Calculation**), and a log file describing the steps and decisions taken by the algorithm. Tinkering with settings and options in the background while PVHC is performing is not advised. A Cancel button is available for this purpose and will interrupt any current task, except for step VI above. Once the control script is executed, the dialogue box disappears and gives way to your control strategy to be carried out. This means your control strategy cannot be interrupted unless explicitly coded in your script. At the end of the latter, step IV is repeated with the dialogue box showing up again.

Furthermore, a PV hosting capacity computation cannot be performed if the following conditions are not met (an error message box will appear):

- At least one **PV system must be selected**.
- The **panel start** parameter must be lower than the lowest **minimum number of panels** among your PV systems.
- At least **one object must be selected** for a power system criteria verification.

- A control script must be selected if the **control option** is enabled.
- The **start** must be earlier than the **end time** of the simulation.
- Any PV system model does not correspond to that selected among **PV models**.
- The **control option** is enabled and **PV model** is set to **Active Power Input** (not supported in PVHC 2018)

Once the algorithm is finished, user settings entered in PVHC will have modified their counterpart object in PowerFactory, namely PV systems, battery systems, and simulation settings.

Executing PVHC can be done **here**.

5.15 Exiting PVHC

There are two ways of exiting the plugin: the **Close** and **Cancel** button **here**.

Closing PVHC will save all current inputs from PV system configurations to current page and tab, except the following parameters which are by default when launching PVHC:

- The **load flow** type.
- The **start** and **end time** as well as the **time step** of quasi-dynamic simulations.
- The QDSL model parameters for the **battery system configuration** (unless PVHC is executed in which case the counterpart object in PowerFactory is modified). A workaround was created which consists in **loading a battery system configuration** previously saved.

The closed PVHC session is thus saved and stored in *settings.xml* located in a folder called *tmp* in the same directory as the executable files. The session is loaded when PVHC is launched again, unless four hours have passed or the project and study case have changed since the last PVHC session, in which case default values are loaded instead.

On the other hand, exiting PVHC using the **Cancel** button will not save the current session. Launching PVHC after cancelling will either load default values or a previously saved PVHC session.

6 Case example

This section presents a case example showcasing the capabilities of PVHC and the content of the results file generated at the end of the algorithm.

6.1 Distribution network

The case example was performed on the CIGRE benchmark low-voltage microgrid network [6] where all RES have been replaced by PV systems. The grid operates at 50 Hz and has a radial layout like usual LV networks, with a feeder departing from the secondary side of the substation and prosumers connected anywhere along the feeder and its branches. The feeder consists of 26 households divided into five groups located at the end of various branches. Finally, a PV system is installed at each of these groups of dwellings, where we assume a fixed mounting system corresponding to typical modern installations on residential roofs. The main lines consist of overhead Al cables with Cu service cables connecting the groups of households.

Measurements of global irradiance and temperature were extracted from a local weather station at a 10 minute resolution. Daily consumption profiles of various home appliances were generating using BEHAVSIM [7], a behavior simulator using stochastic parameters. These profiles were created for each of the 26 households and consist of dishwashers, washing machines, lighting, fridges, and electric boilers.

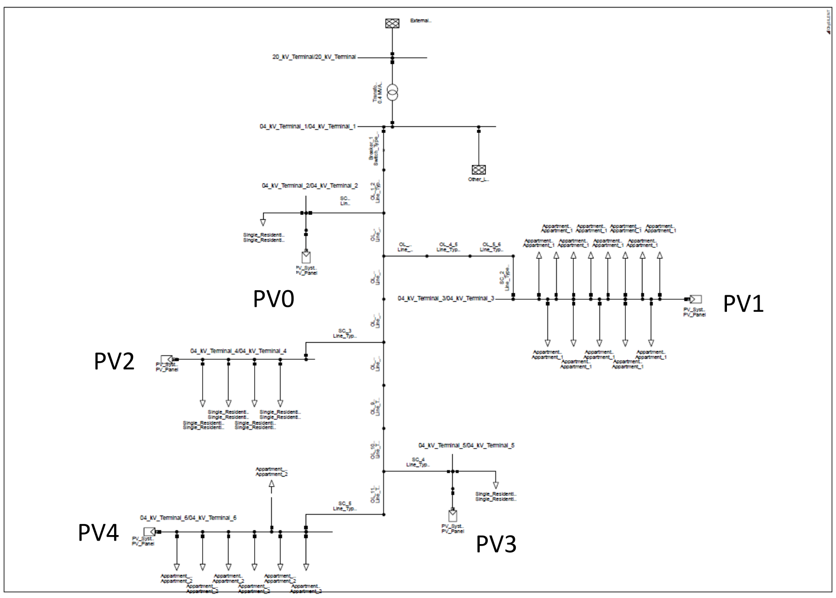

Figure 21 CIGRE benchmark low-voltage microgrid network

6.2 PVHC settings

The unbalanced AC load flow option was chosen for a quasi-dynamic simulation of 1 week at a time step of 10 minutes. Panels are iterated at a step of 10 with the overall power starting at 120 panels. PV systems are ordered according to voltage deviation since it is known from successive simulations that service cables at the end of branches are vulnerable to over-voltages. All PV systems have been selected to take part in the computation of the PV hosting capacity and have the following configurations:

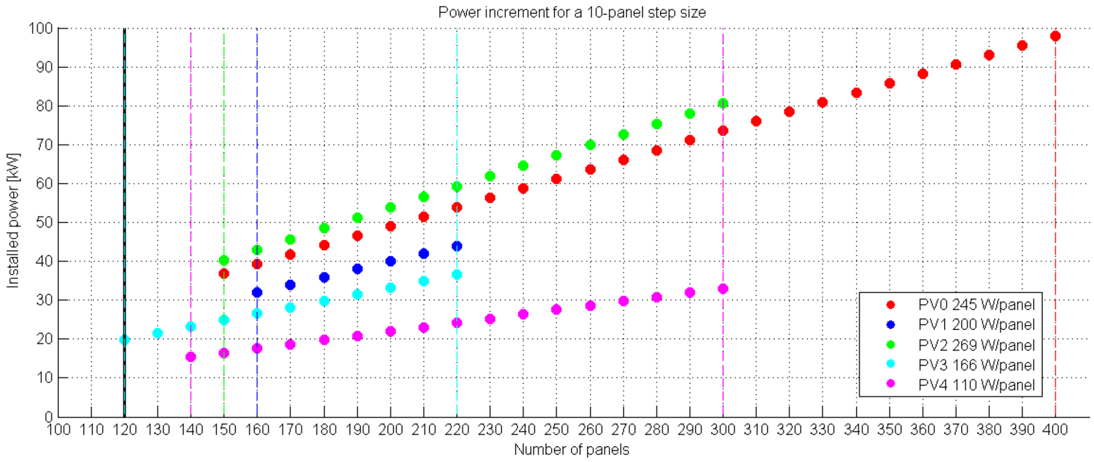

Figure 22 Case example PV configurations

No battery systems have been included into the algorithm. The service cables connecting the rest of the feeder to the PV systems as well as the first line departing from the secondary of the substation have been considered for the verification of power system criteria. The latter has been set to agree with EN 50160 standards with thermal rating thresholds at 100 %, which correspond to default parameters in PVHC.

6.3 PVHC results

Simulations were performed on a computer equipped with a 2.50 GHz Intel® Core™ i5-7200U processor and 16.00 GB of RAM. The computation of the PV hosting capacity took 7 minutes and 38 seconds.

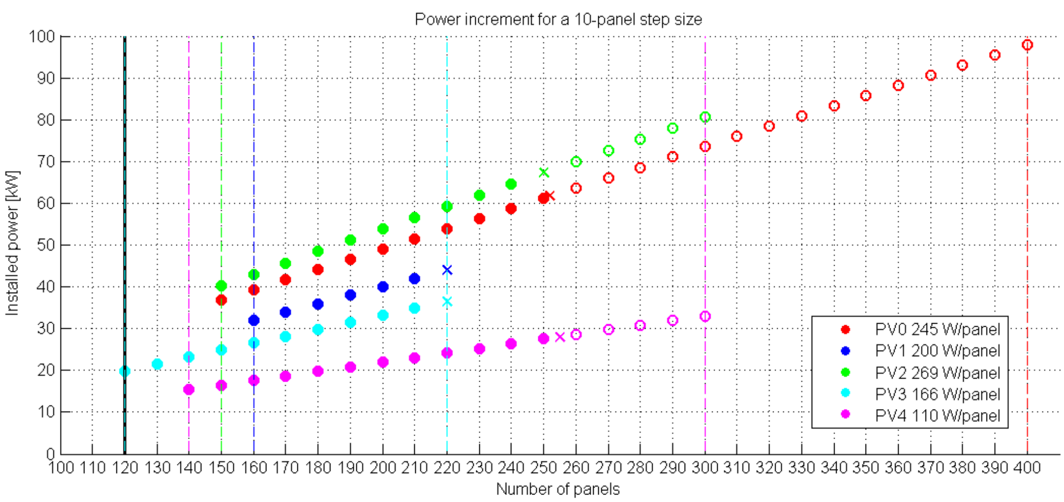

Figure 23 PV hosting capacity results

The blue PV systems have reached their maximum installable number of panels (220), whereas all other PV systems underwent the bisection method because an overvoltage of 1.10 p.u. for more than 5 % of the simulated week was detected at the PCC of PV3 (see Figure 24). PV systems PV0, PV2, and PV4 have respectively reached 252, 250, and 255 panels. The total hosting capacity was computed at 237.56 kVA.

These data were extracted from the *.csv* file generated at the end of the algorithm where all information of simulation settings, chosen thresholds, and PV system configurations are saved. The file includes hosting capacity results as well as the list of flags triggered or not for every selected network element. For this case example (see Figure 24), an overvoltage was detected due to incrementing the power of PV4, then PV2, and finally PV0. Plot of

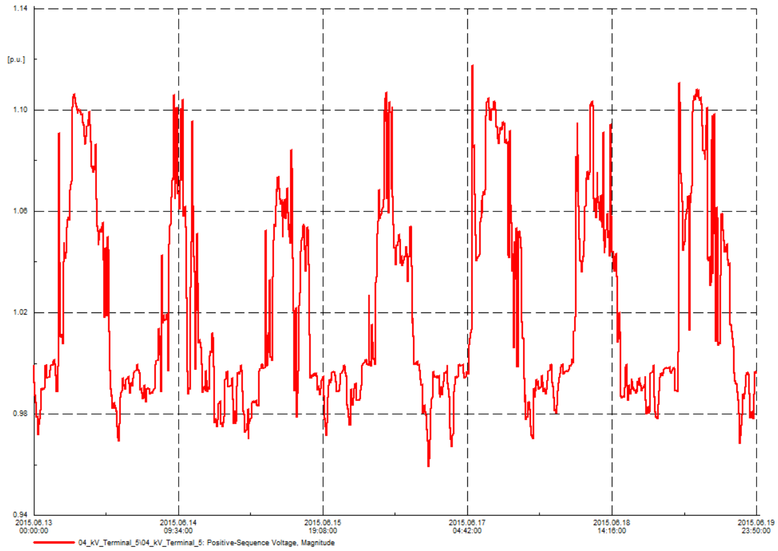

Figure 24 PCC voltage near PV3

61	SC_3			Max. voltage fail	[False]
62				Min. votlage fail	[False]
63				Max. loading fail	[False]
64	SC_4			Max. voltage fail	[True, 'PV_System_4', 'PV_System_2', 'PV_System_0']

Figure 25 Failures detected and causes

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