Storage Element

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1 Purpose

This technical note describes the modelling and dispatch modes of the Storage element implemented in 2019.

2 Why?

OpenDSS Storage element has passed through a major update in 2019. This technical note has been elaborated mainly to explain the new features, but also to expand the previous Storage documentation [1] with a comprehensive description of the model. The new features are:

- Addition of a built-in inverter model, including losses and capability curve;
- Idling losses block has been moved from the grid interface to the DC side of the inverter;
- Possibility to be controlled by an InvControl control element in a similar way to PVSystem element, including the possibility of being controlled simultaneously by a StorageController and an InvControl;
- Addition of new state variables to aid in the understanding of the operation of the element;

Besides the aforementioned features, it is worth commenting that the Storage source code has been formulated for better compatibility with InvControl and PVSystem implementation, facilitating future implementations of smart inverter functionalities in the InvControl source code, which are applicable to both PVSystem and Storage elements.

3 Brief Introduction

The Storage element can operate either in standalone mode or be controlled by a StorageController [2], responsible for commanding its active power dispatch, and/or an InvControl [3], responsible for limiting its active power dispatch and/or requesting reactive power according to different functions.

The Storage model is developed based on the old Storage model, which in turn was originally developed based on the Generator element model. Thus, both the new and the old Storage models have inherited some of the features from the Generator model such as a built-in energy meter and an interface to user-written DLLs.

The Storage element can be used in a Snapshot power flow to simply compute the power flow for a selected state of the Storage element. In that case, you would simply set the state and then solve. However, the strength of the model is in time-varying simulation modes. The model supports Daily, Yearly and DutyCycle modes. Daily or Yearly modes are intended for analyzing energy-related issues over a period of time with time step sizes from several minutes to one hour. DutyCycle mode is intended for studying the effectiveness of energy storage to compensate for short-term second-scale power variations, e.g., during cloud transients affecting solar PV generation.

As follows, the general Storage model is firstly presented and its operation in charging, discharging and idling states is explained. Next, different ways to manage energy storage dispatch are summarized. Then, all available standalone or "self-dispatch" modes are introduced and a summary of the Storage state variables is provided. Then, all "self-dispatch" are illustrated with several examples. Last, all the available Storage model properties are listed.

4 Modelling

The Storage element is a Power Conversion Element (PCE), which, at a high level, is modelled as a constant power load during charging and as a generator that can inject power into the grid during discharging, always subjected to its power rating and it stored energy capacity. The general model is illustrated in Figure 1.

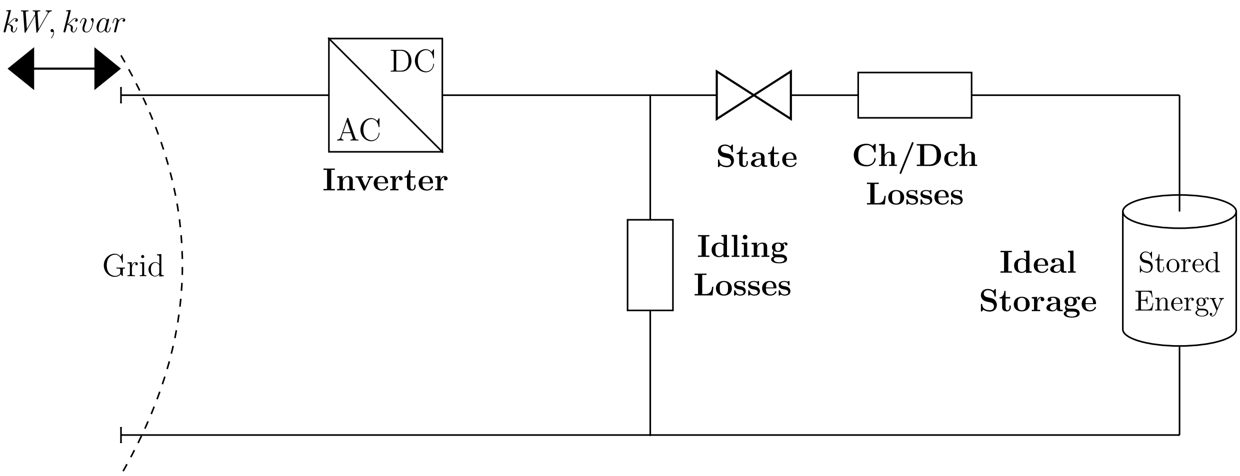

Figure 1: General Model of the Storage Element

The different components of the model are as follows:

- Ideal Storage: represents an ideal, lossless energy storage. Its State of Charge (SOC) varies according to the evolution of the element state amongst charging, discharging and idling along with the associated charging and discharging rates and losses;
- Charging and Discharging Losses: represent the charging and discharging losses associated with the conversion from the storage medium (e.g. battery) to electric energy and vice versa. The model allows to specify separate efficiencies for charging and discharging;
- Inverter: is a key new feature of the new Storage model, which works similarly to the inverter within PVSystem element as a built-in equipment in the model. It allows dispatching reactive power based on several functions, modelling the inverter losses and limiting the rate of charge and discharge based on its ratings. Note that it is different than the InvControl control element which is responsible for providing smart inverter functionality (see [3]);
- State: represents the state in which Storage element operates. The three possible states are: charging, discharging and idling;

- Idling Losses: represent storage self-depletion losses and auxiliary loads (e.g. A/C, control and communication equipment, etc.), which are supplied by the same inverter as the energy storage medium/battery. When in discharging state, the self-depletion losses and auxiliary loads are supplied by the ideal storage, increasing the power that actually discharges the element. When in charging state, they are supplied by the inverter and act to slow the charging of the ideal storage. In idling state, they are supplied by the grid through the inverter. Note that AC auxiliary loads, which are not supplied by the same inverter as the storage medium/battery, can be modeled by a load object connected in parallel to the Storage element.

5 Operation

This section demonstrates the power flow and losses within the element during the operation in each of the three possible states.

The power flow within the Storage element is performed from the interface with the grid to the ideal storage component. First the active power at the interface with the grid, kW and $kvar$ are determined. Then, all the losses (inverter, idling and charging/discharging losses) are subtracted, with the net effect of reducing the power that actually charges/discharges the ideal storage. The power flow within the Storage element is calculated identically in all OpenDSS solution modes (static, daily, yearly, duty) as described in the following subsections. The power flow within the Storage element at simulation time instant t is calculated based on the power at the Storage element grid interface obtained from the final power flow solution (power flow executed in the last control iteration) at simulation time instant t. For time-varying simulations, OpenDSS assumes this flow is constant over the time interval until next time instant $t + \Delta t$, where Δt is the time step size selected. The following nomenclature is used:

- $P_{in}[t]$: power flowing into the storage at t when it is either in charging or idling states;
- $P_{out}[t]$: power flowing out of the storage or into the grid at t when it is in discharging state;
- P_{idl}: constant idling losses;
- $\eta_{inv}[t]$: inverter efficiency at t;
- η_{ch}: charging efficiency;
- η_{dch}: discharging efficiency;
- $E[t]$: energy stored at t;

5.1 Charging State

The Storage element can only enter into charging state if the amount of energy stored, $kWhStored$, is less than the rated storage capacity, $kWhRated$. The rate of charge can be defined through either properties kW (as a negative value) or $\%Charge$ (percentage of the $kWRated$). The power flow within the storage element during the charging state is illustrated in Figure 2.

After the power $P_{in}[t]$ at the storage element grid interface has been determined from the power flow solution[1], the storage inverter losses are determined by:

[1]Note that the powers at the interface with the grid may differ from the specified ones due to the inverter capability

$$P^{ch}_{losses,inv}[t] = P_{in}[t] \times (1 - \eta_{inv}[t]) \tag{1}$$

The power at the DC side of the storage inverter, $P_{in}[t] \times \eta_{inv}[t]$, supplies the idling losses P_{idl}. The charging losses are calculated analogous to the storage inverter losses:

$$P_{losses,ch}[t] = (P_{in}[t] \times \eta_{inv}[t] - P_{idl}) \times (1 - \eta_{ch}) \tag{2}$$

Thus, the total losses are

$$P^{ch}_{losses,tot}[t] = Losses^{ch}_{inv}[t] + P_{idl} + P_{losses,ch}[t] \tag{3}$$

and the power that effectively charges the ideal storage, $P^{ch}_{eff}[t]$, is determined by

$$P^{ch}_{eff}[t] = (P_{in}[t] \times \eta_{inv}[t] - P_{idl}) \times \eta_{ch} \tag{4}$$

or, equivalently,

$$P^{ch}_{eff}[t] = P_{in}[t] - P^{ch}_{losses,tot}[t] \tag{5}$$

The energy stored at the next simulation time step, $t + \Delta t$, is given by:

$$E[t + \Delta t] = E[t] + P^{ch}_{eff}[t] \times \Delta t$$

5.2 Discharging State

The Storage element can only enter into discharging state if the amount of energy stored is greater than the energy capacity to be held in reserve for normal operation, $\%Reserve \times kWhrated$. The discharge rate is defined either with kW (as a positive value) or $\%Discharge$ (percentage of the $kWRated$).

The power flow within the storage element during the discharging state is illustrated in Figure 3.

After the power flowing out of the Storage element, $P_{out}[t]$ has been determined from the power flow solution[2], the storage inverter losses are determined by:

curve and the model selected for variation with voltage (see property *model*).

[2]Note that the powers at the interface with the grid may differ from the specified ones due to the inverter capability curve and the model selected for variation with voltage (see property *model*).

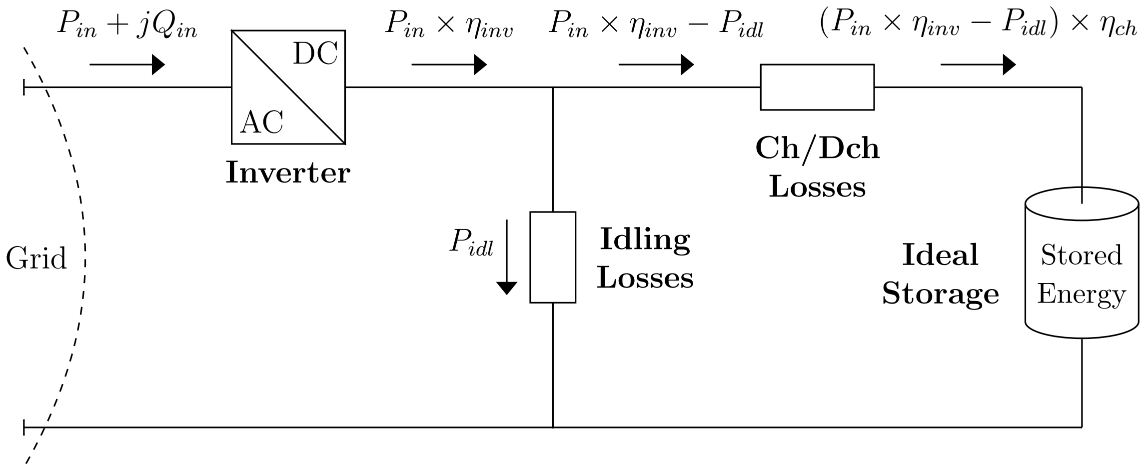

Figure 2: The Internal Power Flow of the Storage Element during Charging State

$$P^{dch}_{losses,inv}[t] = P_{out}[t] \times \left(\frac{1}{\eta_{inv}[t]} - 1\right) \tag{6}$$

The ideal storage supplies the power at the DC side of the inverter along with the idling losses and the discharging losses. The discharging losses are given by:

$$P_{losses,dch}[t] = \left(\frac{P_{out}[t]}{\eta_{inv}[t]} + P_{idl}\right) \times \left(\frac{1}{\eta_{dch}} - 1\right) \tag{7}$$

The total losses during discharging state are calculated with

$$P^{dch}_{losses,tot}[t] = P^{dch}_{losses,inv}[t] + P_{idl} + P_{losses,dch}[t] \tag{8}$$

and the power that effectively discharges the ideal storage, $P^{dch}_{eff}[t]$, is determined by

$$P^{dch}_{eff}[t] = \frac{P_{out}[t]}{\eta_{inv}[t] \times \eta_{dch}} + \frac{P_{idl}[t]}{\eta_{dch}} \tag{9}$$

or, equivalently,

$$P^{dch}_{eff}[t] = P_{out}[t] + P^{dch}_{losses,tot}[t] \quad [W] \tag{10}$$

Therefore, the energy stored at the following time step, $t + \Delta t$, is given by:

$$E[t + \Delta t] = E[t] - P^{dch}_{eff}[t] \times \Delta t$$

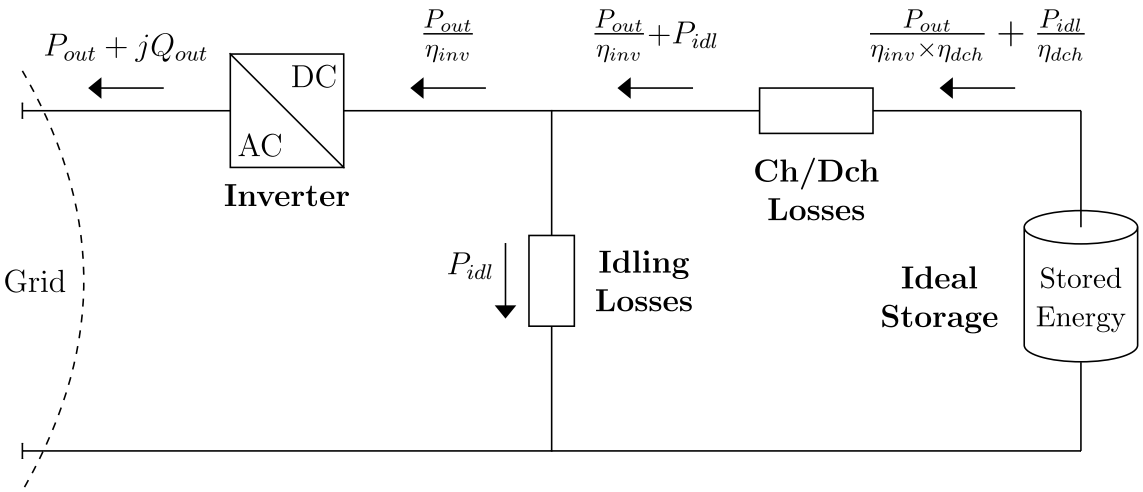

Figure 3: The Internal Power Flow of the Storage Element during Discharging State

5.3 Idling State

When the storage element is in idling state, the idling losses and the associated inverter losses are supplied by the grid[3], i.e., the SOC remains unaltered, as shown in Figure 4. In other words, the storage element works as a load. The idling losses are specified as a percentage of $kWrated$ through the property $\%IdlingkW$.

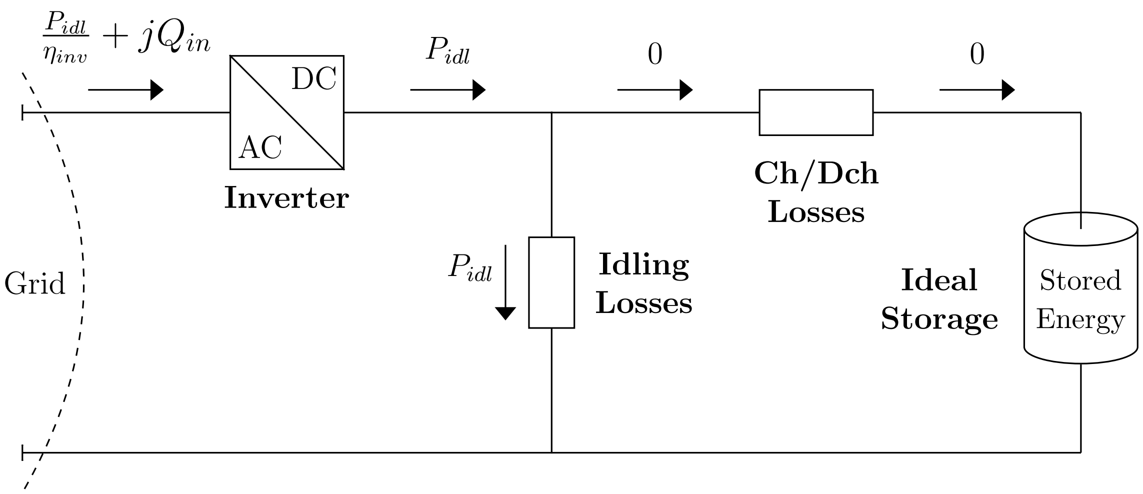

Figure 4: The Internal Power Flow of the Storage Element during Idling State

6 Dispatch Modes

The Storage element has several different dispatch modes, i.e., different ways to control the operation of a Storage element. The dispatch modes can be divided into self-dispatch modes and other dispatch modes. In self-dispatch modes, a Storage element determines its own operation. In the other dispatch

[3]In practice, this is how storage systems operate. Typically, the storage systems maintain a certain SOC, which means that some charging is done to account for the self-depletion and auxiliary loads supplied by the same inverter.

modes, the storage operation is determined by a combination of StorageController and InvControl control elements. The currently available Storage element dispatch modes are summarized in Table 1.

The dispatch modes can be further divided into active and reactive power dispatch modes. Separate dispatch modes can be used for active power and reactive power but it is not possible to simultaneously use multiple dispatch modes for active power or reactive power. It is however, possible to use separate charging-specific and discharging-specific active power dispatch modes. For instance, the following combinations are allowed:

- Active power and reactive power dispatch driven by Follow self-dispatch mode and InvControl's Volt-Var function, respectively;
- Active power and reactive power dispatch driven by StorageController's Time mode and InvControl's Volt-Var function, respectively;
- Active power and reactive power dispatch driven by StorageController's PeakShave (for charging) and PeakShaveLow (for discharging) modes and InvControl's Volt-Var function, respectively;

It is worth mentioning that InvControl's VW function can always be applied simultaneously with any other active power dispatch mode, because it has a "limiting nature", differently from the modes presented in Table 1, which have a "requesting nature".

Table 1: Currently Available Storage Element Dispatch Modes

Measure	**Means**	**Mode/Function**
Active Power	Self-Dispatch	Default
		Follow
		LoadLevel
		Price
		External
		TimeChargeTrigger (Discharge Only)
	StorageController	PeakShave (Discharge Only)
		Follow (Discharge Only)
		Support (Discharge Only)
		Loadshape
		PeakShaveLow (Charge Only)
		Time
		Schedule (Discharge Only)
Reactive Power	Self-Dispatch	Constant PF
		Constant kvar
	InvControl	Volt-Var (VV)
		Dynamic Reactive Current (DRC)
		VV + DRC
		VV + Volt-Watt (VW)

Observation: As specified in IEEE1547-2018[4], the smart-inverter Volt-Watt function applied to energy storage systems may require the element to charge during high voltage scenarios. Thus, the InvControl element could also be added as a mean to control the active power dispatch of a storage element under VW function. However, this functionality has not been implemented yet. Currently, the curve specified for VW function can only limit the active power dispatch to a value as low as zero.

This technical note focuses on the self-dispatch modes, for both active and reactive powers. For more information on the modes/functions available in StorageController and InvControl elements, see [2] and [3].

Three of the five active power self-dispatch modes: Default, LoadLevel and Price, are commanded by two triggers: one for charging, named $ChargeTrigger$, and the other for discharging, $DischargeTrigger$. In general, a Storage element operates in a given state until one of the following events happens:

- The stored energy, $kWhstored$, reaches the element's rated capacity $kWhRated$ when in charging state. In this case, the element automatically goes to idling state;
- The stored energy reaches its minimum reserve, $\%reserve$, when in discharging state. In this case, the element automatically goes to idling state;
- A trigger is activated. In this case, the storage automatically goes to the state determined by the respective trigger, i.e., if $ChargeTrigger$ has been activated, the storage goes to charging state, whereas if the $DischargeTrigger$ has been activated, the storage goes to discharging state;
- The user manually sets a new state: this can be done either through the parameter *state* or kW;
- The storage receives a request from a StorageController element to operate in a specific state;

For the last three cases above, the element only operates in the selected/requested state if there is enough energy stored/left. In other words, a given state and charge/discharge rate can always be requested from a storage element but the storage operation may be limited among other things by the storage energy capacity and the storage inverter operating limits (the inverter capability curve or limit active power output and VW functions). The following subsections introduce the self-dispatch modes.

6.1 Default

In this mode, the triggers follow the specified loadshape corresponding to the present solution mode (properties *daily*, *yearly* and *dutycycle*). When the value of the loadshape is greater than the value specified in $DischargeTrigger$, the storage discharges at a constant power, defined by $\%Discharge$. The discharging continues until either the SOC reaches $\%reserve$ or the value from the curve assumes a value less than $DischargeTrigger$. Analogously, when the value of the loadshape is less than the specified $ChargeTrigger$, the storage charges until either it is fully charged or the loadshape value becomes greater than $DischargeTrigger$. Besides that, time criteria, if active, has priority over the triggers. Time criteria is defined by the property $TimeChargeTrigger$, which corresponds to the time of the day when the storage charging is activated, even if the value from the specified loadshape is not less than $ChargeTrigger$. This mechanism can be utilized, e.g., to charge the storage at the beginning of the day, when the demand is low, to ensure that the storage is fully charged to be discharged during the rest of the day. By default, *TimeChargeTrigger* is active and equal to 2 (2am). To disable this feature, assign any negative value to this property.

In this mode, the triggers follow the specified loadshape corresponding to the present solution mode (properties *daily*, *yearly* and *dutycycle*). Whenever the value from the curve is greater than the value specified in *DischargeTrigger*, the storage discharges at a constant power, defined by %*Discharge*. The discharging continues until either the SOC reaches %*reserve* or the value from the curve assumes a value less than *DischargeTrigger*. In a similar way, whenever the value from the curve is less than the specified *ChargeTrigger* the element charges until either it is fully charged or the curve assumes a value greater than *DischargeTrigger*. Besides the aformentioned rules, there is another criteria that, when active, has priority over the triggers. It is a time criteria and it is defined by the property *TimeChargeTrigger*. It corresponds to the time of the day when the storage charging is activated, even if the value from the specified loadshape is not less than *ChargeTrigger*. This mechanism is normally utilized to charge the storage at the beginning of the day, when the demand is low, to ensure that the element is fully charged for operation during the rest of the day. By default, *TimeChargeTrigger* is active and equal to 2 (2am). To disable this feature, assign any negative value to his property.

6.2 Follow

As the name suggests, in this mode, storage charging and discharging follow a loadshape until the storage is either fully charged or discharged. As in the Default mode, the specified loadshape must correspond to the present solution mode (properties *daily*, *yearly* and *dutycycle*). For positive values, the storage is set to discharge and for negative values it is set to charge. A zero value sets the element to idling state. Contrary to the Default mode, the charging and discharging rates are variable and determined by the multiplication of the rated active power of the element, *kWrated*, and the multipliers from the loadshape.

6.3 Price and LoadLevel

In these two modes, the charging and discharging triggers are also utilized, however they are compared to global properties, which can be used, for instance, to model the effect of a control center responsible for managing multiple energy storage elements.

Price mode uses, instead of a loadshape object, a PriceShape object, which represents of an array of prices. The PriceShape object is assigned to the pricecurve global property. The triggers are defined as prices and the rule is that whenever the energy price assigned to *ChargeTrigger* is greater than the price from the global PriceShape, the storage is set to charging state. In other words, the *ChargeTrigger* represents the maximum energy price the storage owner is willing to pay to charge the storage. The storage charging is naturally limited by the storage energy capacity. The *DischargeTrigger* works in an opposite way representing the minimum price that the storage owner is willing to accept to sell energy to the grid. So the element is set to discharging state whenever the price assigned is less than the global energy price. The global property *pricesignal* can also be used to manually set the price of energy during the simulation, which can be useful when, e.g., the prices are determined by an external algorithm. When manually setting the *pricesignal* property, the pricecurve should not be defined as otherwise, it would be used.

The same logic applies to Loadlevel dispatch mode. In this mode, the global loadshape is defined through a loadshape object that must be assigned to either *defaultdaily* or *defaultyearly* global properties, depending on the solution mode being considered.

The commands used for defining the aforementioned properties are illustrated below.

```
// PriceShape object definition
New PriceShape.Price interval=1 npts=24
~ price = [75, 68, 67, 69, 71, 75, 75, 80, 80,  80, 90, 90, 90 , 95, 95, 95,
   105, 105, 110, 110, 110, 90, 90, 90]

// Assigning a global price curve to the simulation
Set pricecurve =  Price

// Assigning a specific global price
Set pricesignal = 100 ! use this when you desire to
! manually assign a global price

// Assigning a global loadshape to the simulation
Set defaultdaily = ''MyDailyLoadShapeName'' ! this will be considered in
! a daily mode simulation
Set defaultyearly = ''MyYearlyLoadShapeName'' ! this will be considered in
! a yearly mode simulation

!Optional
Set loadmult = pernunitvalue  ! loadmult global property also applies
! to loadshapes assigned to defaultdaily and defaultyearly
```

6.4 External

In this mode, the storage state and dispatch values are defined by an external StorageController control element. When a StorageController takes control over a storage element, this mode is automatically activated for the storage element. Using StorageController enables further control modes discussed in [2].

The External mode is also utilized when the user wants to take more direct control over the storage operation, which can be done through the properties *state*, *kW* , *kvar*, *%Charge*, *%Discharge*. The External mode should be selected when there is an external algorithm controlling these properties, which is usually done through COM interface, but could also be performed by scripting the simulation from a script file.

6.5 Reactive Power Dispatch

The reactive power of Storage element is similar to the PVSystem element. As shown in Table 1, the Storage element has two self-dispatch modes for reactive power: constant power factor (PF) and constant reactive power (kvar). The modes can be activated by simply assigning a value to the Storage element *pf* or *kvar* properties.

In constant PF mode, the reactive power is calculated directly from the actual active power being dispatched. By default, the Storage element operates in constant PF mode with unity power factor. A positive power factor means reactive power flowing in the same direction as the active power, whereas a negative power factor means reactive and active powers flowing in opposite directions. Hence, depending on the Storage element operating state, the constant PF mode can cause the Storage element to either generate or absorb reactive power .

In constant kvar mode, the reactive power requested through *kvar* is decoupled from the active power. The sign convention is the same as for active power, i.e., a positive *kvar* means power flowing out of the element (var generation) and a negative *kvar* means power flowing into the element (var absorption).

Note that the active and reactive powers are subject to the inverter capability curve and other limiting functions. Thus, the actual powers at the Storage grid interface may differ from the requested ones. For more information, see [3] and [5].

7 State Variables

Table 2 lists all the state variables of the Storage element. The state variables can be monitored by setting a monitor for the Storage element in mode 3.

Table 2: State Variables of the Storage Element

State Variable	Description
kWh	Stored Energy in kWh.
State	Storage state. 1 for discharging, -1 for charging and 0 for idling.
kWOut	Power flowing out of the element, in kW. It is a result from the power flow. For discharging state.
kWIn	Power flowing into the element in kW. It is a result from the power flow. For charging and idling states.
kvarOut	Power flowing out of the element in kvar as a signed-value. Positive for vars generation and negative for vars absorption.
DCkW	DC power flowing into the storage inverter in kW at the DC side of the inverter as a signed-value. Positive for power flowing into the grid and negative for power flowing into the Storage element.
kWTotalLosses	Total losses in kW.
kWInvLosses	Inverter losses in kW.
kWIdlingLosses	Idling losses in kW.
kWChDchLosses	Charging and discharging losses in kW.
kWh Chng	Energy variation from the last time step, in kWh. Corresponds to the power that effectively charges/discharges the storage medium/battery multiplied by the time step length.
InvEff	Inverter efficiency.
InverterON	Flag indicating the inverter status. See [3].
Vref	Reference voltage used by the voltage-dependent InvControl functionalities. Equal to 9999 if there is no InvControl controlling the Storage element. See [3].

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Table 2 – *Continuation from previous page*

State Variable	Description
Vavg (DRC)	Average voltage of the moving window used in InvControl's DRC function. Equal to 9999 if there is no InvControl controlling the element. See [3].
VV Oper	Flag variable that indicates the status of InvControl's Volt-Var function operation. Equal to 9999 if there is no InvControl controlling the element. See [3].
VW Oper	Flag variable that indicates the status of InvControl's Volt-Watt function operation. Equal to 9999 if there is no InvControl controlling the element. See[3].
DRC Oper	Flag variable that indicates the status of InvControl's DRC function operation. Equal to 9999 if there is no InvControl controlling the element. See [3].
VV_DRC Oper	Flag variable that indicates the status of InvControl's VV + DRC function operation. Equal to 9999 if there is no InvControl controlling the element. See [3].
kWDesired	Nominal power desired or requested by the dispatch mode selected, in kW, if there is enough energy capacity left. Otherwise, it is 0.
kW VW Limit	Active power limit imposed by Volt-Watt function, in kW. See [3]. Equal to 9999 if the function is disabled due to inverter status.
Limit kWOut Function	Active power limit imposed by "Limit DER output function" ($\%kW Rated \times kW Rated$), in kW. See [3].
kVA Exceeded	Flag indicating if inverter kVA rating has been exceeded. See [3].

8 Examples

In this section, several examples are presented to show the operation of the storage element in each of the self-dispatch modes listed in Table 1. For simplicity, a small circuit containing a single storage connected to a voltage source will be utilized, as shown in Figure 5.

In the first example, 8.1, several aspects of the model operation will be described in details. In the following examples, the focus will be given to the aspects related to the storage dispatch itself.

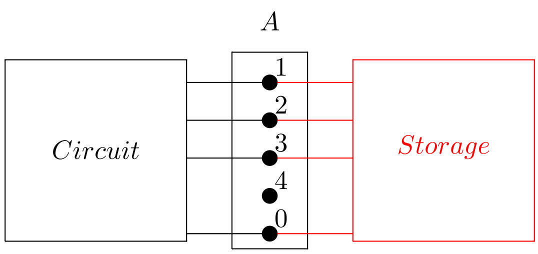

Figure 5: Storage Element Connected directly to a Voltage Source

8.1 Default Mode

In the script presented below, a loadshape is first created to be used as the dispatch curve to drive the storage operation. Since the simulation is performed in daily mode, in the storage definition, it is assigned to the Storage element *daily* property. Note that the element's initial state is set to idling and its initial SOC is set to 50%. Figure 6 presents the evolution of the element SOC, dispatch curve, and charging and discharging triggers. Figure 7 shows the element input and output active powers, and the storage inverter, idling, charging/discharging, and total losses. The curves have been plotted from the data exported from a monitor attached to the storage in mode 3.

```
! Storage Operation in Default Dispatch Mode
Clear

New Circuit.Source bus1=A basekv=0.48 phases=3 pu=1

New LoadShape.dispatch_shape interval=1 npts=24
~ mult = [0.380, 0.220, 0.247, 0.280, 0.313, 0.370, 0.589, 0.672, 0.7477, 0.832,
    0.88, 0.94, 0.989 , 0.985, 0.98, 0.9898, 0.999, 1.0, 0.958, 0.936, 0.913,
   0.800, 0.720, 0.610]

! Inverter Efficiency Curve
New XYCurve.Eff npts=4 xarray=[.1  .2  .4  1.0]  yarray=[.86  .9  .93  .97]

New Storage.Storage1 phases=3 bus1=A kv=0.48  pf=1 kWrated=50 %reserve=20
~ effcurve=Eff kWhrated= 500 %stored=50 %idlingkW=2 state=idling
~ dispmode=default model=1 daily=dispatch_shape
~ chargeTrigger = 0.34  dischargeTrigger = 0.85

New Monitor.Mon_Storage1_State element=Storage.Storage1 mode=3
New Monitor.Mon_Storage1_Powers element=Storage.Storage1 mode=1 ppolar=No

Set voltagebases = [0.48]
Calcvoltagebases

Set mode=Daily
Solve

Plot Monitor object=Mon_Storage1_State channels=(1 2 3 4 7 8 9 10)
Plot Monitor object=Mon_Storage1_Powers channels=(1 3 5)
```

The storage element operation is discussed below in detail for the different time periods:

- **1am - 2am** : The storage SOC is 50% (250 kWh) and the storage is operating in idling state (initial state) absorbing the power necessary to supply its idling losses and associated inverter losses. No state change is requested as the dispatch curve is greater than *ChargeTrigger* and less than *DischargeTrigger*;
- **2am - 6am** : At 2am, the dispatch curve becomes less than *ChargeTrigger*, so the storage changes to charging mode charging at the rated power, *kWRated*;
- **6am - 11am** : At 6am, the charging is ceased as the dispatch curve exceeds the *ChargeTrigger*;
- **11am - 5pm** : At 11am, the storage starts to discharge at rated power, *kWRated*, as the

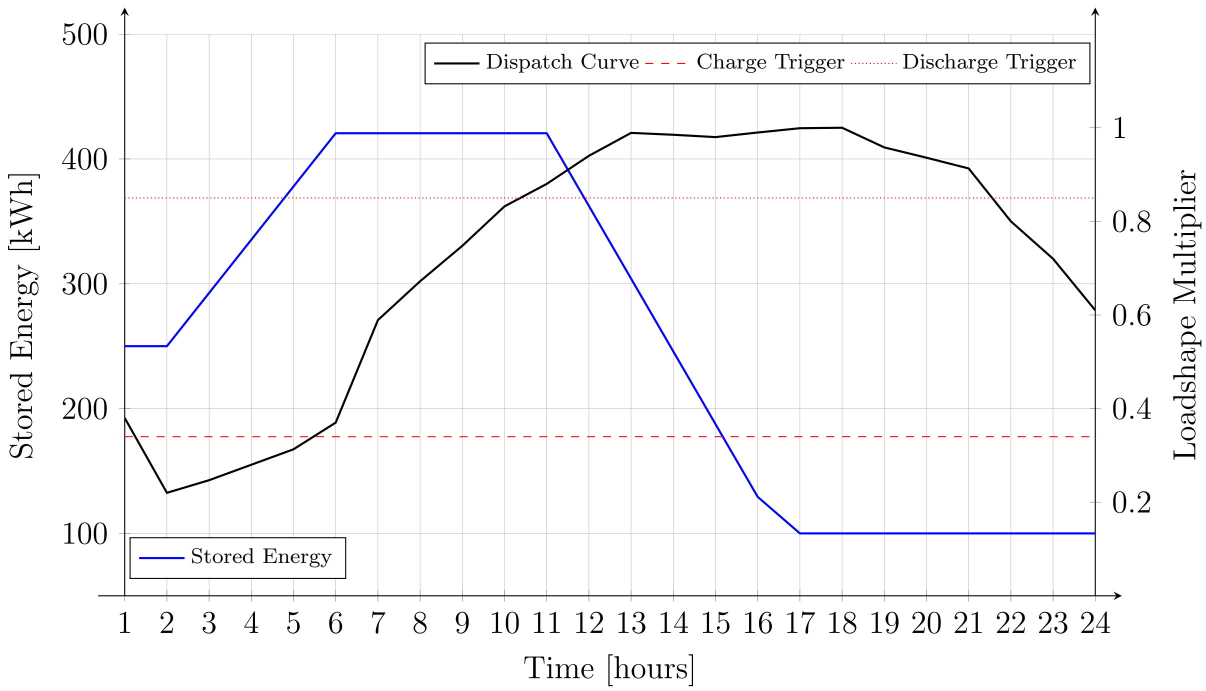

Figure 6: Stored Energy, Dispatch Curve and Triggers in Example 8.1

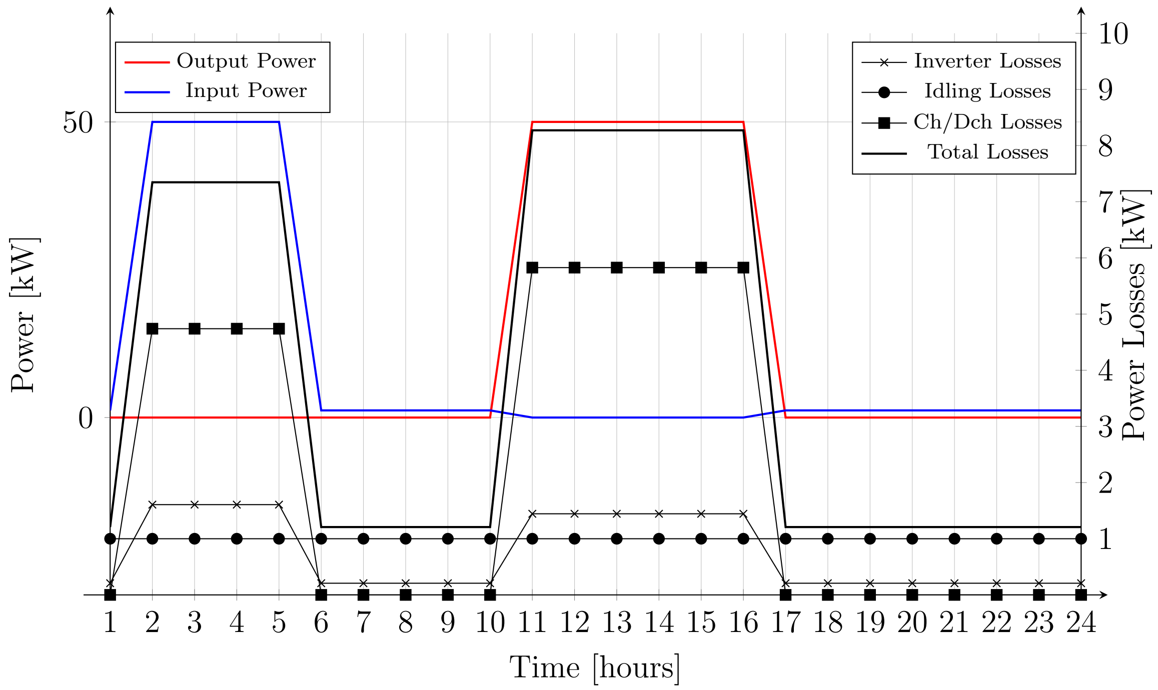

Figure 7: Powers at Storage Interface and Power Losses in Example 8.1

dispatch curve exceeds the $DischargeTrigger$. At 5pm, the discharging is suspended as the stored energy reaches its reserve level (100 kW, 20% of $kWhRated$) even though the dispatch curve stays above $DischargeTrigger$;

- **5pm - 12am** : The element stays in idling state;

Note that the storage total losses 2-6am are different to the storage total losses 11am-5pm even though the power at the storage grid interface is equal between these two periods (but with different directions). This fact is in agreement with the storage element internal power flow discussed in sections 5.1 and 5.2. In charging state, the power at the input of the charging losses block is equal to the power at the grid interface, 50 kW, minus the inverter and idling losses, whereas in discharging state, the power at the input of the discharging losses block is the sum of the output power, the inverter and idling losses and the discharging losses itself, according to equations 2 and 7, respectively. The inverter losses also differ between charging and discharging states but less than the charging/discharging losses.

As η_{ch} e η_{disch} have not been specified, both are equal to their default value 90%. The idling losses are 2% of the rated power, which is equal to 1kW. Consider two time instants: one with the storage charging and second with the storage discharging. Following the equations shown in section 5, the storage losses during these two time instants can be described as shown below.

In charging state, the inverter efficiency (based on the inverter efficiency curve) for 50kW power at the grid interface is $\eta_{inv} \cong 0.968$ (extracted from the report exported from monitor in mode 3). The losses are given by:

$$\begin{aligned} Losses_{inv}^{ch} &= 50 \times (1 - \eta_{inv}) = 1.607 \quad kW \\ Losses_{ch} &= (50 \times \eta_{inv} - 1) \times (1 - 0.9) = 4.739 \quad kW \\ Losses_{tot}^{ch} &= 1.607 + 4.739 + 1 = 7.346 \quad kW \end{aligned}$$

Thus, the power that effectively charges the storage is

$$P_{eff}^{ch} = 50 - 7.346 = 42.654 \quad kW$$

In discharging state, the inverter efficiency curve (based on the inverter efficiency curve) for 50kW power at the grid interface is $\eta_{inv} \cong 0.972$ (extracted from the report exported from monitor in mode 3). The losses are given by:

$$\begin{aligned} Losses_{inv}^{dch} &= 50 \times \left(\frac{1}{\eta_{inv}} - 1\right) = 1.444 \quad kW \\ Losses_{dch} &= \left(\frac{50}{\eta_{inv}} + 1\right) \times \left(\frac{1}{0.9} - 1\right) = 5.827 \quad kW \\ Losses_{tot}^{dch} &= 1.444 + 5.827 + 1 = 8.271 \quad kW \end{aligned}$$

Thus, the power that effectively discharges the element is

$$P_{eff}^{ch} = 50 + 8.271 = 58.271 \quad kW$$

We encourage the user to run the script of this example and to export the state variables from monitor "Mon_Storage1_State" to verify these results.

8.2 Follow Mode

In the script below, a different *loadshape* has been used to drive the operation of the element. Figure 8 shows the evolution of the stored energy and the dispatch curve and Figure 9 shows the active power input and output at the storage grid interface.

```
! Storage Operation in Follow Dispatch Mode
Clear

New Circuit.Source bus1=A basekv=0.48 phases=3 pu=1

New LoadShape.dispatch_shape interval=1 npts=24
~ mult = [0, -1.0, -1.0, -1.0, -0.5, -0.5, 0, 0, 0, 0, 0, 0, 0 , 0, 0.5, 0.75,
   1.0, 1.0, 1.0, 1.0, 0.75, 0.5, 0, 0]

! Inverter Efficiency Curve
New XYCurve.Eff npts=4 xarray=[.1  .2  .4  1.0]  yarray=[.86  .9  .93  .97]

New Storage.Storage1 phases=3 bus1=A kv=0.48  pf=1 kWrated=50 %reserve=20
~ effcurve=Eff kWhrated= 500 %stored=50 state=idling
~ dispmode=follow model=1 daily=dispatch_shape

New Monitor.Mon_Storage1_State element=Storage.Storage1 mode=3
New Monitor.Mon_Storage1_Powers element=Storage.Storage1 mode=1 ppolar=No

Set voltagebases = [0.48]
Calcvoltagebases

Set mode=Daily
Solve

Plot Monitor object=Mon_Storage1_State channels=(3 4)
Plot Monitor object=Mon_Storage1_Powers channels=(1 3 5)
```

Note that a negative dispatch value means power flowing into the storage, i.e., charging state, and a positive value means power flowing out of the storage, i.e., discharging state. Note also the similarity of the dispatch curve and the storage powers at the grid interface. As presented in section 6.2, in follow mode, the charge and discharge rates are determined as a product of the dispatch curve value and the storage rated power, *kWRated*. For instance, at 3am, the multiplier is -1, so the storage charges at its rated power, 50 kW . At 3pm, a mutiplier of 0.5 leads the element to discharge at 25 kW.

To force the element to go to idling state, just specify a multiplier equal to 0. Finally, it is worth mentioning again that the storage operation will follow the dispatch curve only if there is still enough energy capacity left. For instance, at 10pm, the multiplier would lead the storage to discharge at 25 kW . However, at this time step, *kWhstored* has already reached the reserve value (100 kW), so the element goes to idling state.

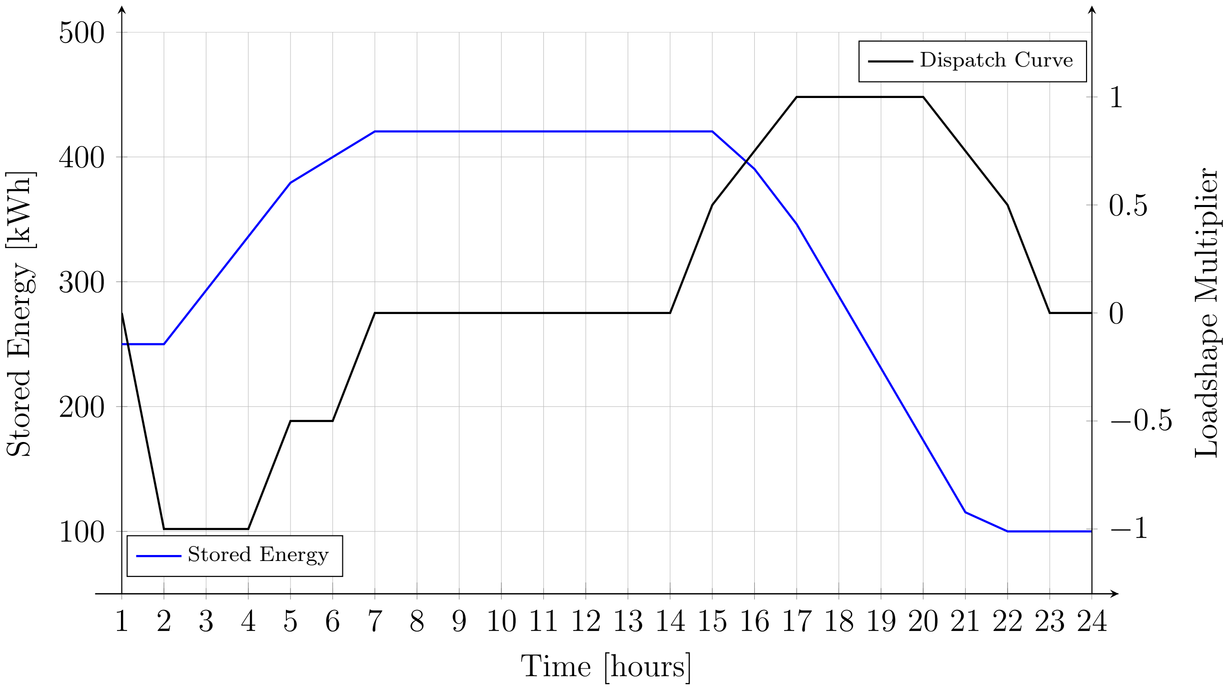

Figure 8: Stored Energy and Dispatch Curve in Example 8.2

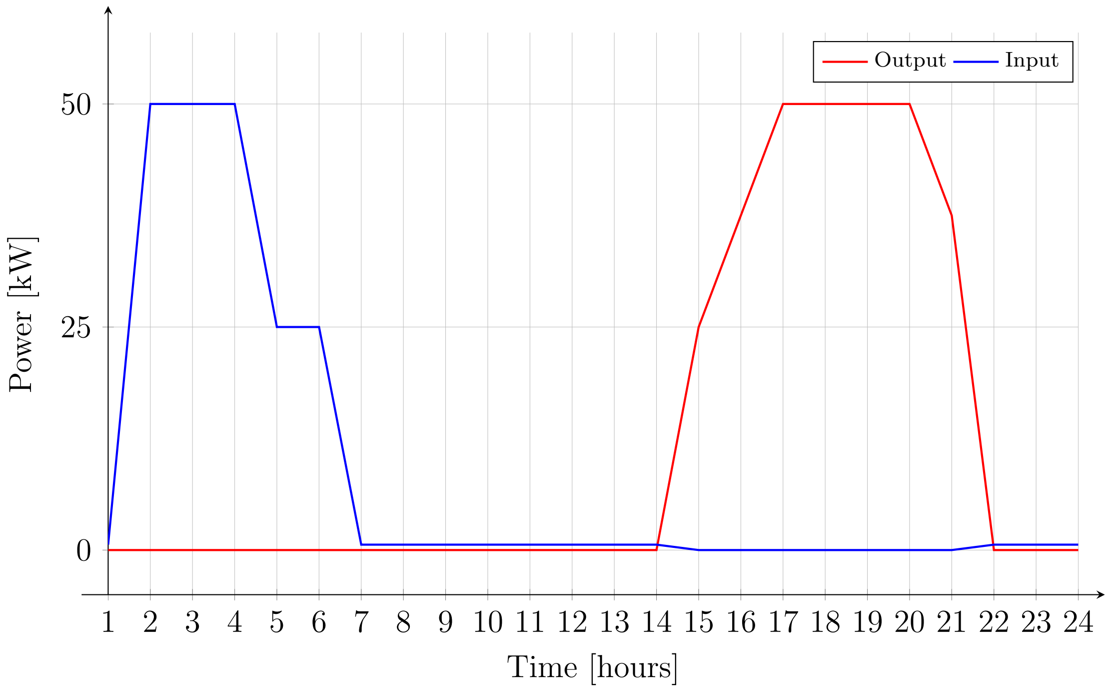

Figure 9: Powers at Storage Interface in Example 8.2

8.3 Price and LoadLevel Modes

As these modes are very similar, the storage operation is illustrated only for the Price mode. In the script below, a PriceShape object has been defined as an hypothetical energy price that varies throughout the day. Note that the definition of this object is very similar to a LoadShape object. The PriceShape element is assigned to the global price curve, *pricecurve*. Figures 10 and 11 show the resulting storage operation.

```
! Storage Operation in Price Mode
Clear

New Circuit.Source bus1=A basekv=0.48 phases=3 pu=1

New PriceShape.Price interval=1 npts=24
~ price = [75, 68, 67, 69, 71, 75, 75, 80, 80,  80, 90, 90, 90 , 95, 95, 95,
   105, 105, 110, 110, 110, 90, 90, 90]

! Inverter Efficiency Curve
New XYCurve.Eff npts=4 xarray=[.1  .2  .4  1.0]  yarray=[.86  .9  .93  .97]

New Storage.Storage1 phases=3 bus1=A kv=0.48  pf=1 kWrated=50 %reserve=20
~ kWhrated= 500 %stored=50 state=idling debugtrace=yes dispmode=price model=1
~ dischargeTrigger = 100 chargeTrigger= 74

New Monitor.Mon_Storage1_State element=Storage.Storage1 mode=3
New Monitor.Mon_Storage1_Powers element=Storage.Storage1 mode=1 ppolar=No

Set voltagebases = [0.48]
Calcvoltagebases

Set pricecurve=Price
Set mode=Daily
Solve

Plot Monitor object=Mon_Storage1_State channels=(1 2 3 4 5 6 7)
Plot Monitor object=Mon_Storage1_Powers channels=(1 3 5)
```

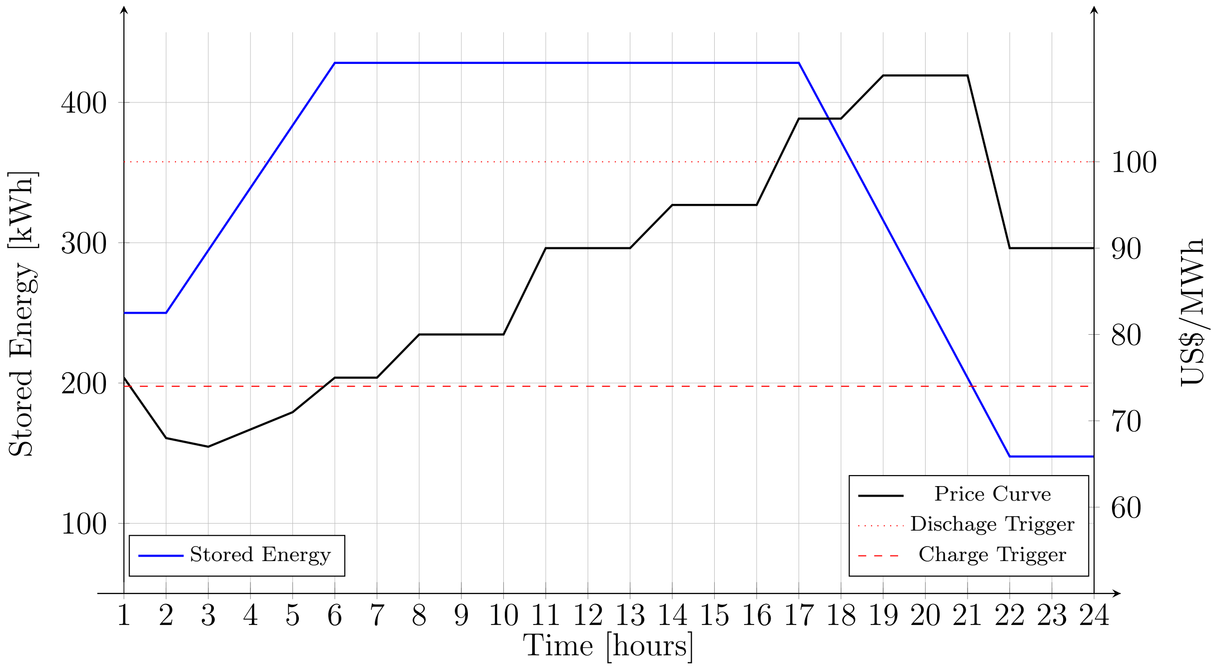

Figure 10: Stored Energy, Price Curve and Triggers in Example 8.3

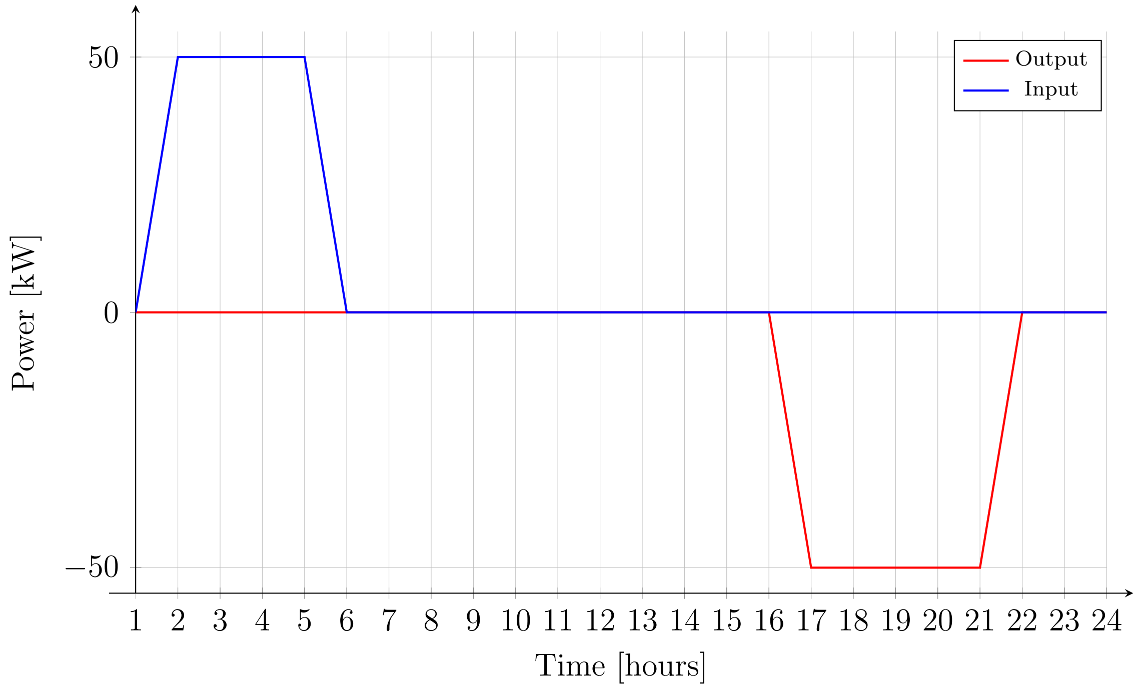

Figure 11: Powers at Storage Interface in Example 8.3

8.4 External Mode

This example shows how a "manual" control of the storage dispatch can be accomplished. In this example, the simulation is broken into smaller time periods that are each solved by issuing the *solve* command for a desired number of time steps specified with the global property *number*. The storage state and power are set to desired values in the beginning of each time period.

```
! Storage Operation in External Mode
Clear

New Circuit.Source bus1=A basekv=0.48 phases=3 pu=1

! Inverter Efficiency Curve
New XYCurve.Eff npts=4 xarray=[.1  .2  .4  1.0]  yarray=[.86  .9  .93  .97]

New Storage.Storage1 phases=3 bus1=A kv=0.48  pf=1 kWrated=50 %reserve=20
~ effcurve=Eff kWhrated= 500 %stored=50 state=idling dispmode=External

New Monitor.Mon_Storage1_State element=Storage.Storage1 mode=3
New Monitor.Mon_Storage1_Powers element=Storage.Storage1 mode=1 ppolar=No

Set voltagebases = [0.48]
Calcvoltagebases

Set mode=Daily
Set stepsize=1h

// Idles in the first two hours
// 1am-2am
Set number=2
```

```
Solve

// Charges for the next 5 hours with 80% of rated power
// 3am-7am
Edit Storage.Storage1 state=charging  %charge=80 ! setting state directly
Set number=5
Solve

// Idles for the next 10 hours
// 8am-5pm
Edit Storage.Storage1 state=idling
Set number= 10
Solve

// Discharges for the next 5 hours with half of rated power
// 6pm-10pm
! setting state directly through kw (positive means discharging)
Edit Storage.Storage1 kW=25
Set number=5
Solve

// Idles for the last two hours
// 11pm-12am
Edit Storage.Storage1 state=idling
Set number= 2
Solve

Plot Monitor object=Mon_Storage1_State channels=(1 2 3 4 5 6 7)
Plot Monitor object=Mon_Storage1_Powers channels=(1 3 5)
```

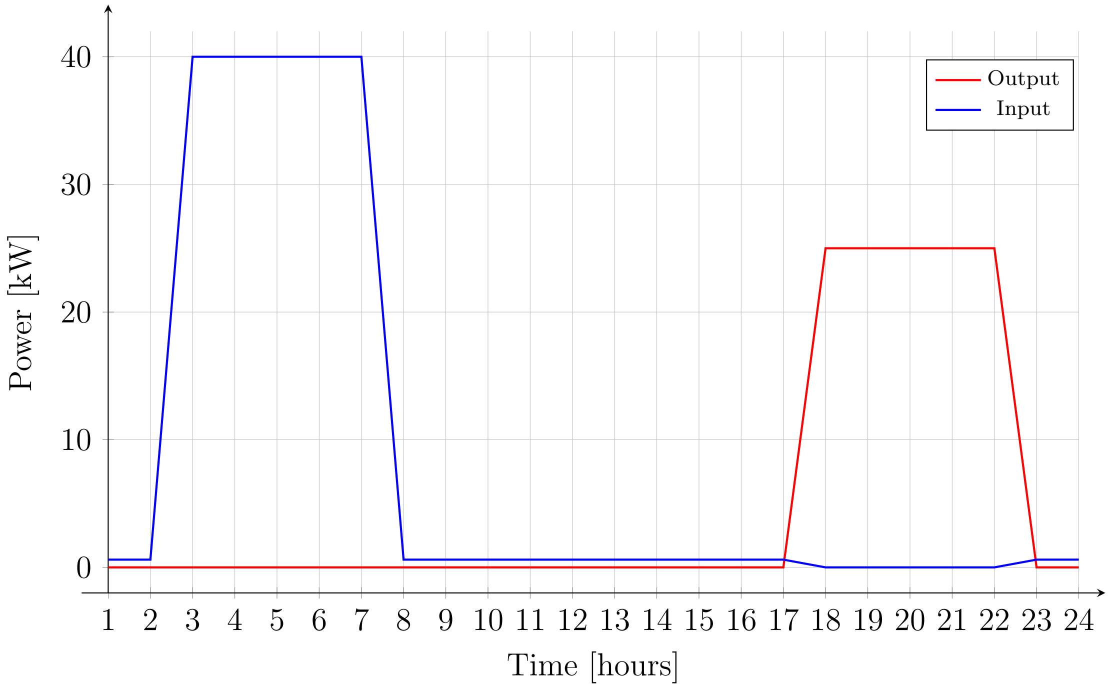

Figure 12: Powers at Storage Interface in Example 8.4

From 3am to 7am, the element is set to charge with a charging rate of 80%, 40 kW. Both are specified directly through *state* and *%charge* properties. This could also be accomplished by setting *kW* to -40. From 6pm to 10pm, the element is set to discharge with 50 kW through *kW* property. In the other time intervals, the element is set to idling state.

8.5 Reactive Power Dispatch

The next two examples are intended to demonstrate the operation of the storage element under the two reactive power self-dispatch modes: constant PF and constant kvar.

8.5.1 Constant PF Mode

To illustrate the storage operation in the constant PF mode, the Follow active power self-dispatch mode has been considered. The script used is similar to the one in example 8.2 apart from the differences in the dispatch curve and the addition of storage element property $pf = -0.90$.

```
New LoadShape.dispatch_shape interval=1 npts=24
~ mult = [0.0, -0.01, -0.08, -0.12, -0.16, -0.30, -0.50, -0.88, 0.0, 0.0, 0.0,
   0.0, 0.0, 0.0, 0.0, 0.01, 0.08, 0.12, 0.16, 0.30, 0.50, 0.88, 0.0, 0.0]

New Storage.Storage1 phases=3 bus1=A kv=0.48  pf=1 kWrated=50 %reserve=20
~ effcurve=Eff kWhrated= 500 %stored=50 state=idling
~ dispmode=follow pf=-0.90 model=1 daily=dispatch_shape
```

Figure 13 shows the active and reactive powers at the interface with the grid. Note that because of the negative power factor, the reactive power has an opposite sign to the active power. Figure 16 shows the PQ plane with the resulting operating points throughout the simulation. All points are over the constant -0.9 power factor line, even during idling state.

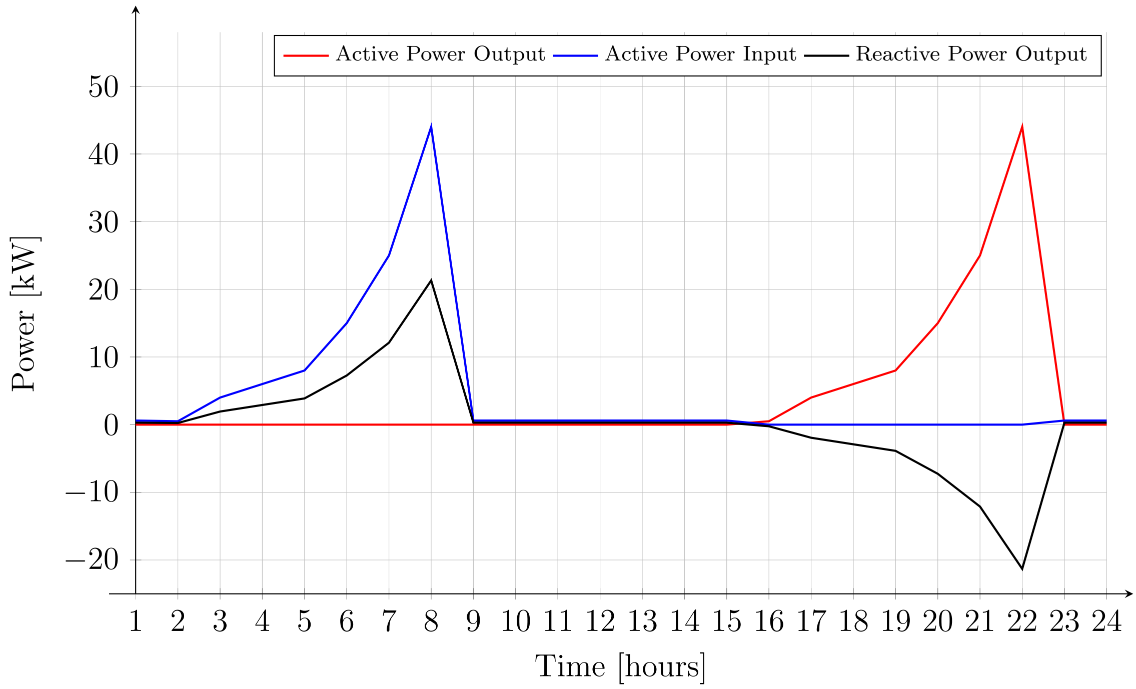

Figure 13: Powers at Storage Interface in Example 8.5.1

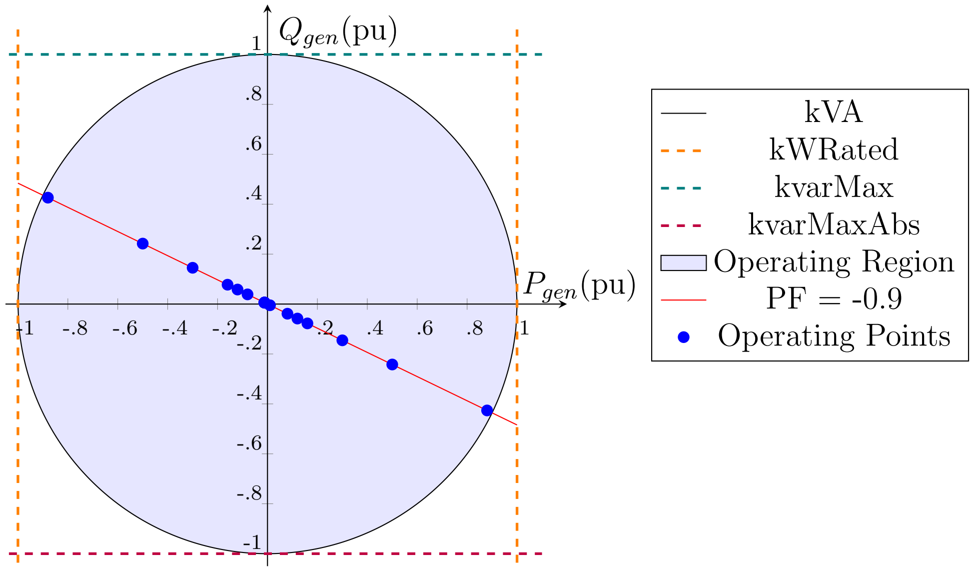

Figure 14: PQ Plane with Inverter Capability Curve and Operating Points under Constant PF Mode

8.5.2 Constant kvar Mode

This example illustrates the storage operation in the constant kvar mode using the dispatch curve from example 8.5.1 but with a constant reactive power generation of 20 kvar.

```
New Storage.Storage1 phases=3 bus1=A kv=0.48  pf=1 kWrated=50 %reserve=20
~ effcurve=Eff kWhrated= 500 %stored=50 state=idling
~ dispmode=follow kvar=20 model=1 daily=dispatch_shape
```

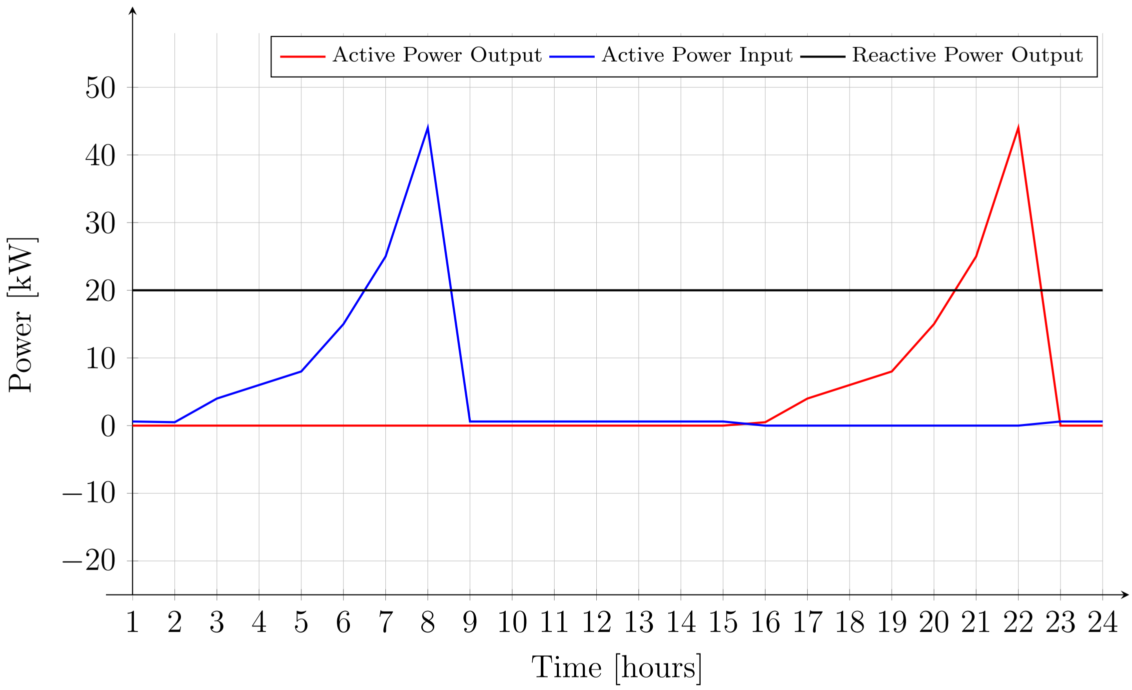

Figure 15: Powers at storage interface in example 8.5.2

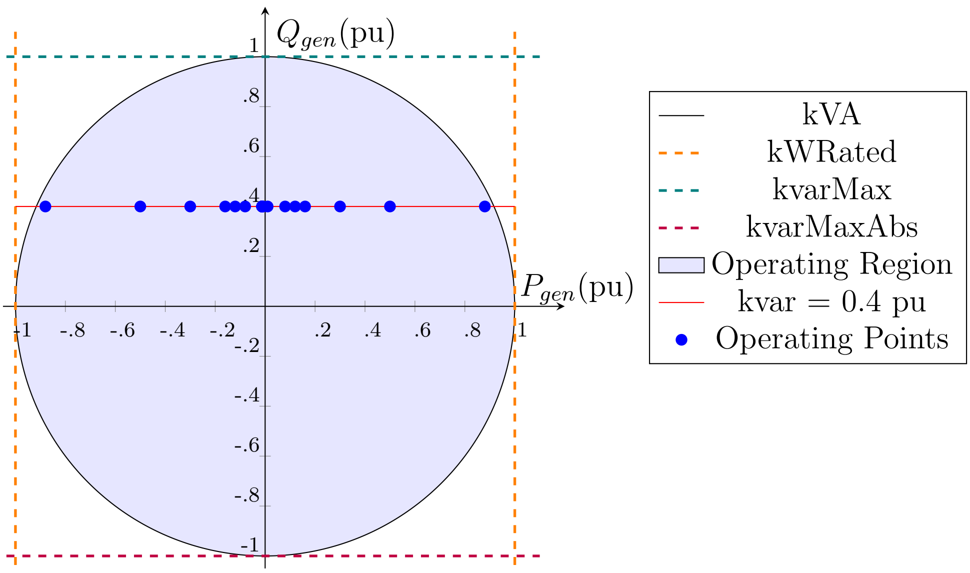

Figure 16: PQ Plane with Inverter Capability Curve and Operating Points under Constant kvar Mode

9 List of properties

Table 3 lists all the available properties of the storage element. Some of them are referenced in Figures 17 and 18.

Table 3: Properties of the storage Element

Property	Description
(1) phases	Number of Phases, this Storage element. Power is evenly divided among phases.
(2) bus1	Bus to which the Storage element is connected. May include specific node specification.
(3) kv	Nominal rated (1.0 per unit) voltage, kV, for Storage element. For 2- and 3-phase Storage elements, specify phase-phase kV. Otherwise, specify actual kV across each branch of the Storage element. If wye (star), specify phase-neutral kV. If delta or phase-phase connected, specify phase-phase kV.
(4) conn	{ *wye* | *LN* | *delta* | *LL* }. Default is *wye*.
(5) kW	Get/set the requested kW value. Final kW is subjected to the inverter ratings. A positive value denotes power coming OUT of the element, which is the opposite of a Load element. A negative value indicates the Storage element is in Charging state. This value is modified internally depending on the dispatch mode.
(6) kvar	Get/set the requested kvar value. Final kvar is subjected to the inverter ratings. Sets inverter to operate in constant kvar mode.
(7) pf	Get/set the requested PF value. Final PF is subjected to the inverter ratings. Sets inverter to operate in constant PF mode. Nominally, the power factor for discharging (acting as a generator). Default is 1.0. Enter a negative value for leading power factor (when kW and kvar have opposite signs). A positive power factor signifies kw and kvar at the same direction.
(8) kVA	Indicates the inverter nameplate capability (in kVA). Used as the base for Dynamics mode and Harmonics mode values. See Figure 18.
(9) %CutIn	Cut-in power as a percentage of inverter kVA rating. It is the minimum DC power necessary to turn the inverter ON when it is OFF. Must be greater than or equal to %CutOut. Defaults to 0, which means that the inverter state will be always ON for this element. See Figure 18.
(10) %CutOut	Cut-out power as a percentage of inverter kVA rating. It is the minimum DC power necessary to keep the inverter ON. Must be less than or equal to %CutIn. Defaults to 0, which means that, once ON, the inverter state will be always ON for this element. See Figure 18.

Continues on next page

Table 3 – *Continuation from previous page*

Property	Description
(11) EffCurve	An XYCurve object, previously defined, that describes the PER UNIT efficiency vs PER UNIT of rated kVA for the inverter. Power at the AC side of the inverter is discounted by the multiplier obtained from this curve.
(12) varFollowInverter	Boolean variable (Yes|No) or (True|False). Defaults to False which indicates that the reactive power generation/absorption does not respect the inverter status. When set to True, the reactive power generation/absorption will cease when the inverter status is off, due to DC kW dropping below %CutOut. The reactive power generation/absorption will begin again when the DC kW is above %CutIn. When set to False, the Storage will generate/absorb reactive power regardless of the status of the inverter.
(13) kvarMax	Indicates the maximum reactive power GENERATION (un-signed numerical variable in kvar) for the inverter. Defaults to kVA rating of the inverter. See Figure 18.
(14) kvarMaxAbs	Indicates the maximum reactive power ABSORPTION (un-signed numerical variable in kvar) for the inverter. Defaults to kvarMax. See Figure 18.
(15) WattPriority	{Yes|No*|True|False} Set inverter to watt priority instead of the default var priority.
(16) PFPriority	If set to true, priority is given to power factor and WattPriority is neglected. It works only if operating in either constant PF or constant kvar modes. Defaults to False.
(17) %PminNoVars	Minimum active power as percentage of kWrated under which there is no vars production/absorption. Defaults to 0 (disabled). See Figure 18.
(18) %PminkvarMax	Minimum active power as percentage of kWrated that allows the inverter to produce/absorb reactive power up to its maximum reactive power, which can be either kvarMax or kvarMaxAbs, depending on the current operation quadrant. Defaults to 0 (disabled). See Figure 18.
(19) kWrated	kW rating of inverter active power output. Base for Loadshapes when DispMode=Follow. Sets kVA property if it has not been specified yet. Defaults to 25. See Figure 18.
(20) %kWrated	Upper limit on active power as a percentage of kWrated. Defaults to 100 (disabled).
(21) kWhrated	Rated storage capacity in kWh. Default is 50.
(22) kWhstored	Present amount of energy stored, kWh. Default is same as kWhrated.
(23) %stored	Present amount of energy stored, % of rated kWh. Default is 100.
(24) %reserve	Percentage of rated kWh storage capacity to be held in reserve for normal operation. Default = 20. This is treated as the minimum energy discharge level unless there is an emergency. For emergency operation set this property lower. Cannot be less than zero.

Continues on next page

Table 3 – *Continuation from previous page*

Property	Description
(25) state	{ IDLING | CHARGING | DISCHARGING } Get/Set present operational state. In DISCHARGING mode, the Storage element acts as a generator and the kW property is positive. The element continues discharging at the scheduled output power level until the storage reaches the reserve value. Then the state reverts to IDLING. In the CHARGING state, the Storage element behaves like a Load and the kW property is negative. The element continues to charge until the max storage kWh is reached and then switches to IDLING state. In IDLING state, the element draws the idling losses plus the associated inverter losses.
(26) %Discharge	Discharge rate (output power) in percentage of rated kW. Default = 100.
(27) %Charge	Charging rate (input power) in percentage of rated kW. Default = 100.
(28) %EffCharge	Percentage efficiency for CHARGING the storage element. Default = 90.
(29) %EffDischarge	Percentage efficiency for DISCHARGING the storage element. Default = 90.
(30) *%IdlingkW*	Percentage of rated kW consumed by idling losses. Default = 1.
(31) *%Idlingkvar*	Deprecated.
(32) *%R*	Equivalent percentage internal resistance, ohms. Default is 0. Placed in series with internal voltage source for harmonics and dynamics modes. Use a combination of %IdlingkW, %EffCharge and %EffDischarge to account for losses in power flow modes.
(33) *%X*	Equivalent percentage internal reactance, ohms. Default is 50%. Placed in series with internal voltage source for harmonics and dynamics modes. (Limits fault current to 2 pu.)
(34) model	Integer code (default=1) for the model to be used for power output variation with voltage. Valid values are: 1:Storage element injects/absorbs a CONSTANT power. 2:Storage element is modeled as a CONSTANT IMPEDANCE. 3:Compute load injection from User-written Model.
(35) vminpu	Default = 0.90. Minimum per unit voltage for which the Model is assumed to apply. Below this value, the load model reverts to a constant impedance model.
(36) vmaxpu	Default = 1.10. Maximum per unit voltage for which the Model is assumed to apply. Above this value, the load model reverts to a constant impedance model.
(37) Balanced	{Yes|No*} Default is No. Force balanced current only for 3-phase Storage. Forces zero- and negative-sequence to zero.

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Table 3 – *Continuation from previous page*

Property	Description
(38) LimitCurrent	Limits current magnitude to Vminpu value for both 1-phase and 3-phase Storage similar to Generator Model 7. For 3-phase, limits the positive-sequence current but not the negative-sequence.
(39) yearly	Dispatch shape to use for yearly simulations. Must be previously defined as a Loadshape object. If this is not specified, the Daily dispatch shape, if any, is repeated during Yearly solution modes. In the default dispatch mode, the Storage element uses this loadshape to trigger State changes.
(40) daily	Dispatch shape to use for daily simulations. Must be previously defined as a Loadshape object of 24 hrs, typically. In the default dispatch mode, the Storage element uses this loadshape to trigger State changes.
(41) duty	Load shape to use for duty cycle dispatch simulations such as for solar ramp rate studies. Must be previously defined as a Loadshape object. Typically would have time intervals of 1-5 seconds. Designate the number of points to solve using the Set Number=xxxx command. If there are fewer points in the actual shape, the shape is assumed to repeat.
(42)DispMode	One amongst { DEFAULT | FOLLOW | EXTERNAL | LOADLEVEL | PRICE} Dispatch Mode. *Default* = "DEFAULT". In DEFAULT mode, Storage element state is triggered to discharge or charge at the specified rate by the loadshape curve corresponding to the solution mode. In FOLLOW mode the kW output of the STORAGE element follows the active loadshape multiplier until storage is either exhausted or full. The element discharges for positive values and charges for negative values. The loadshape is based on rated kW. In EXTERNAL mode, Storage element state is controlled by an external Storage controller. This mode is automatically set if this Storage element is included in the element list of a StorageController element. For the other two dispatch modes, the Storage element state is controlled by either the global default Loadlevel value or the price level.
(43) DischargeTrigger	Dispatch trigger value for discharging the storage. If = 0.0 the Storage element state is changed by the State command or by a StorageController object. If <> 0 the Storage element state is set to DISCHARGING when this trigger level is EXCEEDED by either the specified Loadshape curve value or the price signal or global Loadlevel value, depending on dispatch mode. See State property.
(44) ChargeTrigger	Dispatch trigger value for charging the storage. If = 0.0 the Storage element state is changed by the State command or StorageController object. If <> 0 the Storage element state is set to CHARGING when this trigger level is GREATER than either the specified Loadshape curve value or the price signal or global Loadlevel value, depending on dispatch mode. See State property.

Continues on next page

Table 3 – *Continuation from previous page*

Property	Description
(45) TimeChargeTrig	Time of day in fractional hours (0230 = 2.5) at which storage element will automatically go into charge state. Default is 2.0. Enter a negative time value to disable this feature.
(46) class	An arbitrary integer number representing the class of Storage element so that Storage values may be segregated by class.
(47) DynaDLL	Name of DLL containing user-written dynamics model, which computes the terminal currents for Dynamics-mode simulations, overriding the default model. Set to "none" to negate previous setting. This DLL has a simpler interface than the UserModel DLL and is only used for Dynamics mode.
(48) DynaData	String (in quotes or parentheses if necessary) that gets passed to the user-written dynamics model Edit function for defining the data required for that model.
(49) UserModel	Name of DLL containing user-written model, which computes the terminal currents for both power flow and dynamics, overriding the default model. Set to "none" to negate previous setting.
(50) UserData	String (in quotes or parentheses) that gets passed to user-written model for defining the data required for that model.
(51) debugtrace	{yes|no}.Default is no. Turn this on to capture the progress of the Storage model for each iteration. Creates a separate file for each Storage element named "STORAGE_name.csv".

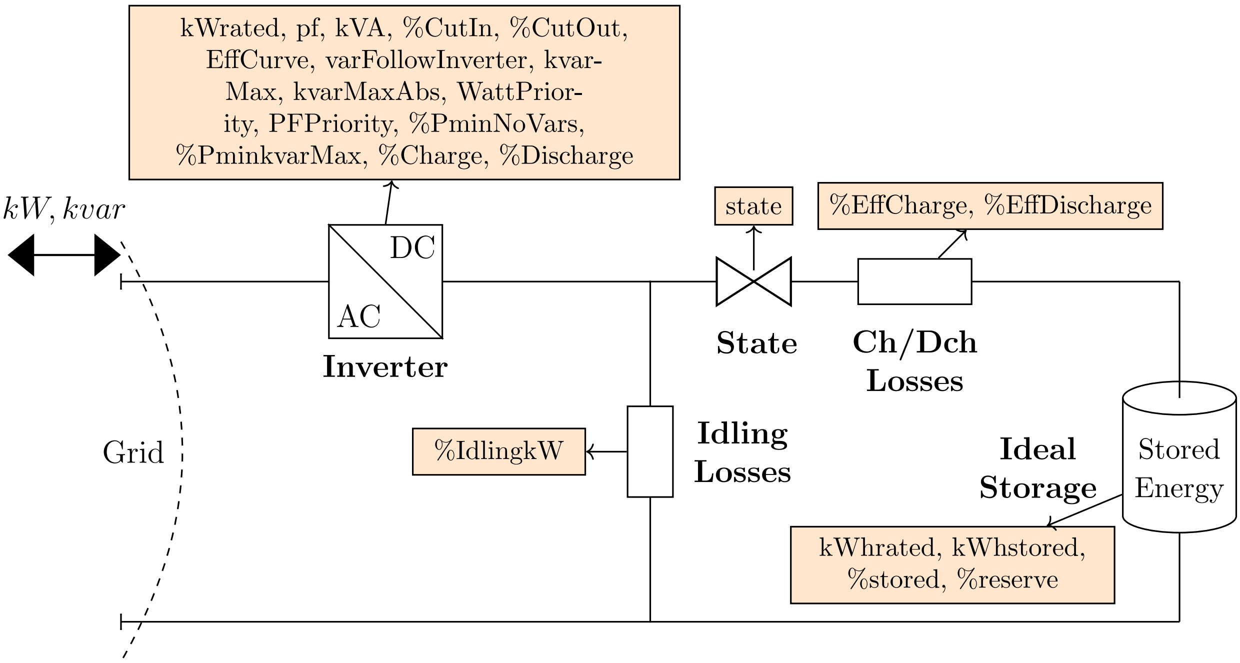

Figure 17: General Model of the Storage Element with Mapping of Properties and Internal Components

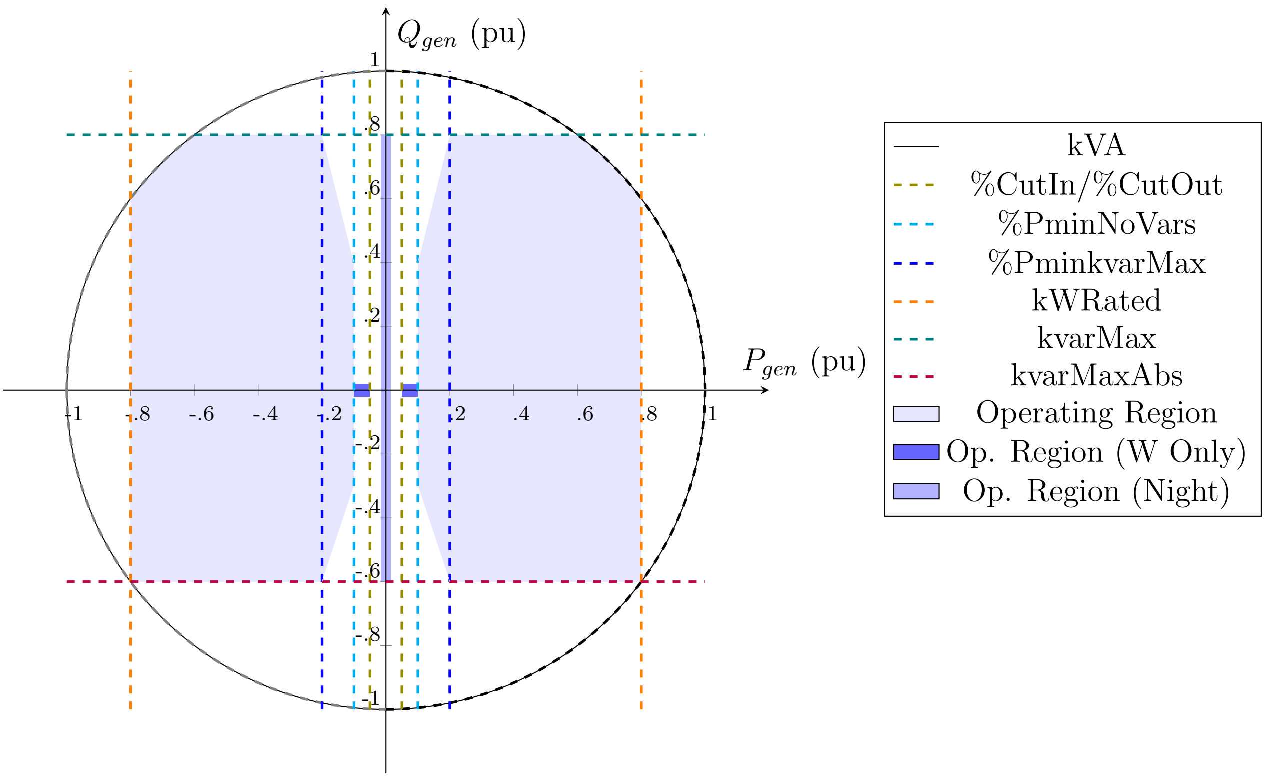

Figure 18: General Inverter Capability Curve

10 References

[1] R. Dugan and D. Montenegro, “Opendss storage element and storagecontroller element,” EPRI, OpenDSS Tech. Note, October 2019.

[2] C. Rocha, J. Peppanen, P. Radatz, M. Rylander, and R. Dugan, “Storagecontroller element,” EPRI, OpenDSS Tech. Note, November 2019.

[3] P. Radatz, W. Sunderman, and C. Rocha, “Opendss pvsystem and invcontrol element models,” EPRI, OpenDSS Tech. Note, November 2019.

[4] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, Std., April 2018.

[5] C. Rocha, P. Radatz, J. Peppanen, M. Rylander, and R. Dugan, “Inverter modelling,” EPRI, OpenDSS Tech. Note, 2019.