Tutorial 7: HVDC Link

This tutorial explains how separate electrical islands are connected via an HVDC link, allowing for the controlled transmission of energy between the islands. The tutorial looks at how the HVDC link can set the risk, and how this risk can be mitigated if the HVDC link has more than one branch. Also covered is how the HVDC control system can be used to share reserve between islands via the HVDC link.

We start with a simple model and progressively add to it to demonstrate the various features of the HVDC link.

The finished model is also available in the Sample models, where it is named “HVDC Link”.

Electrical Islands

The power produced by generators and consumed by the loads is alternating current (AC) power.

An AC electrical island represents a set of electrically connected components, i.e., generators, buses, branches and loads.

Connecting AC islands

If two isolated AC electrical islands are connected by an AC branch, i.e., the branches we have dealt with so far, this will form a single AC electrical island. For example, build the model shown in Figure 83 using the default parameters. This model has two separate electrical islands.

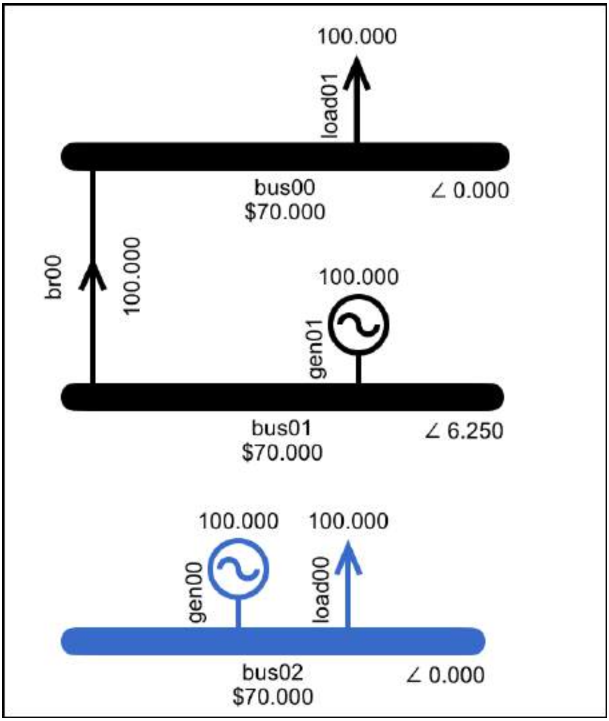


Figure 83: Two separate electrical islands

As soon as an AC branch is added between the two islands, they form a single island as shown in Figure 84.

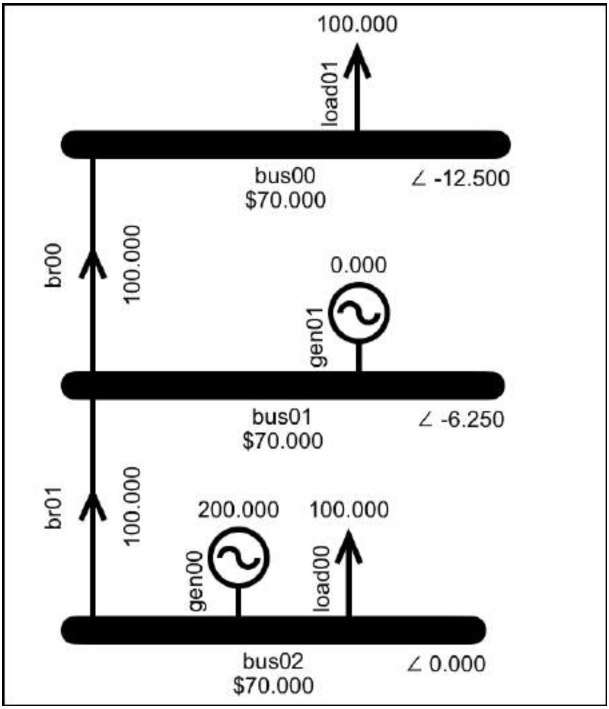


Figure 84: AC islands connected via an AC branch form a single island

HVDC Link

An HVDC link connects two AC systems while allowing them to remain independent. The control system of the HVDC link controls the power that flows between the two islands. The "HVDC" in HVDC link refers to the voltage of the link, i.e., High Voltage Direct Current. Power entering the HVDC link from an AC system is converted to HVDC and at the other end of the link the power is converted back to AC and enters the other AC system.

Adding an HVDC link

The HVDC power is transmitted via one or more HVDC branches. An HVDC branch is a cable or transmission circuit. Physically the conductor is the same as an AC branch, with resistance, reactance and a maximum flow.

To add an HVDC link with a single HVDC branch, double tap the AC branch br01 and select the HVDC switch to the on position, as indicated in Figure 85.

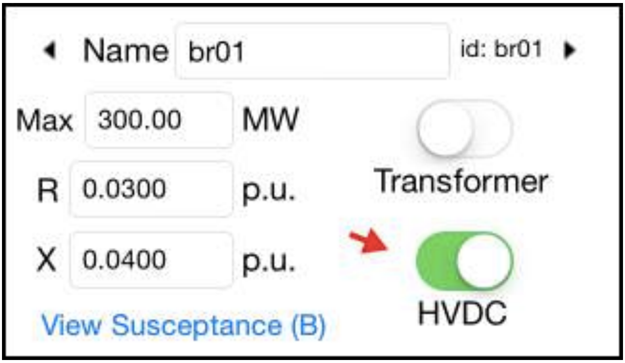


Figure 85: Branch Data Display with HVDC switch indicated

With br01 as an HVDC branch the two islands are separate, as shown in Figure 86. The symbol on the HVDC branch represents a thyristor. Thyristors are large semiconductors that are the key component in the conversion between AC voltage and DC voltage.

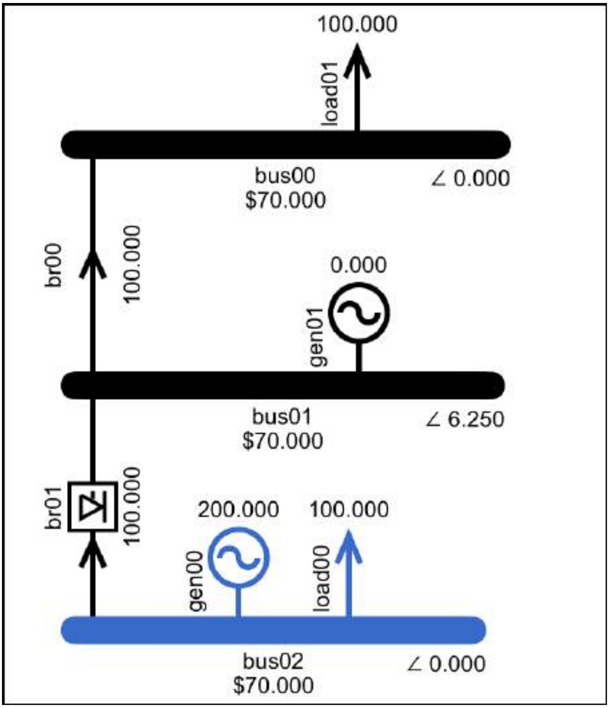


Figure 86: AC islands joined by an HVDC link

HVDC branch has no power flow constraint

The power flow in an AC branch is determined by the power flow constraint, as described in Tutorial 2: Modelling Transmission. The power flow constraint models the physical reality that a change in the voltage phase angle across a branch will result in a change in power flow.

With an HVDC branch it is the HVDC control system that determines the flow. Hence if the phase angle changes at one end of the HVDC link there is no change in the HVDC branch flow, unless initiated by the control system.

The electricity market model represents this independence by not subjecting HVDC branches to the power flow constraint. This can be seen in Figure 86 where the phase angles either side of the HVDC branch are not related to the branch flow.

To see this more clearly, double tap bus01 and select it to be the reference bus for island 1 (as shown in Figure 87), then re-solve and the result is shown in Figure 88. Notice that the phase angles either side of the HVDC link are zero, and that despite this the flow is non-zero.

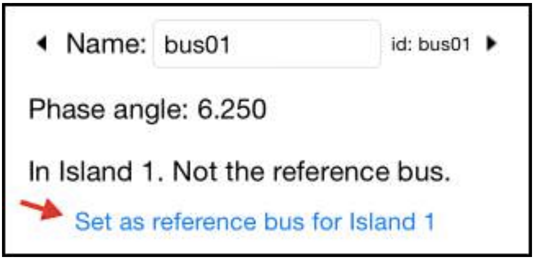


Figure 87: Setting bus01 to be the reference bus in island 1

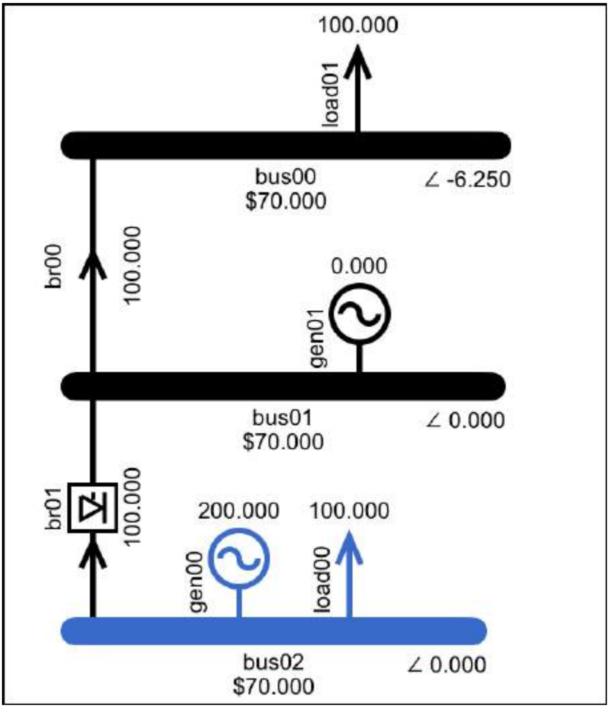


Figure 88: With bus01 as reference bus in island 1 it is easy to see that the HVDC flow is not dependent on phase angles

HVDC Risk

With two islands connected by an HVDC link, if the scheduled generation is in the opposite island to the load then the generation must be dispatched *and* a signal issued to the HVDC control system in order to send the generation from the sending island (with the generation) to the receiving island (with the load) via the HVDC link.

In the receiving island, the power from the HVDC link is a set amount resulting from an instruction issued to a control system. In this way the HVDC link is similar to a generator and can set the risk in the receiving island.

The constraint that identifies an HVDC branch as a risk is shown in Equation 21. This constraint acts in parallel with the generator risk constraint discussed in Tutorial 5: Risk and Reserve. Whichever is the larger of the AC generator risk and the HVDC branch risk will set the island risk (or if they represent the same risk quantity then they can both set the risk).

Equation 21: Island largest risk constraint for HVDC branch

$$BranchFlowToIsland_{HVDCBranch} - BranchLosses_{HVDCBranch} \leq LargestRiskHVDC_{Island}$$

To demonstrate the HVDC as a risk setter, increase gen01's energy offer price to $110, give it 250MW of $9 reserve and switch its Risk to off, so that it is not a risk unit. Edit gen00 so that it is also not a risk unit. Solve the model with Reserves enabled and Reserve Sharing disabled. The result is shown in Figure 89.

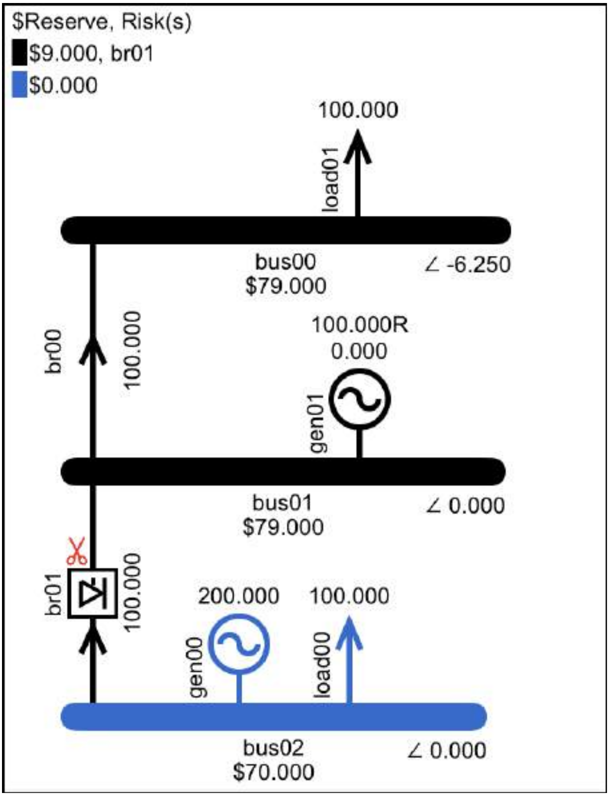


Figure 89: HVDC link as risk setter

Because the power at gen00 is cheaper than gen01 the solver uses the HVDC link to transport power from gen00 in island 2 (blue) to load01 in island 1 (black). The red risk setter symbol on the HVDC branch indicates that it is setting the risk in Island 1. The $9 cost of the reserve that covers the HVDC risk is incorporated into the energy price for Island 1.

Island 2 has no risk setter hence its reserve price is $0.

Note that it is the received transfer that is covered, i.e., flow – losses. Confirm this by solving with losses set to on, to get the result shown in Figure 90.

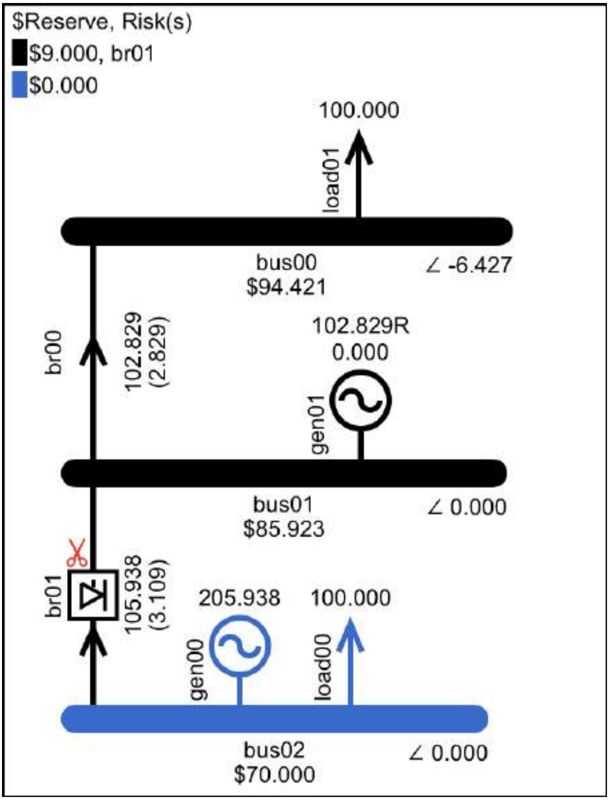


Figure 90: HVDC risk is net transfer

Viewing the HVDC risk constraints

The HVDC risk constraints that the solver creates for br01, with losses included, are shown in Figure 91. The risk of the flow minus losses is assigned to the LargestRiskDC variable for the island.

```
br01:
CalcRiskEachHVDC(LTE) constraint:
Shadow Price: $0.00
 +1.00000*br01_{BrFlowPos}
-1.00000*br01_brSeg00_{SegLossPos}
-1.00000*br01_brSeg01_{SegLossPos}
-1.00000*br01_brSeg02_{SegLossPos}
-1.00000*br01_{HVDCSubtractorToToIsland}
-1.00000*island02_{LargestRiskDC}  <= 0.00000

br01:
CalcRiskEachHVDC(LTE) constraint:
Shadow Price: $9.00
 +1.00000*br01_{BrFlowNeg}
-1.00000*br01_brSeg00_{SegLossNeg}
-1.00000*br01_brSeg01_{SegLossNeg}
-1.00000*br01_brSeg02_{SegLossNeg}
-1.00000*br01_{HVDCSubtractorToFromIsland}
-1.00000*island01_{LargestRiskDC}  <= 0.00000
```

Figure 91: HVDC risk calculation with losses included

Note that the constraints include an HVDC Subtractor, which is explained in the next sub-section.

The island constraints that cover the risk are shown in Figure 92. Note that the HVDC risk is covered separately from the AC risk… if the HVDC link is used to share reserve between islands, then the shared reserve cannot be used to cover the risk of the HVDC link that transports it. Reserve sharing is covered later on in this tutorial.

ISLAND01

```
island01:
ReserveCoversACRisk(LTE) constraint:
Shadow Price: $0.00
 +1.00000*island01_{LargestRiskAC}
-1.00000*bus01_gen01_resOffer00_{Cleared}  <=
0.00000

island01:
ReserveCoversHVDCRisk(LTE) constraint:
Shadow Price: $9.00
 +1.00000*island01_{LargestRiskDC}
-1.00000*bus01_gen01_resOffer00_{Cleared}  <=
0.00000
```

ISLAND02

```
island02:
ReserveCoversACRisk(LTE) constraint:
Shadow Price: $0.00
 +1.00000*island02_{LargestRiskAC}  <= 0.00000

island02:
ReserveCoversHVDCRisk(LTE) constraint:
Shadow Price: $0.00
 +1.00000*island02_{LargestRiskDC}  <= 0.00000
```

Figure 92: Constraints that schedule reserve to calculate risk

HVDC Subtractor

When the HVDC link consists of more than one HVDC branch then the spare capacity on one of the branches can offset the potential risk presented by the transfer on the other. To demonstrate this, add another HVDC branch between island 1 and island 2. Solve with Losses selected OFF, to produce the result shown in Figure 93.

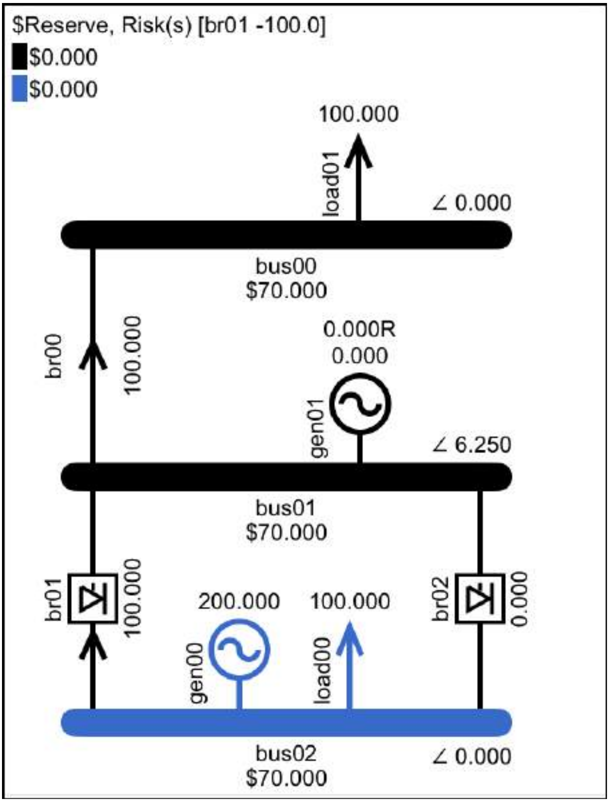


Figure 93: Parallel HVDC branch offsets HVDC risk

With the parallel HVDC branch, the HVDC risk in island 1 is now zero. This is because the transfer on br01 is 100MW, while the spare capacity on br02 is at least 100MW. If br01 were to trip, then the HVDC control system would use br02 to replace the lost transfer.

If the solver uses a subtractor to reduce the HVDC risk then the reserve heading at the top of the display lists any HVDC branch with non-zero flow, followed by the subtractor that was applied to the risk presented by this flow. Here br01 is the potential risk setter and the solver has applied a subtractor of -100 (which it obtained from the spare capacity on br02).

Subtractor constraints

The subtractor constraints for br01 are shown in Figure 94.

```
br01:
CalcHVDCSubtractorToToIsland(LTE) constraint:
Shadow Price: $0.00
 +1.00000*br01_{HVDCSubtractorToToIsland}
+1.00000*br02_{BrFlowPos}  <= 300.00000

br01:
CalcHVDCSubtractorToFromIsland(LTE) constraint:
Shadow Price: $0.00
 +1.00000*br01_{HVDCSubtractorToFromIsland}
+1.00000*br02_{BrFlowNeg}  <= 300.00000
```

Figure 94: Subtractor calculation constraints

There are two constraints that calculate the branch's subtractor; one for forward flow and one for reverse flow (where forward flow is flow from the branch's from-island to the branch's to-island, and reverse flow is vice-versa).

The RHS of the branch's subtractor equation is the sum of the capacity of all *other* HVDC branches that have the same from-island and to-island as the branch in question. The LHS includes the subtractor variable, along with the flow from all other HVDC branches, effectively subtracting these flows from their capacity on the RHS.

HVDC Reserve Sharing

If the HVDC control system has the appropriate settings then the HVDC link can be used to share reserve between islands, i.e., reserve can be scheduled in one island to cover a generation risk in the other island.

In the event of a generator tripping, the island's frequency will drop. The HVDC control system will respond to the frequency drop by increasing the HVDC transfer to replace the lost generation. The increase in HVDC transfer will drop the frequency in the reserve-sending island, causing the reserve in the reserve-sending island to respond, effectively covering the increase in HVDC transfer.

The amount of reserve that can be shared must be covered by cleared reserve in the reserve-sending island, this is enforced by the constraint shown in Equation 22.

$$ReserveShared_{FromIsland} \leq \sum_{\substack{Gen \\ in\ FromIsland}} ClearedReserve_{Gen}$$

Equation 22: Reserve shared is covered by cleared reserve

To demonstrate reserve sharing, first simplify things by removing the HVDC branch br02. Then set gen00 as a risk unit. Solve this model with Reserves and Reserve Sharing enabled. The result is shown in Figure 95.

Other island risk

In the reserve sharing result shown in Figure 95, gen00 is the risk setter in island 2 (the blue island). The 200MW of reserve to cover this risk is provided by gen01 in island 1 and shared to island 2 via HVDC branch br01.

The risk setter for island 1 is listed as “other island”. The HVDC is no longer the risk setter in island 1, because the highest risk is now the risk presented by the reserve being shared to the other island.

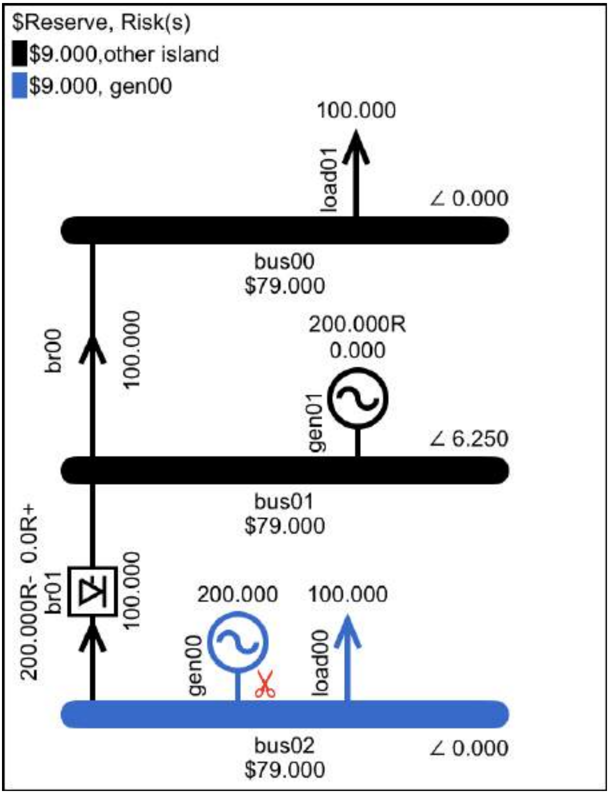


Figure 95: HVDC reserve sharing: reserve on gen01 in island 1 covers risk presented by gen00 in island 2

Reserve sharing direction

When reserve sharing is enabled, each HVDC branch that is sharing reserve has a label showing how much reserve it is sharing and in which direction. The reserve quantity has a "+" if it is shared in the same direction as energy flow and a "-" if it is in the opposite direction.

If there is no energy flow then the "+" is for reserve that is shared in the direction that would be positive flow, i.e., from the branch's from-bus to the branch's to-bus (where the from-bus is the bus with the name that is alphabetically before the name of the to-bus… the from-bus and the to-bus are explicitly identified on the branch's Data Display).

Reserve Sharing "Reserve covers risk" constraint

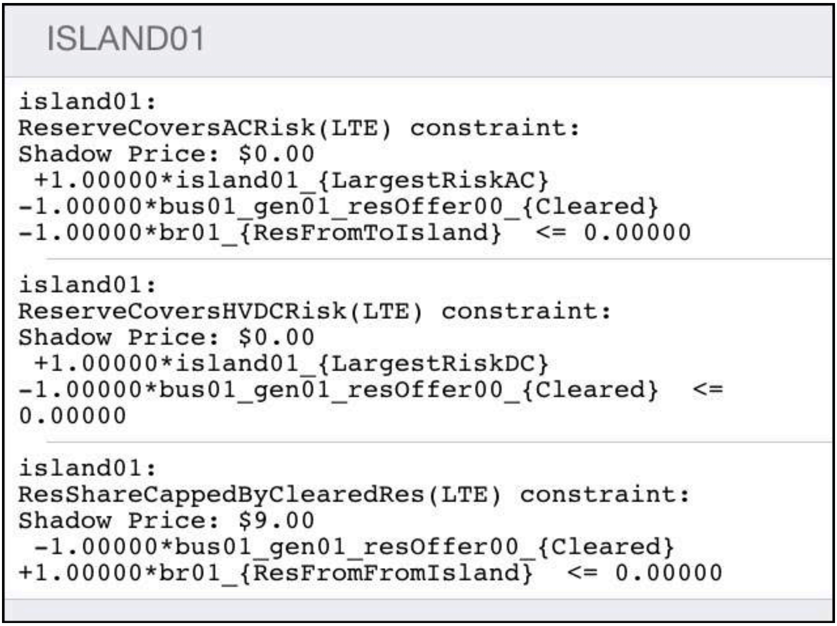
When reserve sharing is enabled, the reserve from the other island is included in the "reserve covers risk constraint", as shown by Equation 23.

Equation 23: Reserve covers risk constraint, with reserve sharing

$$\sum_{\substack{Gen \\ in\ Island}} ClearedReserve_{Gen}$$

$$+ ReserveShared_{OtherIsland} \le LargestACRisk_{Island}$$

The actual constraints for Island01 are shown in Figure 96. Note that, as discussed above, the reserve from the other island can only be used to cover the AC risk.



```
ISLAND01

island01:
ReserveCoversACRisk(LTE) constraint:
Shadow Price: $0.00
 +1.00000*island01_{LargestRiskAC}
-1.00000*bus01_gen01_resOffer00_{Cleared}
-1.00000*br01_{ResFromToIsland}  <= 0.00000

island01:
ReserveCoversHVDCRisk(LTE) constraint:
Shadow Price: $0.00
 +1.00000*island01_{LargestRiskDC}
-1.00000*bus01_gen01_resOffer00_{Cleared}  <=
0.00000

island01:
ResShareCappedByClearedRes(LTE) constraint:
Shadow Price: $9.00
 -1.00000*bus01_gen01_resOffer00_{Cleared}
+1.00000*br01_{ResFromFromIsland}  <= 0.00000
```

Figure 96: Reserve sharing constraints for Island01

HVDC setting risk and sharing reserve

Shared reserve received from the other island cannot be used to cover the risk presented by the HVDC. However, provided that the HVDC risk itself is covered by cleared reserve from within the island, the HVDC link can be used to share some or all of this cleared reserve to cover the AC risk in the other island.

To see the HVDC setting the risk in one island and also sharing reserve to the other island, add a new generator gen02 to bus02, edit its energy price to be

$120 and its reserve to be 30MW of reserve at $7. Edit load01 so that its quantity is only 10MW.

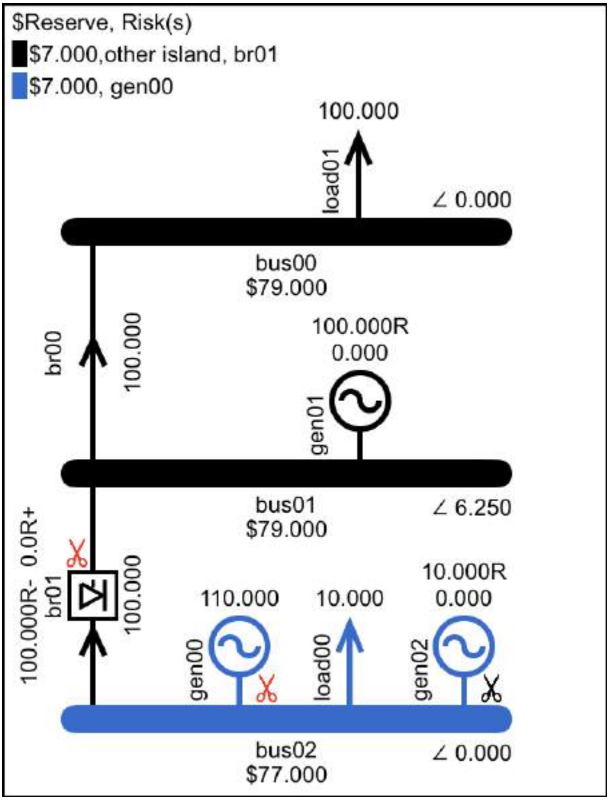


Figure 97: HVDC link as risk setter and sharing reserves

The result is shown in Figure 97. The HVDC risk of 100MW in island 1 is being covered by reserve of 100MW scheduled on gen01. This reserve is also being shared by the HVDC to cover 100MW of the risk presented by gen00 in island 2.

Reserve sharing in both directions

The reserve shared by the HVDC link can be shared in both directions at the same time. To demonstrate this, add a new generator gen03 to bus01, leaving its default parameters unchanged.

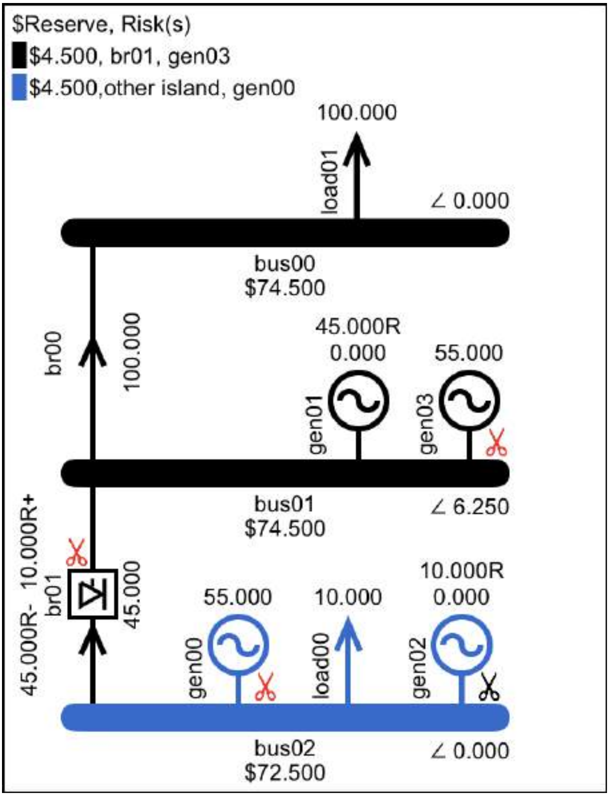


Figure 98: Reserve sharing in both directions

The results are shown in Figure 98. The risk in each island is covered partly by reserve from the other island.

HVDC capacity limit constraint

In the event of a tripping that results in the loss of generation, the reserve that is scheduled to cover the risk will respond to replace the missing energy. If reserve that is shared via the HVDC link is called upon then it will need to share the capacity of the link with the energy transfer that is already scheduled.

The requirement to ensure that the HVDC link is capable of providing the shared reserve as energy, while still maintaining its scheduled energy transfer, is represented by the constraint shown in Equation 24. This constraint limits the sum of the energy and reserve scheduled on the HVDC branch to be within the capacity limit of the branch, i.e., the branch's maximum flow.

Equation 24: Capacity limit on HVDC branch

$$Energy_{HVDCBranch} + Reserve_{HVDCBranch} \leq MaxFlow_{HVDCBranch}$$

The HVDC branch capacity constraint can be demonstrated by editing HVDC branch br01 to reduce its max flow to 50MW. The result is shown in Figure 99.

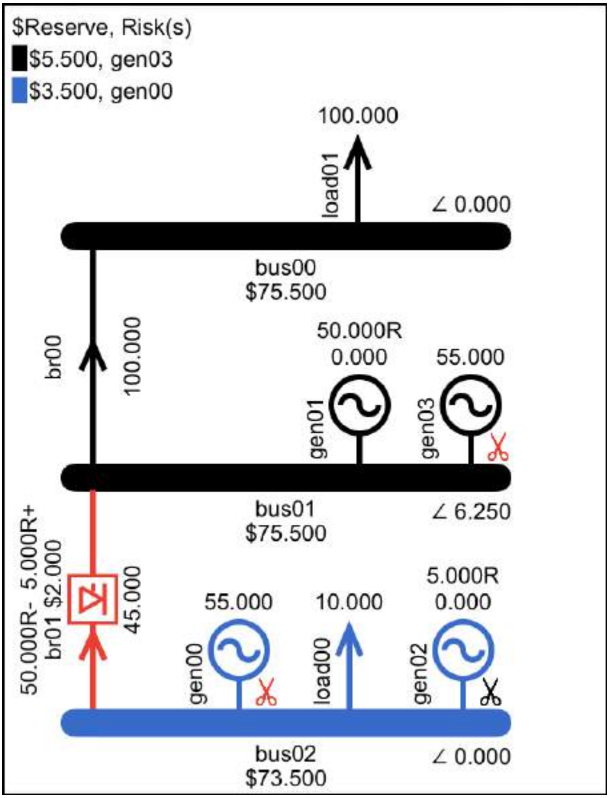


Figure 99: HVDC link binding on capacity limit of 50MW

Note that the HVDC capacity constraint takes account of direction. From island 2 to island 1 the HVDC link is scheduling energy and reserve, hence the energy of 45MW limits the scheduled reserve to 5MW. In the opposite direction, with no scheduled energy transfer, the scheduled reserve is only limited by the 50MW capacity of the branch.

Reserve sharing price separation

In the result shown in Figure 99, the binding HVDC capacity constraint results in different reserve prices between the two islands. With the binding constraint separating the two islands, extra reserve in one island will not have a *direct* impact on reserve supply in the other island. However, because the capacity constraint is binding due to a combination of energy and reserve transfer, rather than being a hard constraint that restricts only the reserve, the inter-island reserve prices are not completely un-related, there relationship is dependent on the value of the energy trade-off that would need to be made in order to allow more reserve to be transferred.

Summary

In this tutorial we looked at HVDC links that connect AC power systems. We saw that the conductors in the HVDC link have the same physical properties as the branches in the AC system, and that it is the ability to control their flow via the HVDC control system that makes an HVDC link special in terms of how it is modelled.

We built models to investigate the special features of the HVDC link. Apart from the fact that the power flowing in the HVDC link is not directly related to the phase angles, most of the special features relate to risk and reserve. We saw how the HVDC link is modelled as a potential risk setter, and how this risk can be mitigated if the HVDC link has more than one HVDC branch. The HVDC link can also share reserve between islands, and we built models to demonstrate the various levels of complexity that arise when this feature is implemented.

Note that the HVDC investigation model is available pre-built in the Samples section of the app.