TO: WECC ATSMWG

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SUBJECT: PROPOSAL FOR HYBRID-STATCOM MODEL (SVSMO4)

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From 2010 to 2012, with much technical input from EPRI, within the WECC SVC Task Force a series of three (3) generic dynamic models, and associated power flow models, were developed for representing static var systems (SVS). These models are called SVSMO1 (for TCR-based SVCs), SVSMO2 (for TSC/TSR based SVCs) and SVSMO3 (for STATCOMs) [1], [2]. These models were subsequently adopted by the major vendors of power system stability software [1], and have been in used in for the past eight years or so. In addition, these models have been validated against many disturbance events, as shown for example in [1] and [3]. The main goal of these models was to provide models in positive-sequence simulation programs with a focus on generic, non-proprietary models that are open source, well documented [2] and available publicly.

Here we will not go into the details of Static Var Systems (SVS) and the three main technologies (TCR-based SVC, TSC/TSR based SVC and STATCOMs)[1], since those detail can be readily found in [2], in terms of the models, and for a more detailed account of the technology the interested reader can consult the many references provided in section 5 of reference [2]. Here some basic understanding of the various technologies is assumed.

In the past several years, a new technology of SVS has been introduced by several of the major equipment vendors[2]. This new technology is commonly referred to as a Hybrid-STATCOM. The concept behind the Hybrid-STATCOM is to combine the best of both the thyristor based and VSC-based technologies. The concept is that a very large reactive-power range can be achieved by combining a STATCOM with coordinated switching of thyristor switched capacitor/reactors. In this way the following can be achieved:

1. The ability of achieving a rather large dynamic reactive-power range, with full ability to smoothly control the reactive-power over the entire range of the device.

2. Optimizing the size and foot-print of a large device by being able to combine a VSC and TSC/TSR.

3. The ability to take advantage of both the features of a STATCOM (i.e. current limited device given slightly better speed of dynamic performance), while extending capacitive and reactive range of the device through extremely fast (sub-cycle) thyristor switched capacitor and reactor.

For a more detailed explanation of the technology, the reader may consult the links in footnote 1.

To explain the difference between a standard SVC, a standard STATCOM and a Hybrid-STATCOM, let us consider the following figures. Figure 1 shows the typical voltage-current (VI) characteristics of an SVC. An SVC being a passive device (i.e. switched or controller reactor and capacitor) at its reactive limits it is a constant impedance device and thus reactive current falls linearly with voltage, which means that reactive power falls as the square of voltage at the limits of the device. Figure 2 shows the typical VI characteristics of a STATCOM.

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[1] TCR – thyristor controller reactor; TSC – thyristor switched capacitor; TSR – thyristor switched reactor

[2] See for example: https://www.hitachiabb-powergrids.com/us/en/offering/product-and-system/facts/statcom/statcom-hybrid, or https://www.gegridsolutions.com/products/brochures/powerd_vtf/statcom_gea31986_lr.pdf, https://www.siemens-energy.com/global/en/offerings/power-transmission/facts/portfolio/svcplus.html

A STATCOM is a constant current device at its reactive limits, which means that reactive power falls linearly with voltage at the limits of the device. Note, in both cases the slope at the top of the VI curve depicts the slope (or reactive droop) that is typically introduced into the controls (see [1] or [2]). The inflections in the VI characteristics at very low voltages, represents the under-voltage strategy for the SVC, and for the STATCOM the converter blocking at very low voltages [3].

Figure 3 shows the VI characteristics for a Hybrid-STATCOM. As can be seen, the TSC and TSR add dynamic range to the two ends of the STATCOM.

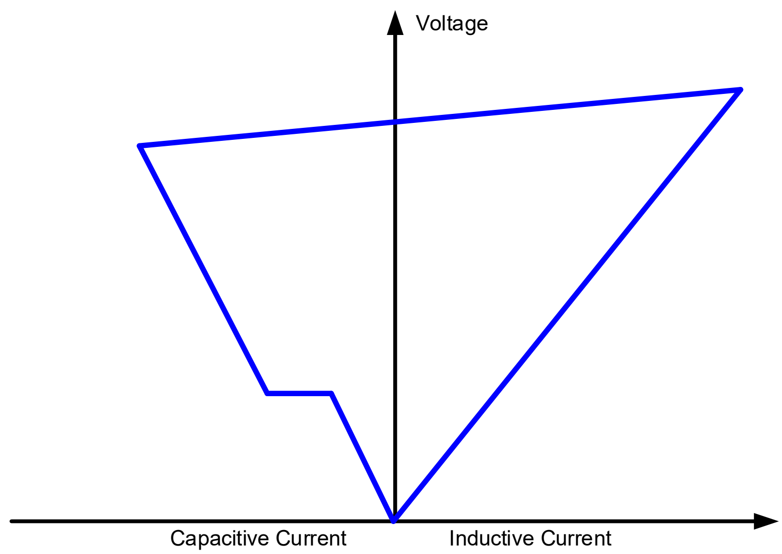

Figure 1: VI characteristic of an SVC.

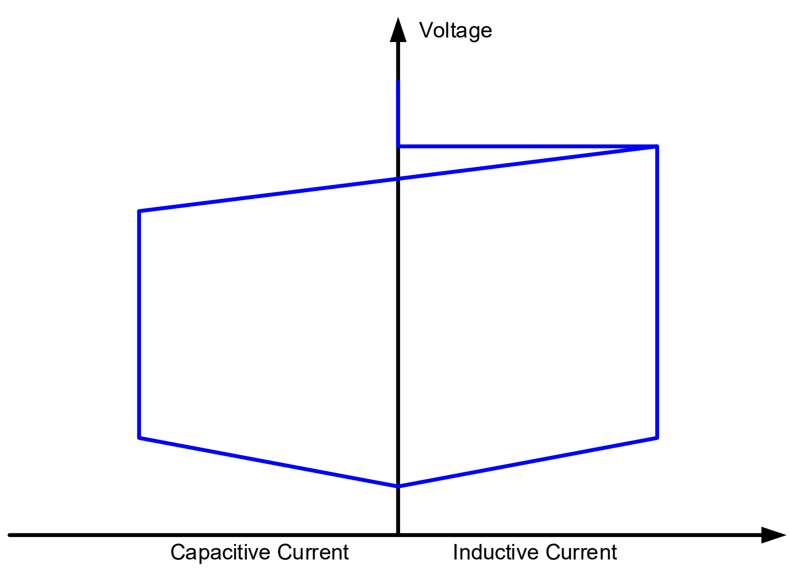

Figure 2: VI characteristic of a STATCOM.

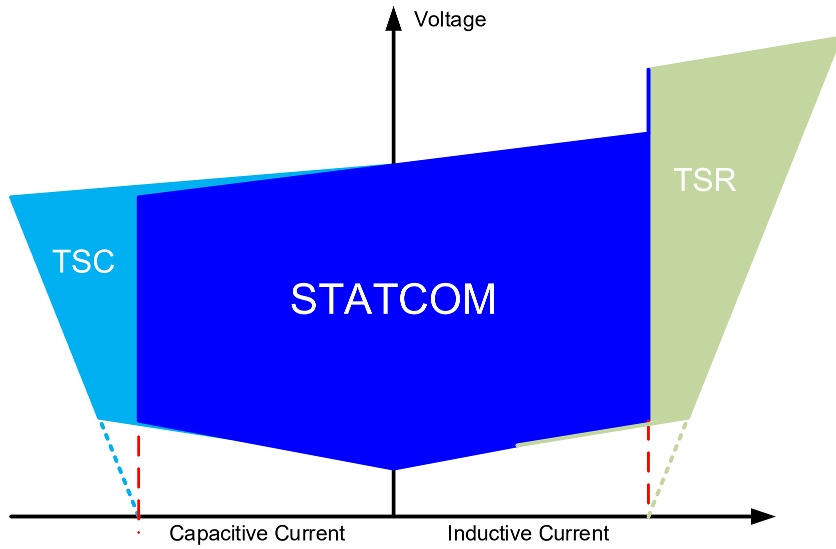

Figure 3: VI characteristic of a Hybrid-STATCOM.

1.0 Power Flow Modeling:

For power flow analysis, the existing power flow models that were developed for the existing generic SVS models [2] should actually be adequate for modeling a hybrid-STATCOM. Let us present an example. Consider Figure 4. In this figure an example is shown of how one might model a hybrid-STATCOM in GE PSLF™ using the existing power flow model features. Here the model is of an example hybrid-STATCOM with the following specifications, as seen effectively at the transmission level:

1. ± 100 MVar STATCOM
2. 50 MVar TSC
3. 50 MVar TSR

The STATCOM portion is modeled by the SVD shown with ID "SV" – it is modeled as a type 6 SVD. The TSC and TSR are represented explicitly as a shunt capacitor (ID "tc") and shunt reactor (ID "tr") on the same bus. These shunts are then linked, through their SVD control bus parameter to the SVD such that they are automatically controlled, for power flow solution iterations, by the SVD. Thus, as can be seen in the figure for the solution on the left the hybrid-STATCOM has switched in the reactor to help keep the bus voltage down, while on the right the opposite is true. The example here is completely "hypothetical" on a simple micro-WECC case. It is for illustrative purposes only – no conclusions should be drawn from this example other than that the existing power flow models can be made to model a hybrid-STATCOM. Also, in the example here the unit transformer has not been explicitly modeled, and thus the assumption is that the effective reactive rating of the VSC, TSC and TSR are being modeled, as seen on the transmission (EHV) bus. One could, if desired, model the unit transformer explicitly, for power flow, and represent the actual physical branches on the low voltage side of the transformer.

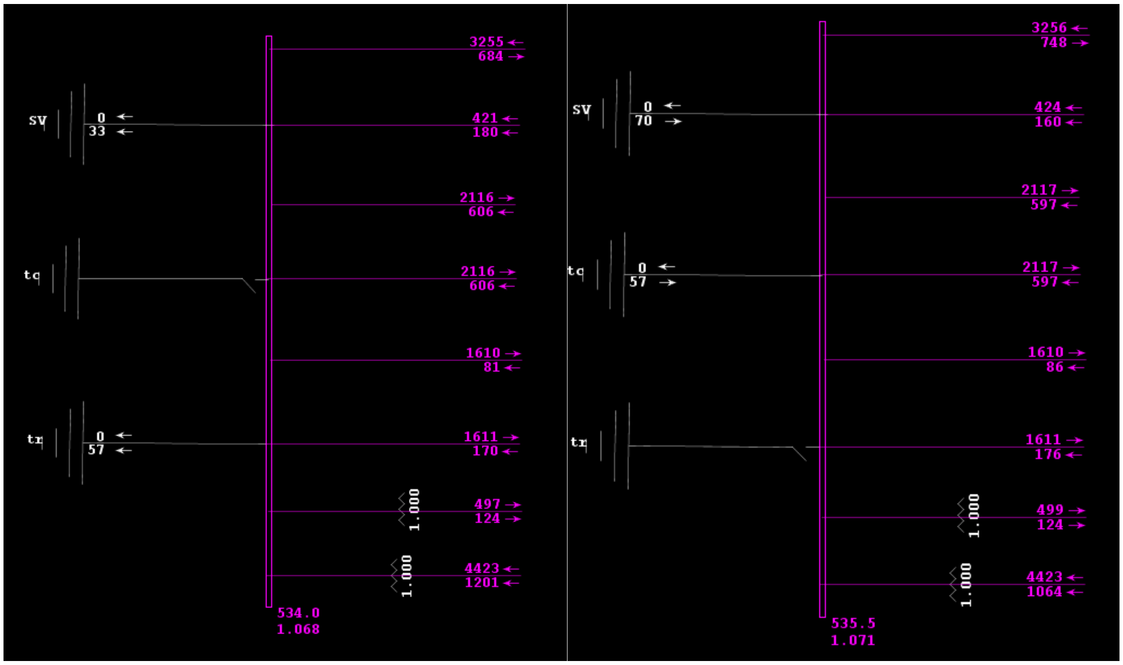

Figure 4: Hybrid-STATCOM power flow modeling.

<u>2.0 Dynamic Stability Model:</u>

The model presented here is intended for power system planning studies, using positive-sequence stability programs, and to represent the general dynamic behavior of a hybrid-STATCOM. The model does not represent the specific details of actual controls for any specific vendor.

Moreover, for the sake of an initial attempt to develop and test a model, we further assume that:

- there is at most only one TSC and one TSR (this can easily be expanded in a final adopted model), and
- for now we will not model the logic for automatically switching, where available, the much slower mechanically switched shunt capacitors and reactors. **<u>Note:</u>** this logic can be easily copied from other models being developed (e.g. REPC_C for the RES models) and the pseudo code is provided for completeness below in Appendix A.

Finally, the unit transformer is not explicitly modeled (see for example Appendix B of [2] for why this is quite valid for TSC/TCR branches; for the VSC[3] piece the modeling of the unit transformer can have a marked impact and thus access is given to *Imaxt* for user-written code to implement current limit controls, if desired, to limit the secondary voltage).

Thus, the core of the dynamic model is based on SVSMO3 [1], [2]. There is no need to explain the details of the voltage control loop, the droop/slope model, and the slow-current regulator, deadband controls – all of this is the identical to SVSMO3 and explained in detail in [2]. The key difference is in the way the TSC and TSR branch are incorporated and switched.

The proposed model structure is shown Figure 5. Comparing it to the SVSMO3 [2] model it will be easily seen that the only real difference is in the addition of the switching logic of the TSC/TSR. In the case of the hybrid-STATCOM (SVSMO4) the output of the main voltage control loop (state **s2**) is the total reactive current demand (*It*). This total reactive current should be equal to the sum of the reactive current being produced from the TSC and TSR (if they are in-service) and the VSC. Now remember that the TSC and TSR branches must be explicitly modeled as a shunt capacitor and reactor branch, respectively, in the power flow model. The logic

[3] VSC – voltage source converter, the basic building block of a STATCOM

in the block labeled TSC/TSR Switching Logic may be diagrammatically depicted as shown in Figure 6. Thus, at each integration time step the total reactive current demand (*It*) is developed, then if it falls in the ORANGE regions shown in Figure 6 the appropriate action is taken to automatically switch the TSC (the respective explicit shunt capacitor model in the network at the hybrid-STATCOM bus), and if in the BLUE region than the appropriate action is taken to switch the TSR. Then the current of the VSC is determined as $I_{CONV} = It – I_{CAP} - I_{IND}$, where I_{CAP} and I_{IND} are the reactive currents being produced by the TSC and TSR, respectively.

To illustrate the functioning of this proposed model and user-written version of the model was developed in GE PSLF™. We then modeled a hypothetical hybrid-STATCOM with a total dynamic range of ± 150 MVar, such that it is comprised of a ± 100 MVar VSC, a 50 MVar TSC and a 50 MVar TSR. Then a simulation was performed where the voltage reference of the SVSMO4 model was stepped three times, once down at 1 second, then back up to the initial value at 10 second and finally up further at 15 seconds. The simulation results are shown in Figure 7 and Figure 8. It can be seen clearly that:

- the total reactive current injected into the network is smooth and continuous,
- as the output of the VSC (*Iconv*) decreases and goes below *Ilin* = -0.5, then the TSR is immediately switched in and the VSC accordingly adjusted; remember that all this happens in real-life in sub-cycle time frames,
- then as the VSC output increases (when the voltage reference is step up again at 10 seconds) then once it reached *Ilout* = 0.2, the TSR is switched out and the VSC current quickly adjusted again, and
- finally as the voltage reference is step up even further (at 15 seconds) and the VSC output rises above *Icin* = 0.5 then TSC is switched in and the VSC current also immediately adjusts accordingly.

The full parameter list for the model is provided in Table 1. It is important to understand that the choice of the size of the TSC and TSR branch, as compared to the size of the VSC, and the choice of the switching in and out points for the TSC and TSR, must be chosen carefully to avoid hunting of the controls and forcing of the VSC into limits.

<u>Note:</u> the flow chart logic for the under/over-voltage strategy is shown in Figure 10, in the Appendix.

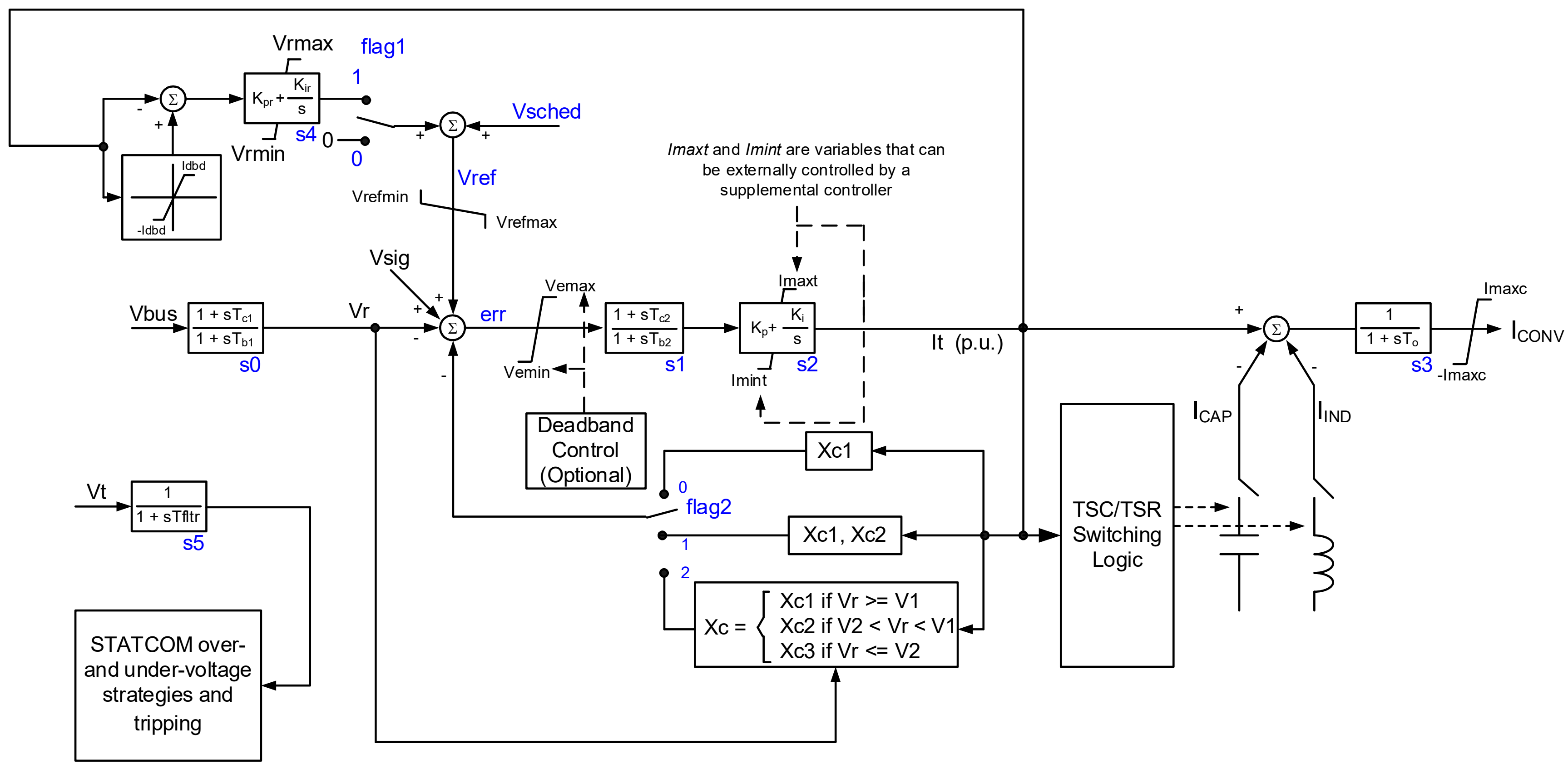

Figure 5: Block diagram of the proposed SVSMO4 hybrid-STATCOM model.

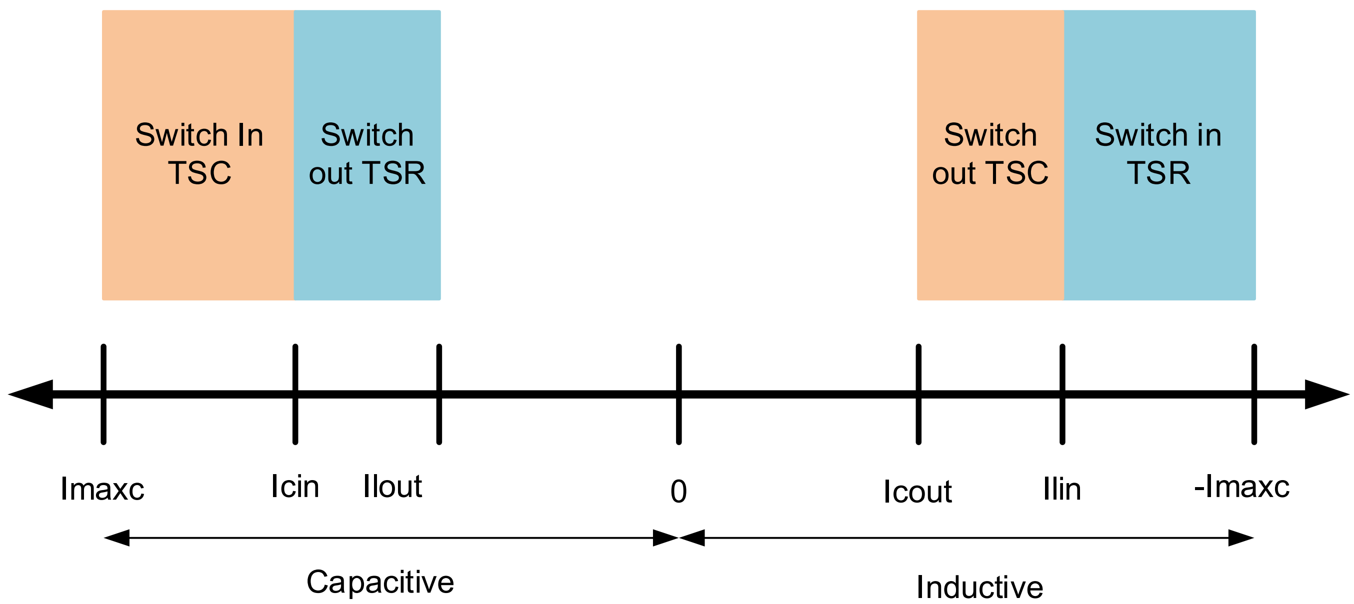

Figure 6: Switching logic for the TSC and TSR.

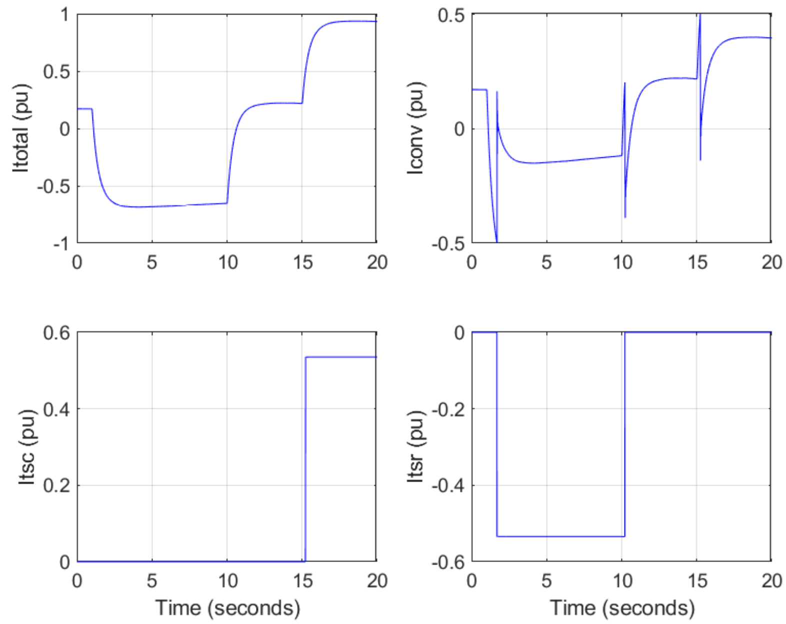

Figure 7: Simple example simulation with SVSMO4. A Vref step was injected to first force the output of the hybrid-STATCOM down at 1 second, and then back up at 10 seconds, and then further up at 15 seconds.

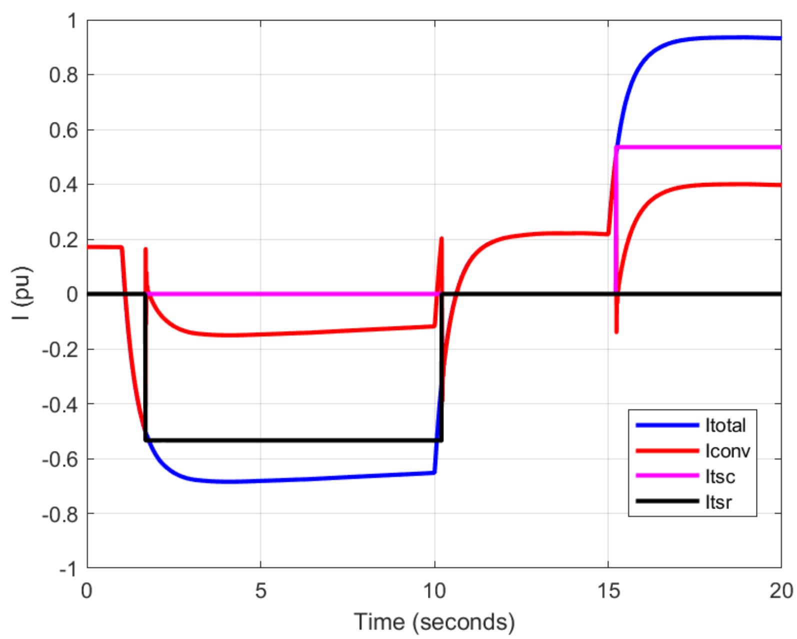

Figure 8: Simple example simulation with SVSMO4. A Vref step was injected to first force the output of the hybrid-STATCOM down at 1 second, and then back up at 10 seconds, and then further up at 15 seconds.

Table 1: Parameter List for SVSMO4.

Parameter	Description	Typical Range/Value
Flag1	Turn on (1) or off (0) the slow-current controller	N/A
Flag2	Tune on (1) of off (0) the nonlinear droop	0
Tc1	Voltage measurement lead time constant [s]	0
Tb1	Voltage measurement lag time constant [s]	0.02 to 0.1
Kp	Proportional gain [pu/pu]	N/A
Ki	Integral gain [pu/pu/s]	N/A
vemax	Voltage error maximum limit [pu]	0.1 to 1
vemin	Voltage error minimum limit [pu]	-0.1 to -1
Imaxc	Maximum continuous current rating of the VSC [pu]	1.0
dbd	Voltage deadband [pu]	N/A
Kdbd	Ratio of outer to inner deadband	2 – 10
Tbdb	Deadband time [s]	0.1 – 1
Kpr	Proportional gain of slow-reset controller [pu/pu]	N/A
Kir	Integral gain of slow-rest controller [pu/pu/s]	N/A
Idbd	Range of deadband in current for slow-reset controller [pu]	N/A
Vrmax	Maximum limit on slow-reset controller output [pu]	0.05
Vrmin	Minimum limit on slow-rest controller output [pu]	-0.05
UV	Voltage below which device goes into undervoltage strategy (block TSC and	0.2 – 0.3
OV	Voltage above which device goes into overvoltage strategy (block VSC & force	1.15 – 1.25
Ttrip	Time after which device trips if voltage in > OV [s]	0.5 – 1
Tplld	Time delay for PLL after blocking [s]	0.1 – 0.15
Icin	VSC current level above which TSC is switched in [pu] (>0)	N/A
Icout	VSC current level below which TSC is switched out [pu] (<0)	N/A
Ilin	VSC current level below which TSR is switched in [pu] (<0)	
Ilout	VSC current level above which TSR is switched out [pu] (>0)	
Xc1	Nonlinear droop slope 1 (also used for standard droop when Flag2 = 0) [pu/pu]	0.01 – 0.05
Xc2	Nonlinear droop slope 2 [pu/pu]	N/A
Xc3	Nonlinear droop slope 3 [pu/pu]	N/A
Vc1	Nonlinear droop upper voltage [pu]	N/A
Vc2	Nonlinear droop lower voltage [pu]	N/A
Tc2	Lead time constant [s]	0
Tb2	Lag time constant [s]	0.02 – 0.1
Tfltr	Voltage measurement filter time constant	0.02 – 0.1

Appendix A: MSS Switching Logic:

Logic can be added to the model to emulate the automated switching of mechanically switched shunts (MSS), similar to that which has already been proposed for other public models like REPC_C. Namely,

Q = reactive output of the hybrid-STATCOM (Note: we use Q or total reactive current It in Figure 5)

If (Qdn1 < Q < Qup1)

Do nothing

Else

```
    If (Qdn2 < Q < Qup2)
        If (Q < Qdn1) {that is Q is too inductive}
            After Tdelay1 seconds (Q must remain in this range for that duration before even initiating switching) initiate the switching out of any in-service shunt capacitor first or if all MSCs are out, then switch in the first available shunt reactor, if nothing is available then there is nothing you can do; remember the breaker time after MSS switching engaged; the discharge time of the capacitor must always be obeyed once it is switched out
        Else {must be too capacitive, since landing here we are already outside of Qdn1 < Q < Qup1}
            After Tdelay1 seconds (Q must remain in this range for that duration before even initiating switching) initiate the switching out of any in-service shunt reactor first or if all MSRs are out, then switch in the first available shunt capacitor, if nothing is available then there is nothing you can do; remember the breaker time after MSS switching engaged; the discharge time of the capacitor must always be obeyed if previously switched out in the run
        End
    Else
        If (Q < Qdn2) {that is Q is too inductive}
            After Tdelay2 seconds (Q must remain in this range for that duration before even initiating switching) initiate the switching out of any in-service shunt capacitor first or if all MSCs are out, then switch in the first available shunt reactor, if nothing is available then there is nothing you can do; remember the breaker time after MSS switching engaged; the discharge time of the capacitor must always be obeyed once it is switched out
        Else {must be too capacitive, since landing here we are already outside of Qdn2 < Q < Qup2}
            After Tdelay2 seconds (Q must remain in this range for that duration before even initiating switching) initiate the switching out of any in-service shunt reactor first or if all MSRs are out, then switch in the first available shunt capacitor, if nothing is available then there is nothing you can do; remember the breaker time after MSS switching engaged; the discharge time of the capacitor must always be obeyed if previously switched out in the run
        End
    End
End
```

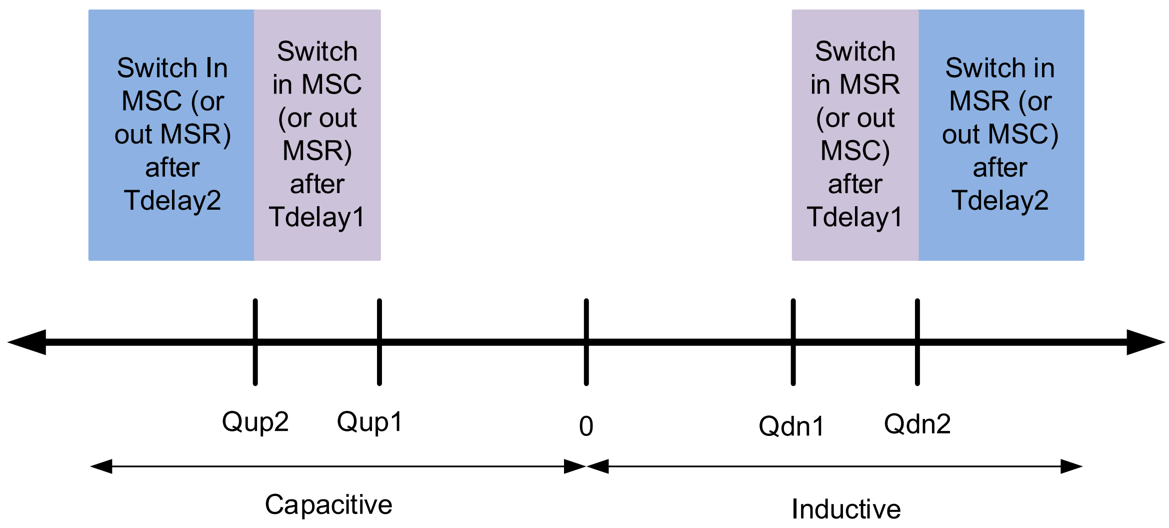

Figure 9: MSS switching logic.

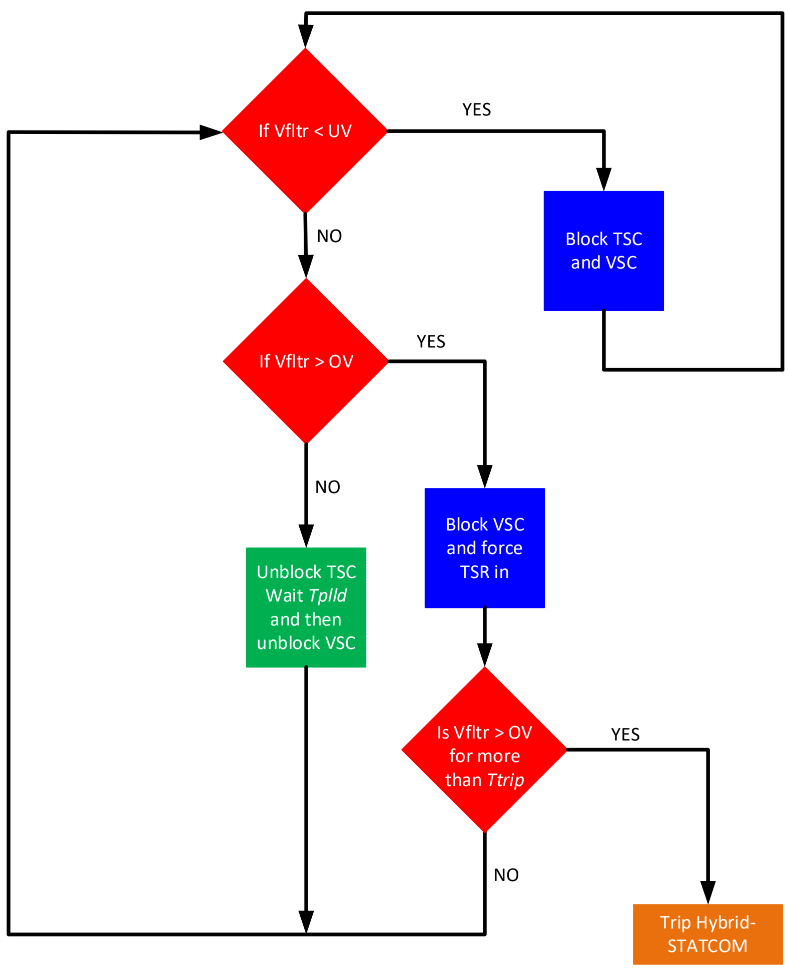

Figure 10: Under and over-voltage strategy.

Acknowledgements:

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References:

[1] P. Pourbeik, D. J. Sullivan, A. Boström, J. Sanchez-Gasca, Y. Kazachkov, J. Kowalski, A. Salazar, A. Meyer, R. Lau, D. Davies and E. Allen, "Generic Model Structures for Simulating Static Var Systems in Power System Studies—A WECC Task Force Effort", IEEE Transactions on PWRS, August 2012.

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[3] P. Pourbeik and G. Stefopoulos, "Validation of Generic Models for Stability Analysis of two Large Static Var Systems in New York using PMU Data", *Proceedings of the IEEE T&D Show and Exposition*, April 2014.