RTDS Tutorial

Intelligent Electrical Power Grids, TU Delft

Advanced Controllers for MMC-HVDC Grids

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Introduction:

To function, high voltage DC (HVDC) systems need control strategies to manage the evacuation of generated wind energy to the main grid using modular multi-level converters (MMC) as power electronic interfaces. Underground cables (UGC) and overhead transmission lines (OHL) are used to transmit the generated power. The idea is that the control should be able to operate the MMC-HVDC systems for different operational transients such as power flow changes, wind speed variations, DC/AC grid faults, etc. A good controller should be able to show faster settling time and minimum voltage and power variations for any transient occurring in the system.

In this tutorial, we will discuss state-of-the-art PI control along with different advanced controllers such as sliding mode control (SMC), super-twisted sliding mode control (STSMC), backstepping control (BSC), and model predictive control (MPC). We will apply different controller to compare their performance on the benchmark CIGRE MMC-HVDC grids with the real-time digital simulator (RTDS). At the end of this tutorial, you should be able to:

- Develop an understanding of the need for a controller for HVDC systems and the mathematical manipulations to simplify the system dynamics (ABC-DQ)
- Understand the implementation of outer and inner loops for a better-controlled system operation using linear PI controllers and different non-linear controllers like SMC, STSMC, BSC, and MPC
- Understand the differences in the performance of the different controllers and compare them with real-time validation using RTDS

To follow the tutorial, you should:

- Be able to do basic simulations in RSCAD
- Have the basic knowledge of mathematical formulation of MMC-HVDC system using differential equations
- Have the theoretical knowledge of linear and non-linear controllers (such as SMC, STSMC, BSC, and MPC)

Overview of Test System:

A 3-bus multi-terminal grid (±525kV) is considered as the MMC-HVDC configuration as shown in Fig. 1. MMC 1 and MMC 3 are connected to the power grid for the evacuation of generated power. MMC 2 is connected to the offshore wind park generating renewable power. As MMC 2 has to create its grid to extract the wind power, it operates in grid-forming mode (GFM) as shown in the Dispatch level in Fig. 1. This means that the system frequency is given externally as shown as θ_{vso} in the control level. MMC 1 is used to control the DC link voltage of the system whereas MMC 2 is controlled in the power reference mode as shown in Dispatch level. This intuitively means that MMC 2 evacuates a fixed amount of power whereas MMC 1 evacuates the intermittent difference of power (P_{MMC3}-P_{MMC2}) to maintain the DC voltage of the system.

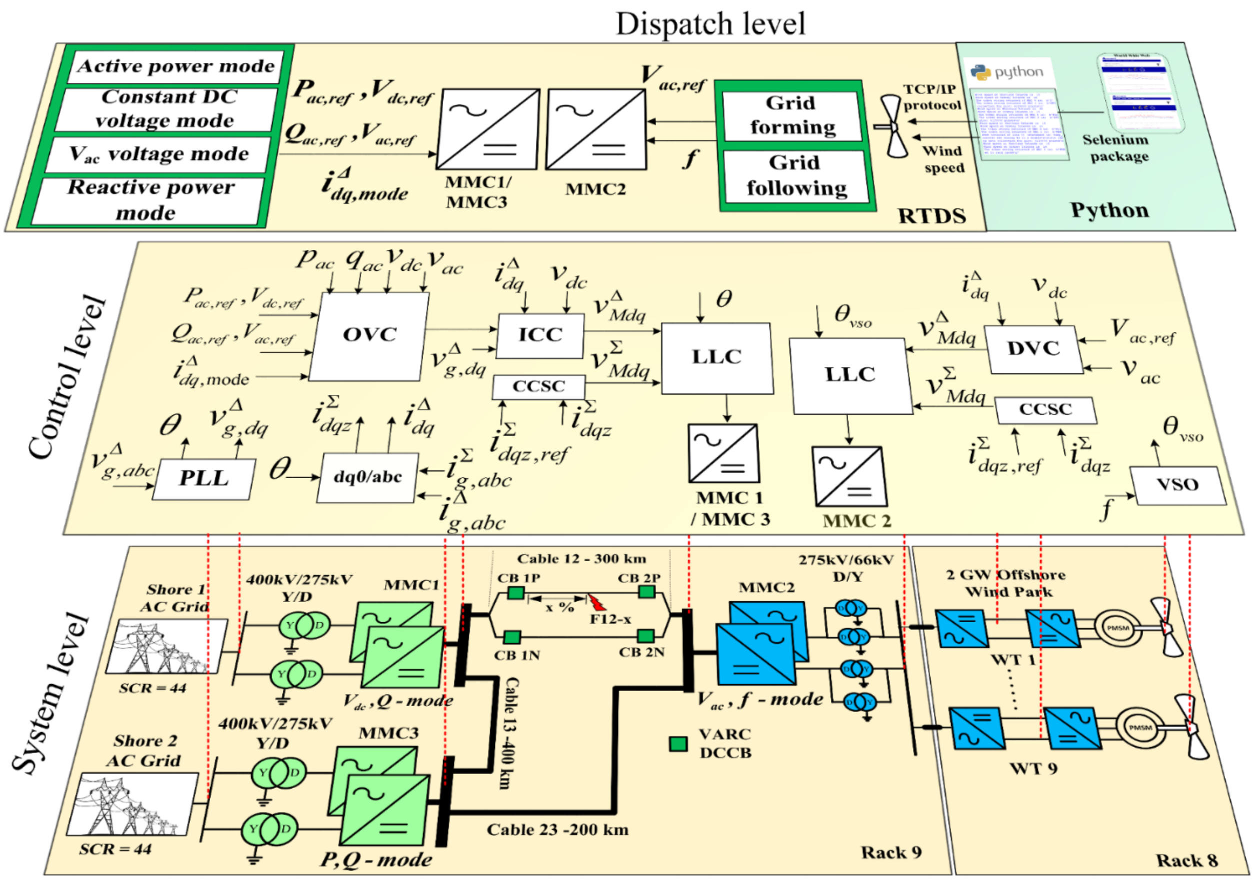
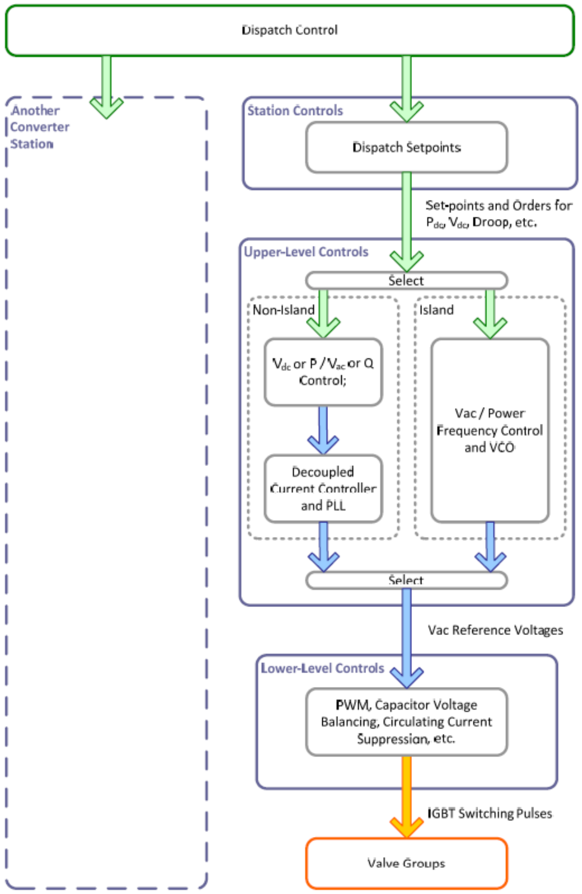


Figure 1: MMC-HVDC Test System

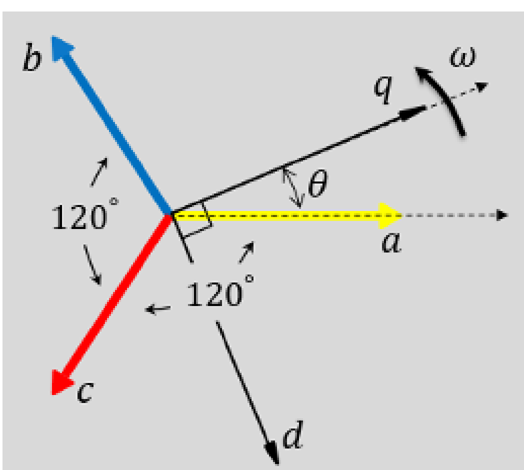
[1] L. Liu, A. Shetgaonkar, A. Lekić, “Interoperability of classical and advanced controllers in MMC based MTDC power system”, International Journal of Electrical Power & Energy Systems, Volume 148, 2023, 108980.
[2] T. K. Vrana, Y. Yang, D. Jovcic, S. Dennetiere, J. Jardini, and H. Saad, “The cigre b4 dc grid test system,” Electra, vol. 270, no. 1, pp. 10-19, 2013.



All converters have outer and inner controlling loops. Outer loops are different control objectives to be achieved while the inner loop is system current control. Inner loop ensures safety and current saturations for abnormal events.

- Offshore converters (island *aka* GFM) have outer controls for:
  1. AC voltage or active power
  2. Frequency with PLL
- Onshore converters (non-island *aka* GFL) have outer controls for:
  1. DC voltage or active power
  2. AC voltage or reactive power

ABC to DQ Transformation:



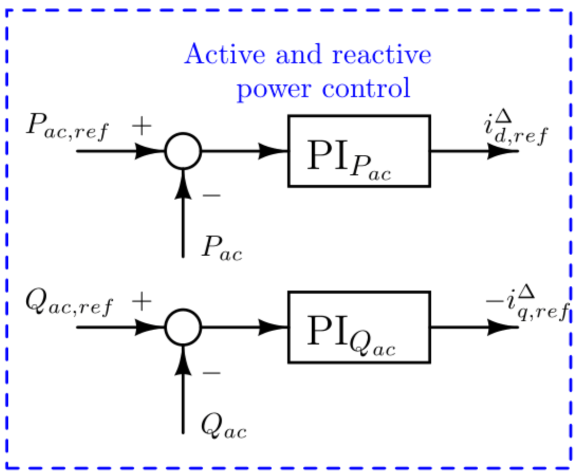
$$\mathbf{P}_{\omega_0}(t) = \frac{2}{3}\begin{bmatrix} \cos(\omega_0 t) & \cos\left(\omega_0 t - \frac{2\pi}{3}\right) & \cos\left(\omega_0 t - \frac{4\pi}{3}\right) \\ \sin(\omega_0 t) & \sin\left(\omega_0 t - \frac{2\pi}{3}\right) & \sin\left(\omega_0 t - \frac{4\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Park Transformation converts the stationary ABC frame to a rotating DQZ frame. The DQZ frame rotates with the fundamental frequency of the ABC grid in the space frame. As a result, the current and voltage variables are DC in nature. This helps in easy control and intuitive decoupled study of active and reactive powers.

Understanding Outer loop control:

Active and Reactive Power Control

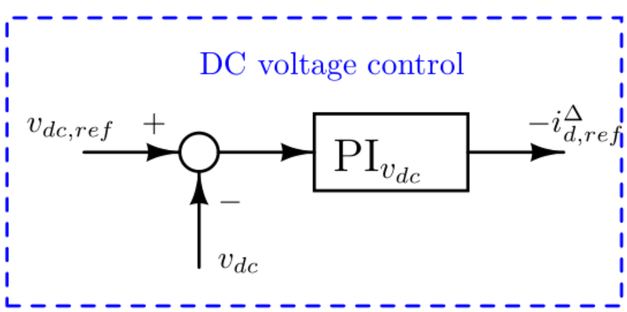
Using Park Transformation gives inherent advantages of independent control of active and reactive powers. The powers (P_{ac}, Q_{ac}) can be calculated as mentioned below. Active power control creates a reference for the d component of the AC current: $i^{\Delta}_{d,\,ref}$. Reactive power control creates a reference for the q component of the AC current: $i^{\Delta}_{q,\,ref}$. This type of control is suitable for grid-following converters operating at grid frequency, determined by the PLL.



$$
\begin{aligned}
P_{ac} &= \frac{3}{2}\left(v_d^G i_d^{\Delta} + v_q^G i_q^{\Delta}\right) \\
Q_{ac} &= \frac{3}{2}\left(-v_d^G i_q^{\Delta} + v_q^G i_d^{\Delta}\right)
\end{aligned}
$$

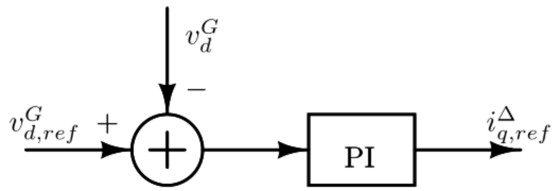
DC Voltage Control

The HVDC system needs control of voltage throughout the system. This is essential to ensure that the generated wind power is evacuated even with transient disruptions experienced by the system with countless practical challenges. This in principle, is ensured by the control of a dedicated converter which absorbs/provides power instantaneously which is the intermittent difference of power (P_{MMC3}-P_{MMC2}) to maintain the DC voltage of the system. This type of control is suitable for grid-following converters operating at grid frequency.



AC Voltage Control

To extract the maximum power from the instantaneously changing wind speed in the wind energy systems, it is important to form a suitable grid on the AC side. This ensures stable AC voltage value through an independent frequency source. The AC voltage control creates a reference for the q component of the AC current: $i_{q,ref}^{\Delta}$. This type of control is suitable for grid-forming converters operating at an independent frequency.



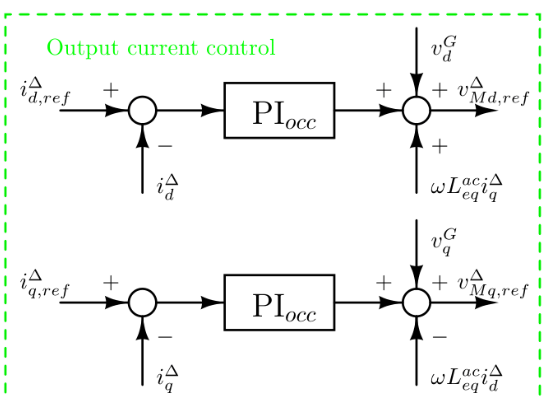
Based on the given test system in Fig. 1, MMC 1 is used to control the DC voltage of the system whereas MMC 3 is used to operate in active and reactive power control. Further, MMC 2 is used in the grid-forming mode to control the AC side voltage.

Understanding Inner Loop Control:

The inner control loop is common for all converters. This loop takes care of the output current with the attribute of limiting it, nullifying the circulating current, and controlling the zero sequence current.

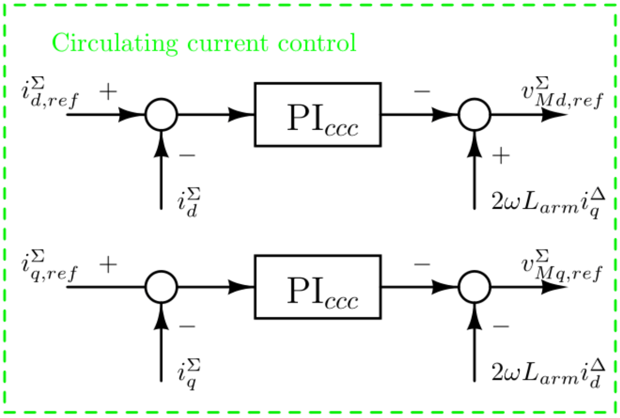
Output Current Control

This loop is used to control the AC output current in the d and q axes, providing AC current control. The loop is used in cascaded form with the active power or DC voltage for the d-axis current and reactive power or AC voltage for the q-axis current. Further, current saturators or limiters are digitally used to compare the output current reference values with the maximum and minimum allowable current values.



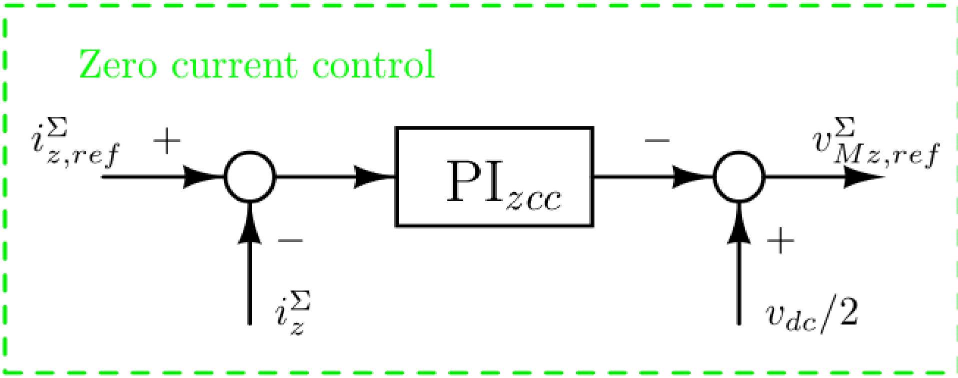
Circulating Current Control

This loop is used to control the d and q components of the average current components. It works toward eliminating the circulating current by following a zero reference for the circulating current.



Zero Sequence Current Control

Zero sequence current arises in an unbalanced circuit, only if there is a path for it to flow. This can overheat the neutral connection wire and can result in losses. As a result, it is essential to control the value of zero sequence current.

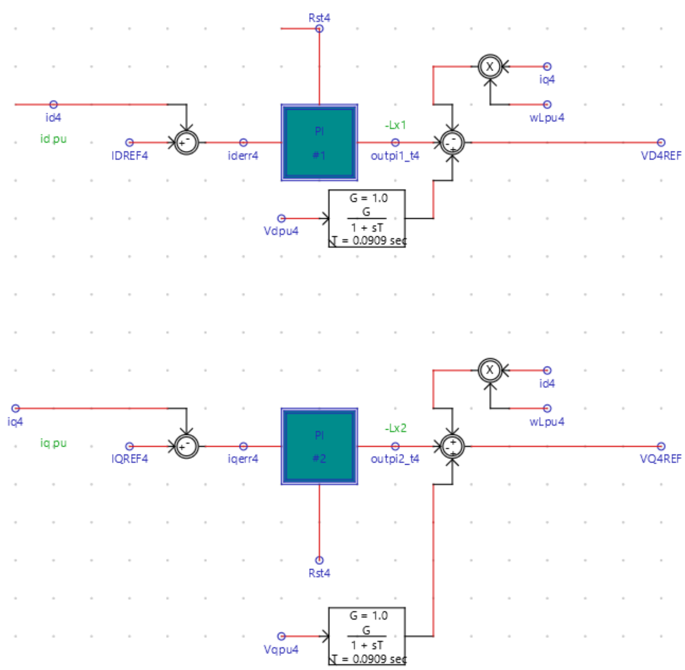


Advanced Controllers for MMC-HVDC system using RSCAD/RTDS:

The concept of advanced controllers is implemented in the inner loop of MMC 3. The idea is to compare the performance of different controllers like PI, SMC, STSMC, BSC, and MPC in real time with different transients. Non-linear controllers find quick convergence in comparison to PI, this gives a better transient response. If the inner loop is resolved quickly using different advanced controllers, the outer loop can be subsequently processed using the state-of-the-art PI controller.

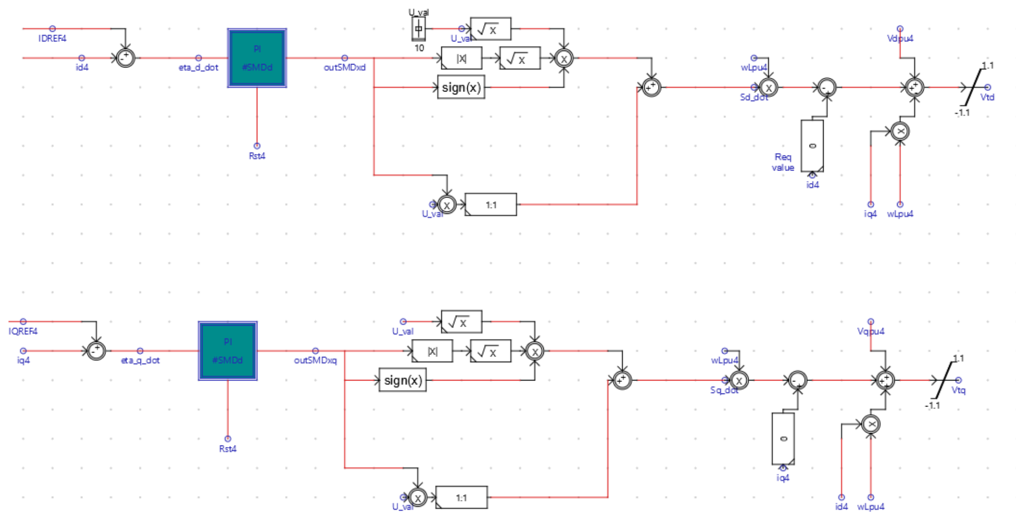
1. Proportional-Integral (PI) controllers

The subtraction of **IDREF4** and **id4** gives the error **iderr4**. The PI controller is a combination of proportional and integral functions designed to make the error converge to zero. A proportional gain is used to minimize the error while the integral gain is responsible for making the error converge to zero using the historic cumulative value of the errors. **Rst4** is the input to reset the integral function in the PI controller to avoid saturation.



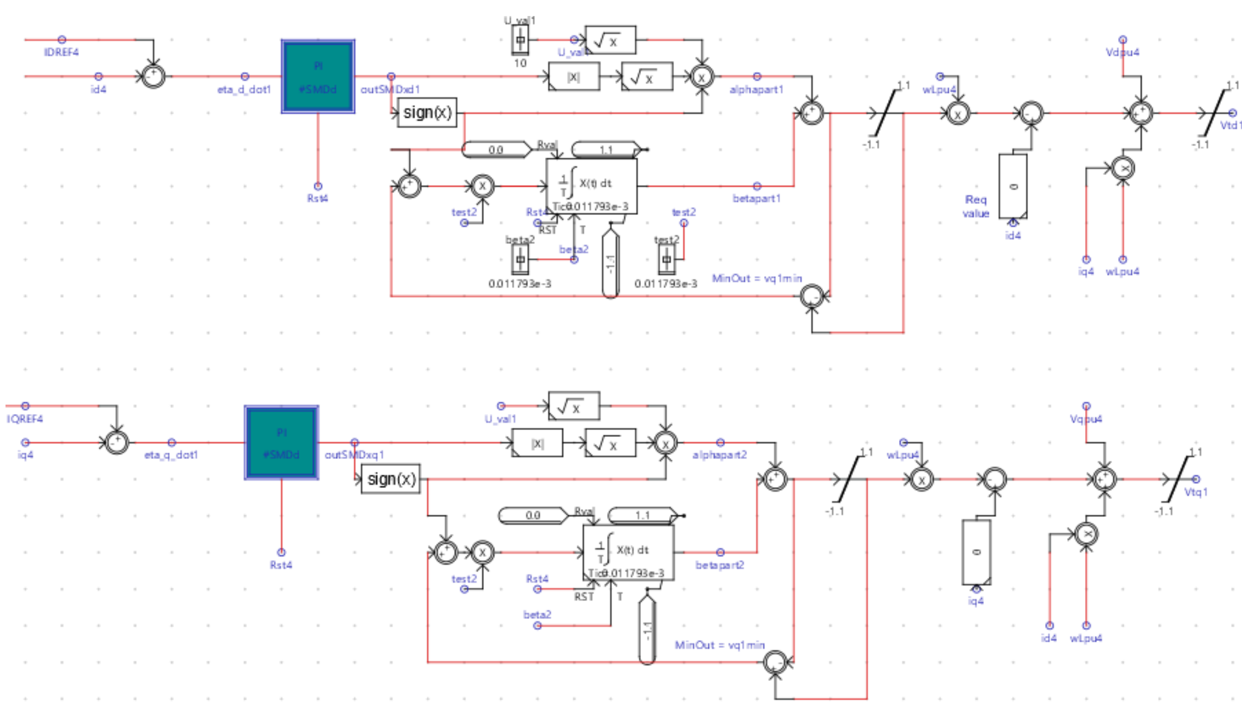
2. Sliding Mode Control (SMC)

Similarly, the subtraction of **IDREF4** and **id4** gives the newly defined SMC error, **eta_d_dot**. A sliding surface is designed to bring the system to a steady state with minimal chattering. This is done by conceptually designing a switching function based on the sliding dynamics convergence. In the runtime of RSCAD/RTDS, the SMC is designed using the following gains: **U_val**=0.95, **ki_SMD**=0.0068, and **kp_SMD**=0.48.



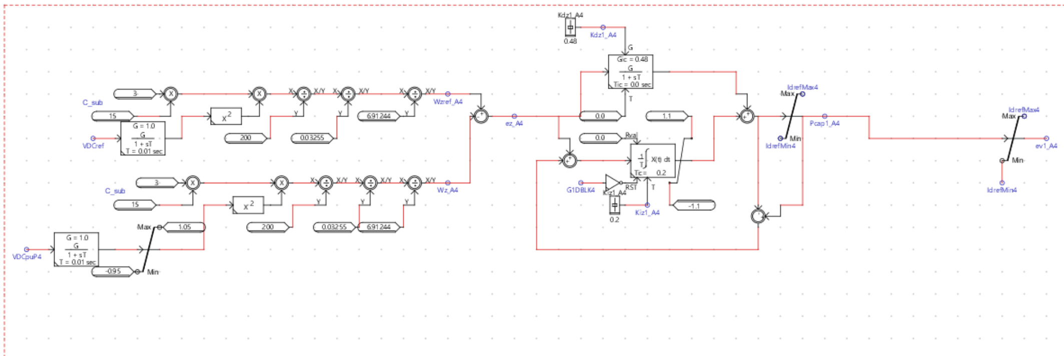
3. Super Twisted Sliding Mode Control (STSMC)

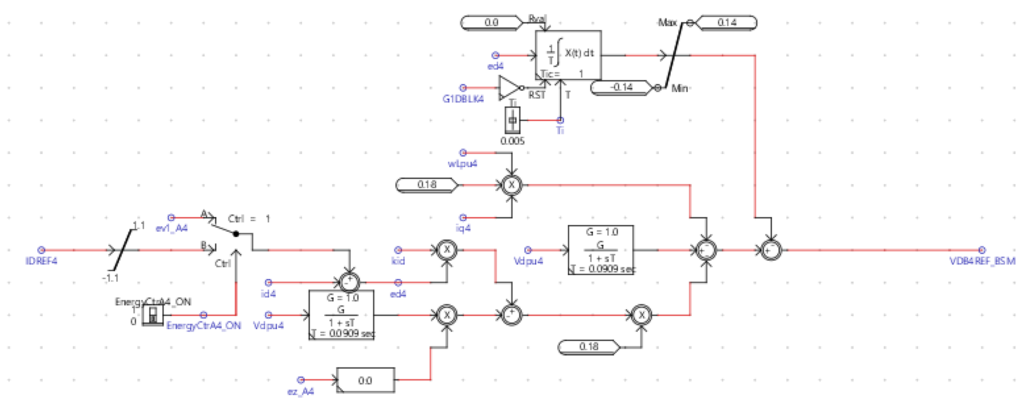
The same error is defined for STSMC as **eta_d_dot1.** STSMC introduces the concept of higher-order SMC by introducing an integral function in the computation of the error function. It reduces the chattering of SMC, further escalating the convergence of the error to zero. In the runtime of RSCAD/RTDS, the SMC is designed using the following gains: **U_val1**=1, **ki_SMD1**=0.95, **kp_SMD1**=0.25, **beta2**=50, **test2**=0.95.



4. Backstepping Control (BSC)

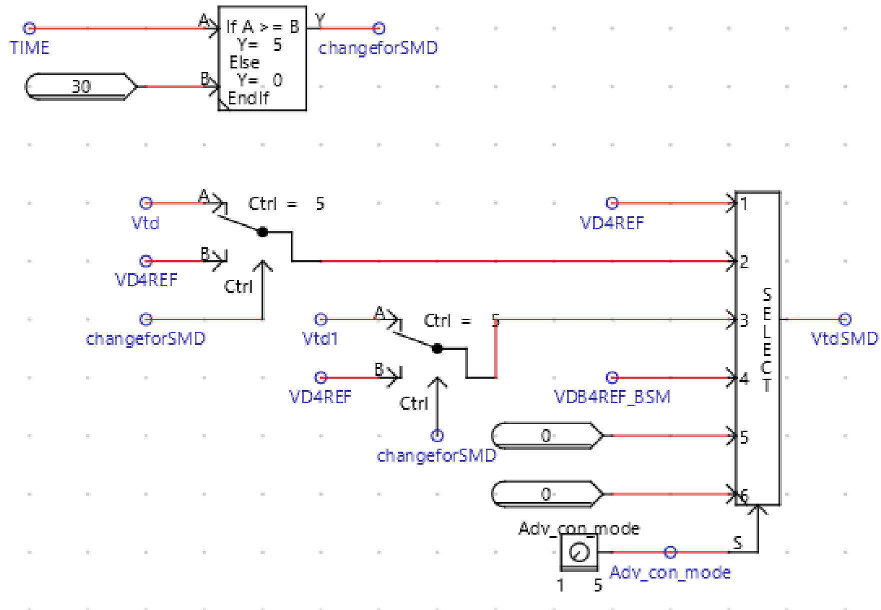
BSC is implemented by using a Lyapunov Energy Function. The function in itself should be positive definite and should be zero at the equilibrium point. If the derivative of the Lyapunov Energy Function is negative, then we can ensure that the system error states would converge to zero. At the steady state, the derivative would finally be zero. Energy functions, **Wzref_A4** and **Wz_A4** give the state **ez_A4** which can be used to define the Lyapunov Function.



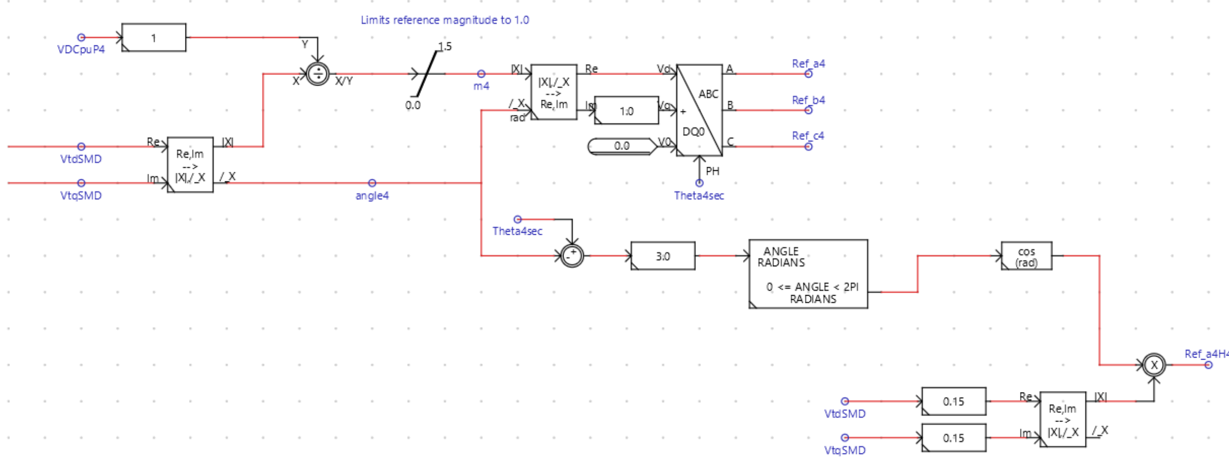


<u>Selecting a controller:</u>

VD4REF is the output of the PI controller whereas **Vtd** is the output of the SMC controller. Similarly, **Vtd1** is the output of the STSMC controller and **VDB4REF_BSM** is the output of the BSC controller. The transition from PI to SMC or STSMC is through a wait window where PI smoothly transitions to SMC or STSMC after *30s*. This is done to use the attributes of PI and once the new operating points (if any) have converged, transition to SMC or STSMC (shown as **changeforSMD**).
If select switch input 1 is used, the **PI** controller is implemented.
If select switch input 2 is used, the **SMC** controller is implemented.
If select switch input 3 is used, the **STSMC** controller is implemented.
If select switch input 4 is used, the **BSC** controller is implemented.



Finally, the generated **VtdSMD** (and similarly, **VtqSMD**) voltages are used to fire the MMC IGBTs using signal, **Ref_a4H4** as shown below.

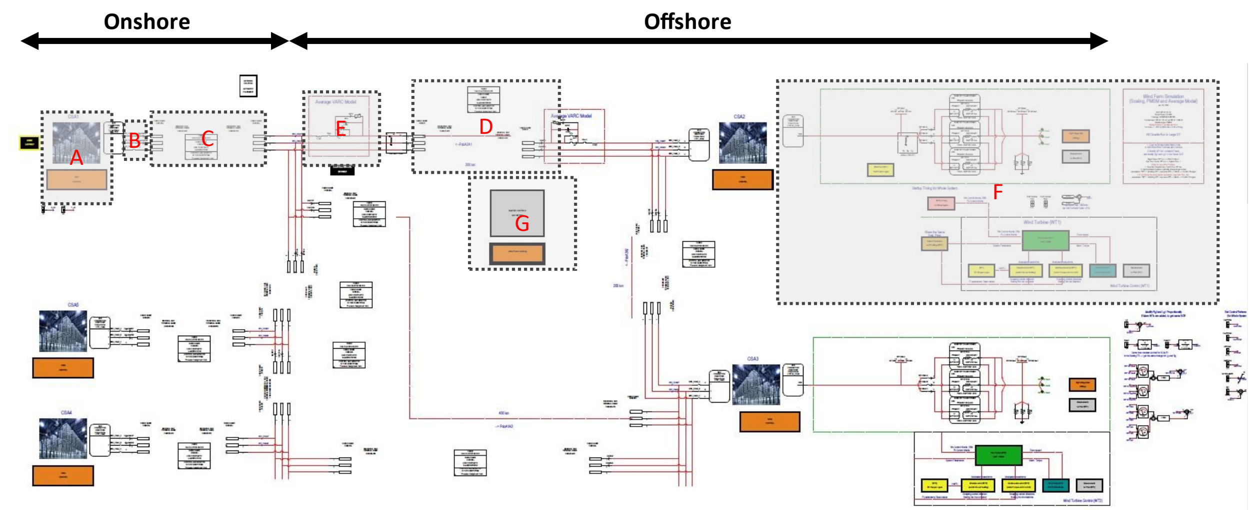


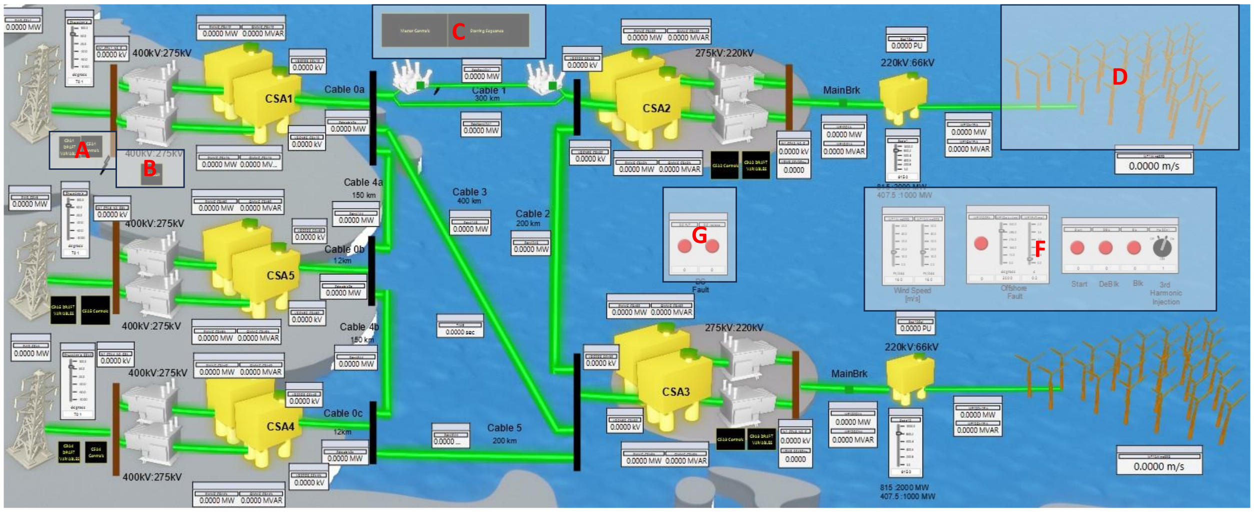
Elaboration of the test system in RTDS:

Considering the draft file, the **A** region indicates the converter station and connection between the *main* and *small timestep*. It also consists of control and protection., meter, and draft variables. In the mentioned network, we have five such stations.

The **B** region indicates the disconnector, which disconnects the converter station from the land and sea land cables. In the above network, we have five such disconnectors. The **C** region is a DMR (Dedicated Metallica Return) land cable with a length of 20 km. This cable connected the onshore converter to the sea cable. In the above network, we have three such land cables. The **D** region is submarine cable. Considering the mentioned network, we have six cables. The length of these cables can be found in the paper.

E region indicates the VARC DC CB. This region also consists of fault logic and the operating time of VARC. In all the models, the VARC is connected to a positive pole and placed at either end of the cable. Region **F** consists of Wind turbines and scaling transformers to mimic the wind power pack/wind farm. We have two such wind power packs. Region **G** has general meters and master controls.





In the *runtime*, we have six regions, Region **A** indicates the control functions & setpoints, and Draft variables. These two blocks in this region remain the same for all the converters. Furthermore, region **B** indicates AC fault duration, fault button, and re-set signal near the *CSA1* converter. Region **C** has two hierarchy boxes, namely *Master control* and *Starting sequence.* As the name indicates, the *Master control* has all necessary global setpoints and control functions. Similarly, *Starting sequence* has control switches that give the breaker close command and de-block signal to the converter station.

Region **D** consists of wind turbine controls, draft variables, and setpoints. Furthermore, region **F** consists of a wind speed control slider, offshore fault and fault duration, and Energisation buttons of the wind turbine. Region **G** consists of DC fault and reclose command for DC breakers.

<u>Tutorial Questions:</u>

Model: CIGRE_3TERMINAL_525KV_RTS_MODEL_3D_CHECK_PI_SMC_STSMC_BSC

1. Inside CSA4 Controls, test the following active power references:
   a. Pref4=0MW,
   b. Pref4=-250MW,
   c. Pref4=-500MW,
   d. Pref4=-1000MW

   Repeat the exercise for different controllers using **Adv_con_mode** switch. Here:
   1-PI
   2-SMC
   3-STSMC
   4-BSC

2. Comment on the following:
   a. Do you see PWR_CSA1 going positive for any above cases?
   b. Do you see the chattering behavior for SMC and chattering reducing upon switching to STSMC?
   c. Do you see any controller making the system unstable for any instant?
   d. Do you find a way to bring back the system to stability?

3. Simulate a DC fault in runtime for each controller by pressing switch, **DC_FLT,** and compare the performances of PI, SMC, STSMC, and BSC.

4. Simulate an AC fault in runtime for each controller by pressing switch, AC fault < **AC_FLT** and compare the performances of PI, SMC, STSMC, and BSC.