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ANALYSIS OF THYRISTOR BASED HVDC TRANSMISSION SYSTEM

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ABSTRACT

A high-voltage, direct current (HVDC) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems. For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. Originally developed in the 1930s, HVDC technology is only really suited to long-range transmission. This is because of the static inverters that must be used to convert the energy to DC for transmission. These are expensive devices, both in terms of capital cost and energy losses. With contemporary HVDC technology, energy losses can be kept to about 3% per 1000km. This makes the connection of remote generating centres much more feasible. Also it can be used as a link between AC systems that are out of sync with each other. This could be different national grids running on different frequencies; it could be different grids on the same frequency with different timing; finally, it could be the multiple unsynchronized AC currents produced by something like a field of wind turbines.

The following project illustrates the Matlab/Simulink modelling of a High Voltage DC Transmission link using 12-pulse Thyristor based convertors between a 500kV, 5000MVA, 60Hz, system to a 345kV, 10000MVA, 50Hz system over a 1000MW(500kV, 2kV) DC interconnections. Through this model the frequency response of the AC system and the DC line and the system Start-up/Stop — steady-state and step response is analysed.

INTRODUCTION

The High Voltage Direct Current Transmission are used for transfer of electric power over a long distance in remote places. The HVDC link are considered better over the HVAC links because of the several reasons discussed below.

High-voltage AC transmission links have disadvantages, which may compel a change to DC technology:

1. Inductive and capacitive elements of overhead lines and cables put limits to the transmission capacity and the transmission distance of AC transmission links.
2. This limitation is of particular significance for cables. Depending on the required transmission capacity, the system frequency and the loss evaluation, the achievable transmission distance for an AC cable will be in the range of 40 to 100 km. It will mainly be limited by the charging current.
3. Direct connection between two AC systems with different frequencies is not possible.

4. Direct connection between two AC systems with the same frequency or a new connection within a meshed grid may be impossible because of system instability, too high short-circuit levels or undesirable power flow scenarios.

Therefore the development of a technology for DC transmissions as a supplement to the AC transmission was taken into consideration by the researchers and engineers.

Initially, the mercury valves were used to make line-commuted current sourced convertors for the HVDC links. Then with development of thyristor, better control over the links was possible. Then comes the thyristors with higher current and voltage ratings eliminated the need of the parallel and series connections and hence reduced the size and improves the control of the convertors.

The advantages of a DC link over an AC link are:

1. A DC link allows power transmission between AC networks with different frequencies or networks, which cannot be synchronized, for other reasons.
2. Inductive and capacitive parameters do not limit the transmission capacity or the maximum length of a DC overhead line or cable. The conductor cross section is fully utilized because there is no skin effect.

For a long cable connection, e.g. beyond 40 km, HVDC will in most cases offer the only technical solution because of the high charging current of an AC cable. This is of particular interest for transmission across open sea or into large cities where a DC cable may provide the only possible solution.

1. A digital control system provides accurate and fast control of the active power flow.
2. Fast modulation of DC transmission power can beused to damp power oscillations in an AC grid and thus improve the system stability.

Considering economic and environmental factors, the HVDC still stand above the HVAC link.

The cost of HVDC and HVAC are calculated over the following factors for a link for 100km;

- AC vs. DC station terminal costs
- AC vs. DC line costs
- AC vs. DC capitalised value of losses

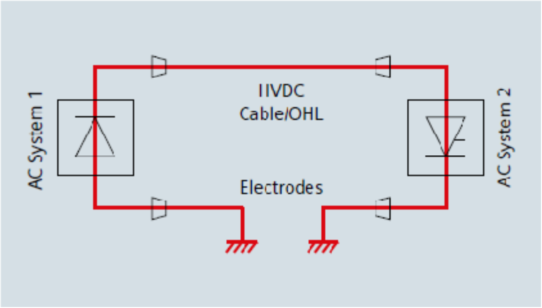
The total cost of the HVDC is found to be very less as compared to the HVAC.

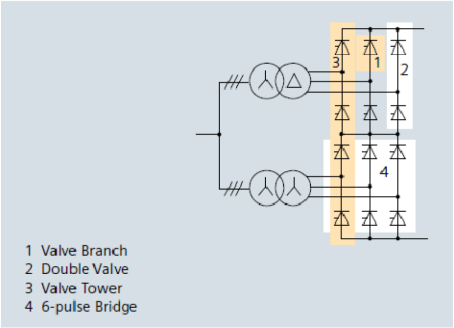
Also, an HVDC transmission system is basically environment friendly because improved energy transmission possibilities contribute to a more efficient utilization of existing power plants. The land coverage and the associated right-of-way cost for an HVDC overhead transmission line is not as high as that of an AC line. This reduces the visual impact and saves land compensation for new projects. It is also possible to increase the power transmission capacity for existing rights of way

HVDC CONVERTORS

The HVDC convertors are distinguished by their DC circuit arrangement. Several arrangement are there.

1. Back-to-back convertors
2. Mono-polar Long Distance Transmissions
3. Bi-polar Long Distance Transmissions
4. Bi-polar with ground return path
5. Bi-polar without dedicated return path for Mono-polar operations



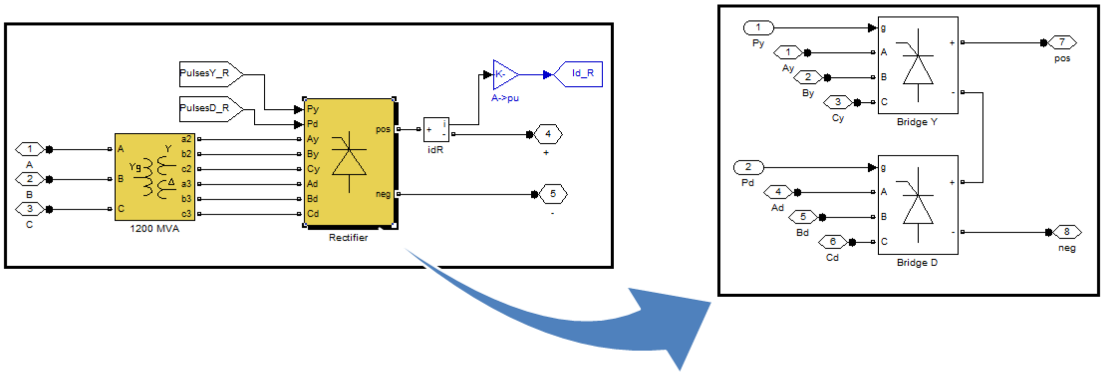


In the project we are using mono-polar long distance transmission convertors. For very long distances and in particular for very long sea cable transmissions, a return path with ground/sea electrodes will be the most feasible solution. Figure: Monopole with ground return path

HVDC converters are usually built as 12-pulse circuits. This is a serial connection of two fully controlled 6-pulse converter bridges and requires two 3-phase systems which are spaced apart from each other by 30 electrical degrees. The phase difference effected to cancel out the 6-pulse harmonics on the AC and DC side.

Figure: Arrangement of valve branches in 12-pulse

Figure: Filter model used in the SIMULINK Model



MAIN COMPONENTS IN HVDC

1. Thyristor valves.

   The thyristor valves make the conversion from AC into DC and thus are the central component of any HVDC converter station. The thyristor valves are of the indoor type and air-insulated.

2. Convertor Transformer.

   The converter transformers transform the voltage of the AC busbar to the required entry voltage of the converter. The 12-pulse converter requires two 3-phase systems which are spaced apart from each other by 30 or50 electrical degrees. This is achieved by installing a transformer on each network side in the vector groups Yy0 and Yd5. At the same time, they ensure the voltage insulation necessary in order to make it possible to connect converter bridges in series on the DC side, as is necessary for HVDC technology.

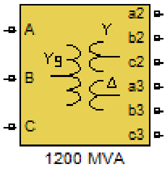
   

   Figure: Convertor Transformer used in SIMULINK Model

3. Smoothing reactors.

   Functions of the Smoothing Reactor

   - Prevention of intermittent current.
   - Limitation of the DC fault currents.
   - Prevention of resonance in the DC circuit.

Figure: Smoothing reactor

  - Reducing harmonic currents including.
  - Limitation of telephone interference.

4. Harmonic filters.

   The filter arrangements on the AC side of an HVDC converter station have two main duties:

   - to absorb harmonic currents generated by the HVDC converter and thus to reduce the impact of the harmonics on the connected AC systems, like AC voltage distortion and telephone interference
   - to supply reactive power for compensating the demand of the converterstation.

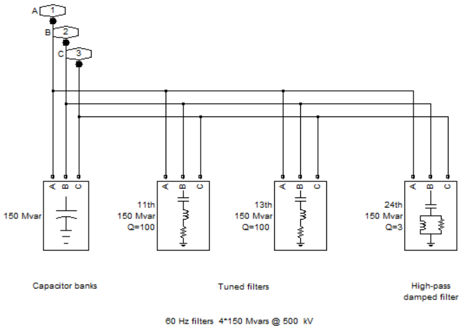


Figure: AC Filter used in SIMULINK Model

5. Surge Arrestors.

   The main task of an arrester is to protect the equipment from the effects of overvoltages. During normal operation, it should have no negative effect on the power system. Moreover, the arrester must be able to withstand typical surges without incurring any damage.

6. DC Transmission line.
7. Control and Protection.

   Main objectives for the implementation of the HVDC control system are reliable energy transmission which operates highly efficient and flexible energy flow that responds to sudden changes in demand thus contributing to network stability.

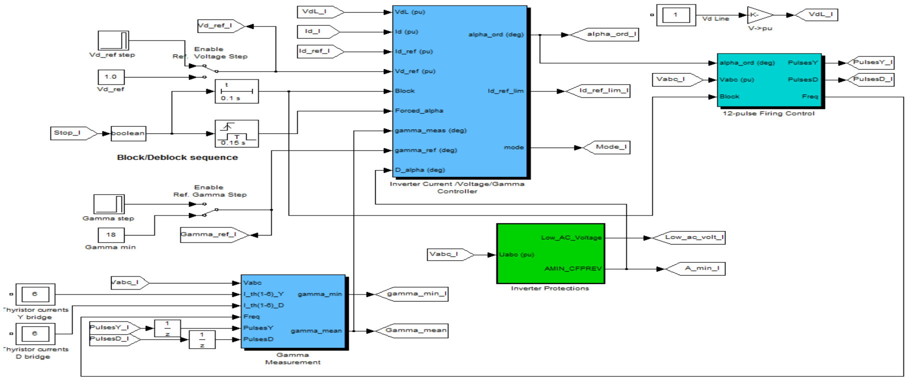


Figure: Control and Protection System in SIMULINK Model

ANALYSIS OF THE MODEL

Description Of HVDC Transmission System

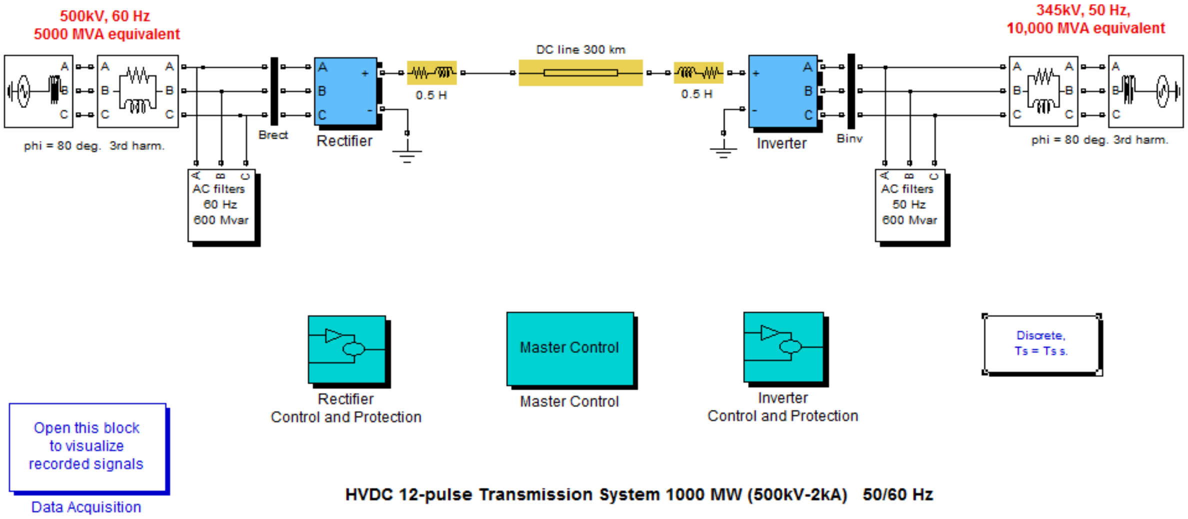
The section illustrates modelling of a high-voltage direct current (HVDC) transmission link using 12-pulse thyristor converters. Perturbations are applied to examine the system performance.

A 1000 MW (500 kV, 2 kA) DC interconnection is used to transmit power from a 500 kV, 5000 MVA, 60 Hz system to a 345 kV, 10000 MVA, 50 Hz system. The AC systems are represented by damped L-R equivalents with an angle of 80 degrees at fundamental frequency (60 Hz or 50 Hz) and at the third harmonic.

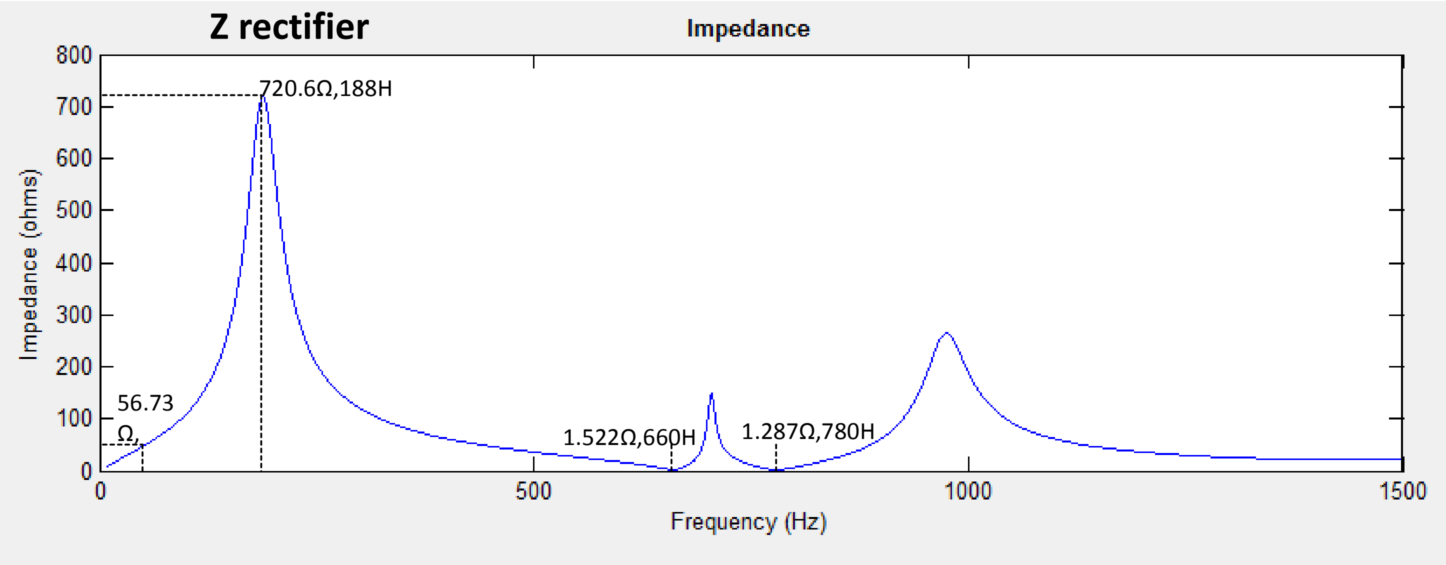
The rectifier and the inverter are 12-pulse converters using two Universal Bridge blocks connected in series. The converters are interconnected through a 300-km line and 0.5 H smoothing reactors. The converter transformers (Wye grounded/Wye/Delta) are modelled with Three-Phase Transformer (Three-Windings) blocks. From the AC point of view, an HVDC converter acts as a source of harmonic currents. From the DC point of view, it is a source of harmonic voltages.

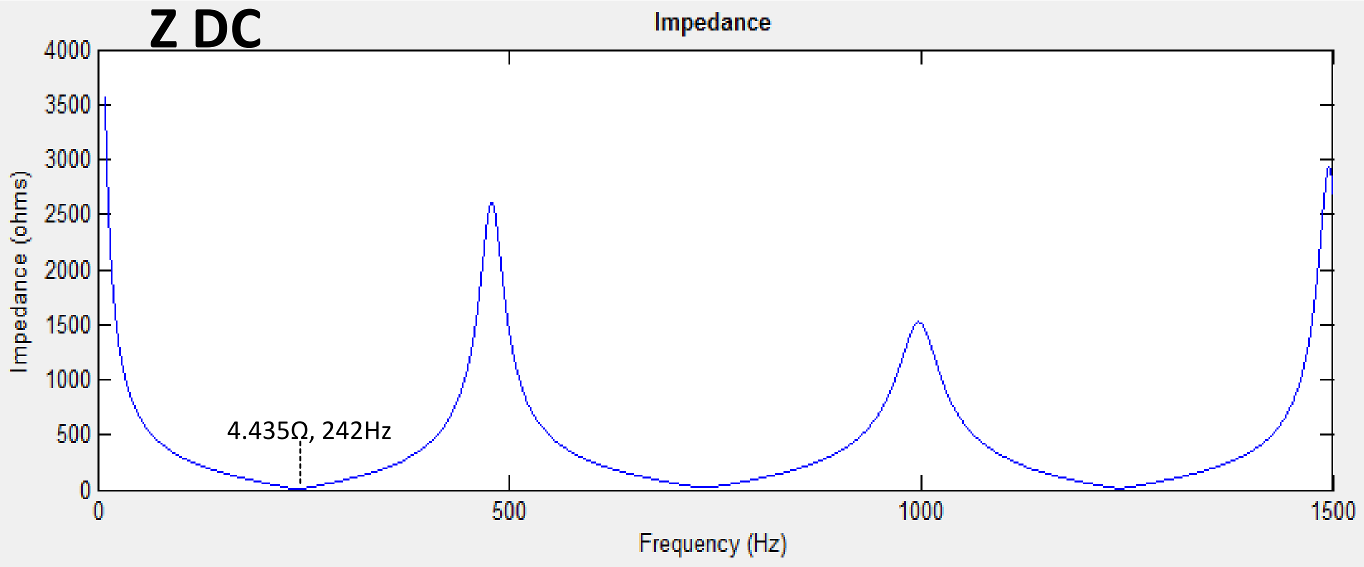
The order n of these characteristic harmonics is related to the pulse number p of the converter configuration: $n = kp \pm 1$ for the AC current and $n = kp$ for the direct voltage, k being any integer. In the example, $p = 12$, so that injected harmonics on the AC side are 11, 13, 23, 25, and on the DC side are 12, 24.

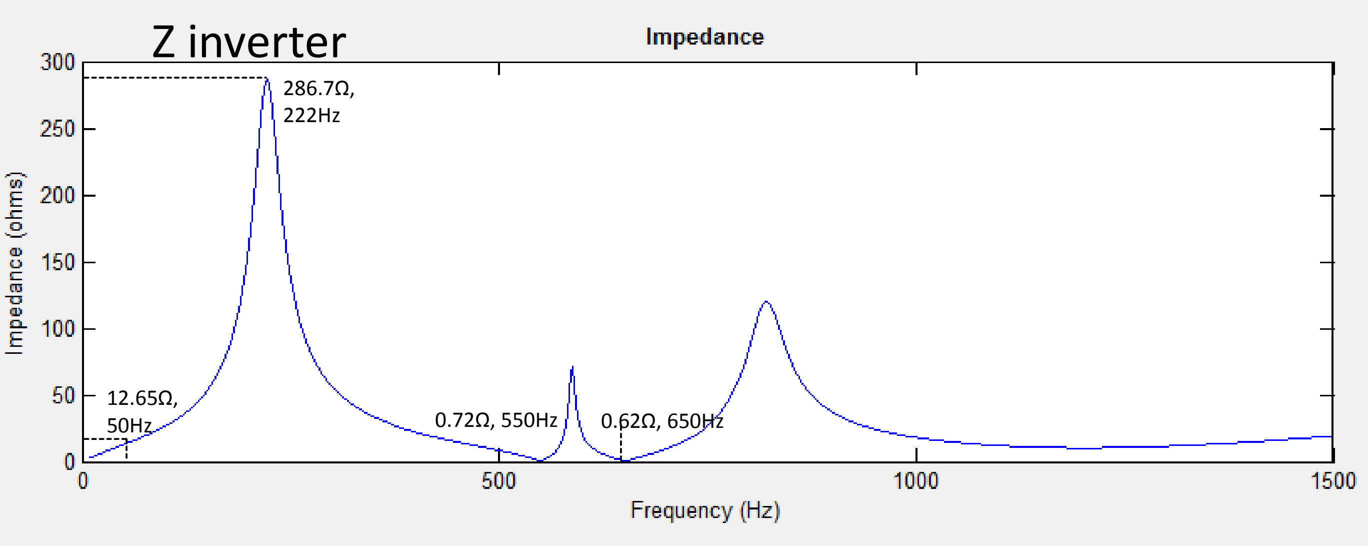
AC filters are used to prevent the odd harmonic currents from spreading out on the AC system. The filters are grouped in two subsystems. These filters also appear as large capacitors at fundamental frequency, thus providing reactive power compensation for the rectifier consumption due to the firing angle α. For $\alpha = 30$ degrees, the converter reactive power demand is approximately 60% of the power transmitted at full load. Inside the AC filters subsystem, the high Q (100) tuned filters at the 11th and 13th harmonics and the low Q (3), or damped filter, used to eliminate the higher order harmonics, e.g., 24th and up. Extra reactive power is also provided by capacitor banks.



Frequency Response of the AC and DC system







Inverter Side:
Peak Impedance of 286.7ohms at 222Hz due to 600Mvar capacitive filters.
Resonance at 650Hz and 650Hz due to the 11th and 13th harmonic filters.

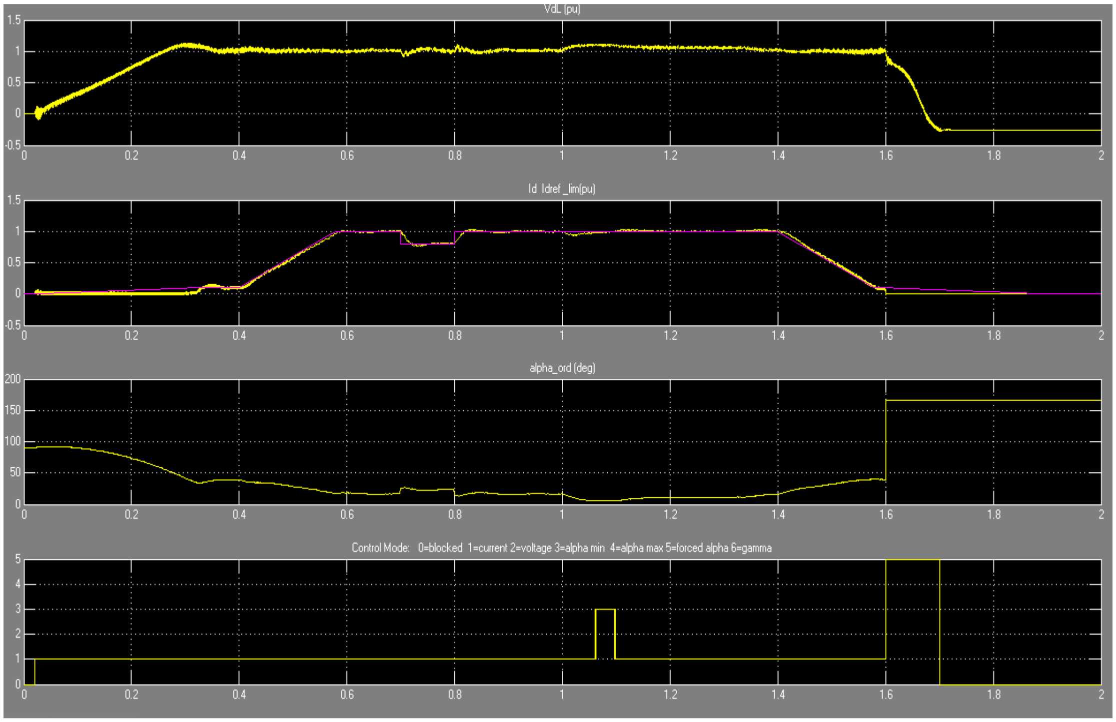
DC side:
For the DC line, note the series resonance at 240 Hz, which corresponds to the main mode likely to be excited on the DC side, under large disturbances.

System Startup/Stop – Steady-State and Step Response

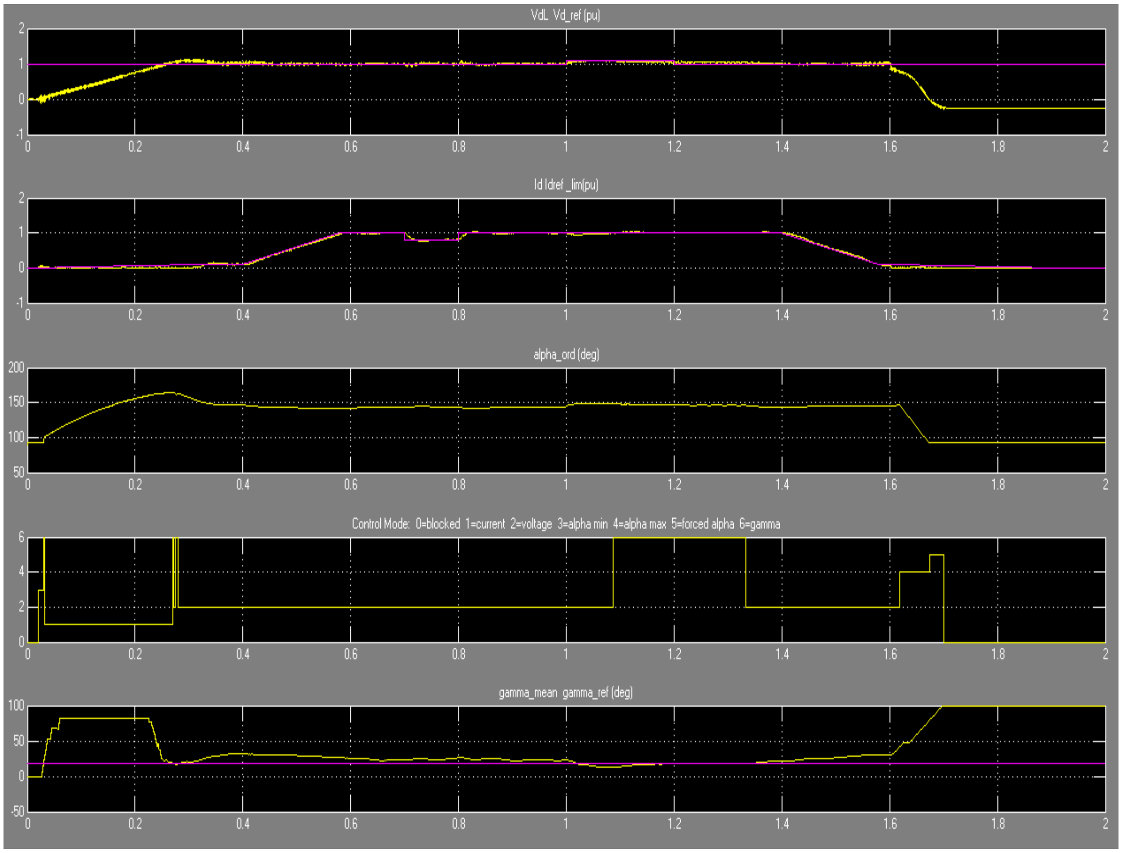
Note that the measured DC currents (Id_R and Id_I in A) and DC voltages (VdL_R and VdL_I in V) are scaled to pu (1 pu current = 2 kA; 1 pu voltage = 500 kV) before they are used in the controllers. The state of the rectifier and inverter controller is given by a number (from 0 to 6) as follows:
0 Blocked pulses
1 Current control
2 Voltage control
3 Alpha minimum limitation
4 Alpha maximum limitation
5 Forced or constant alpha
6 Gamma control

The system is discretized, using sample time Ts = 50e-6 s.
The system is programmed to start and reach a steady state. Then a step is applied first to the reference current and later to the voltage reference so you can observe the dynamic response of the regulators. Finally, a stop sequence is initiated to bring the power transmission smoothly down before blocking the converters. Notice in the Converter Controller that after reception of the Stop signal a Forced_alpha is ordered for 0.150 s, and then 0.1 s later the blocking of the pulses is ordered.

Rectifier



Inverter



In the Master Control, the converters pulse generators are deblocked and the power transmission started by ramping the reference current at t = 20 ms. The reference reaches the minimum value of 0.1 pu in 0.3 s. Observe that the DC current starts to build and the DC line is charged at its nominal voltage. At t = 0.4 s, the reference current is ramped from 0.1 to 1 pu (2 kA) in 0.18 s (5 pu/s). The DC current reaches steady state at the end of the starting sequence at approximately 0.58 s. The rectifier controls the current and the inverter controls the voltage. Trace 1 of both Rectifier and Inverter scopes shows the DC line voltage (1 pu = 500 kV). At the inverter, the voltage reference is also shown. Trace 2 shows the reference current and the measured Id current (1 pu = 2 kA). During the ramp, the inverter is actually controlling the current (Trace 4: Mode = 1) to the value of Id_ref_lim less the Current Margin (0.1 pu) and the rectifier tries to control the current at Id_ref_lim. At the inverter, the control mode changes from current control to gamma control (Mode = 6) before stabilizing to voltage control (Mode = 2) at t = 0.3 s. The rectifier becomes thereafter in control of the current. However, a control mode change will occur and alpha is limited to the minimum value of 5 degrees (Mode = 3) during an increase of the DC voltage initiated by a voltage reference increase at the inverter, as explained in the next paragraph. At steady state (measured at t between 1.3 and 1.4 s), the α firing angles are around 16.5 degrees and 143 degrees respectively on the rectifier and inverter side. At the inverter, two Gamma Measurement blocks measure the extinction angle γ for each thyristor of the two six-pulse bridges (i.e., the bridge connected to the Wye and Delta windings) by determining the elapsed time expressed in electrical degrees from the end of current conduction to the zero crossing of the commutating voltage. The mean value of the measured gamma for the last 12 extinctions (6 of the Delta converter and 6 of the Wye converter) is shown in traces 5 along with Gamma reference. In steady state, the mean γ is around 22.5 degrees.

At t = 0.7 s, a -0.2 pu step is applied during 0.1 s to the reference current so that you can observe the dynamic response of the regulators. Later on, at t = 1.0 s, a 0.1 pu step is applied during 0.2 s at the inverter reference voltage. Observe that at the inverter the extinction angle reaches the reference value (e.g., the minimum acceptable value) and that the Gamma regulator takes control at t around 1.1 s. At t around 1.3 s the voltage regulator retakes control of the voltage.

At t = 1.4 s the Stop sequence is initiated by ramping down the current to 0.1 pu. At t = 1.6 s a Forced-alpha (to 166 deg) at the rectifier extinguishes the current and at the inverter the Forced-alpha (to 92 deg with a limited rate) brings down the DC voltage due to the trapped charge in the line capacitance. At t = 1.7 s the pulses are blocked in both converters.

Comparison of Theory and Simulation Results in Steady State

The following expression relates the mean direct voltage *Vd* of a 12-pulse bridge to the direct current *Id* and firing angle α (neglecting the ohmic losses in the transformer and thyristors):

$$Vd = 2\times\left(Vdo\times\cos(\alpha) - Rc\times Id\right)$$

where *Vdo* is the ideal no-load direct voltage for a six-pulse bridge:

$$Vdo = \left(3\sqrt{2}/\pi\right)\times Vc$$

Vc is the line-to-line RMS commutating voltage that is dependent on the AC system voltage and the transformer ratio.
Rc is the equivalent commutating resistance.

$$Rc = (3/\pi)\times Xc$$

Xc is the commutating reactance or transformer reactance referred to the valve side.

The following parameters were taken for simulation:
Vc = 0.96 * 200 kV/0.90 = 213.3 kV
Id = 2 kA
α = 16.5º
Xc = 0.24 pu, based on 1200 MVA and 222.2 kV = 9.874 Ω

Therefore, this theoretical voltage corresponds well with the expected rectifier voltage calculated from the inverter voltage and the voltage drop in the DC line (R = 4.5 Ω) and in the rectifier smoothing reactor (R = 1 Ω):

$$Vd = VdL_{inverter} + \left(R_{DCline} + R_{inductance}\right) \times Id$$
$$Vd = 500\ kV + (4.5\ \Omega + 1\ \Omega) \times 2 = 511\ kV$$

The μ commutation or overlap angle can also be calculated. Its theoretical value depends on α, the DC current *Id,* and the commutation reactance *Xc*.

$$Vdo = \left(3\sqrt{2}/\pi\right) \times 213.3 = 288.1\ kV$$
$$Rc = (3/\pi) \times 9.874 = 9.429\ \Omega$$
$$Vd = 2 \times \left(288.1\ kV \times \cos(16.5°) - 9.429 \times 2\right) = 515\ kV$$
$$\mu = \mathrm{acos}\left[\cos(\alpha) - \frac{Xc \cdot Id \cdot \sqrt{2}}{Vc}\right] - \alpha$$
$$\mu = \mathrm{acos}\left[\cos(16.5°) - \frac{9.874 \cdot 2 \cdot \sqrt{2}}{213.3}\right] - 16.5° = 17.6°$$

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