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# Dynamic Performance of an HVDC Link

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*This paper presents the results of a simulation study on a 12 pulse* HVDC (*High Voltage Direct Current*) *using a system in Matlab/Simulink. The object of the study is to investigate the steady state and dynamic performance of the system. First we examine response of current regulator after change in current reference in order to see the behavior of the controllers in controlling the desired current. Next, we present the digital simulation of a test system and show the response to a DC fault in the line and the AC fault at inverter side. The results are evaluated to enhance the recovery of the system from the disturbances for a full range of typical disturbances. The presented approach benefits from Simulink's advantages in modeling and simulating dynamical systems.*

**Keywords**: HVDC, Recovery, Fault Simulation, VDCOL.

## 1. INTRODUCTION

High voltage direct current (HVDC) convert AC voltage to DC voltage in a rectifier and transmits DC power through the transmission line, and then reconverts DC into AC power in inverter and supplies the power. As a voltage, current and transmission power in the DC transmission can be controlled rapidly, when compared with the AC transmission, it is robust against a disturbance and increases a dynamic characteristic of AC power system and decreases a short-circuit capacity. The controllability of HVDC links is often cited as an important advantage of DC systems. This controllability can be valuable in improving the dynamic performance of large power systems. To achieve the promised advantages, control systems must perform appropriately for various disturbances and system condition.

HVDC technology finds application in the transmission of power over long distances or by means of under water cable, and in the interconnection of differently managed power systems which may be operated synchronously or asynchronously [6] [11].

Several general purpose mathematical modeling applications are now providing advanced environments for solving complex network problems. Matlab uses a specialized Toolbox, named Simulink, for simulating control systems. Simulink is capable of simulating dynamical systems and has a powerful graphic user-interface with a large library of blocks [2] [3] [6].

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The work presented here uses an example of an HVDC link in order to simulate its steady and dynamic state operation. Perturbations which consist on ac-dc fault conditions are applied with the goal of examining system performance. Compared with other research tasks, the results are obtained accurately and efficiently by Simulink.

## 2. HVDC SYSTEM MODEL

The HVDC system modeled, using the Simulink package, is based on a point-to-point DC transmission system. The DC system is a monopolar, 12 pulse converter using two universal bridge connected in series, rated 1000 MW (2000 A, 500 kV) at the inverter. DC interconnection is used to transmit power from a 500 kV, 5000 MVA, 60 Hz network (system_1) to 345 kV, 10 000 MVA, 50 Hz network (system_2). The receiving end and sending end AC systems are separated by a 300 km transmission line (figure 1).

### 2.1. The AC system

The AC networks, both at the rectifier and inverter end, are modeled as infinite sources separated from their respective commutating buses by system impedances. The impedances are represented as L-R//L networks having the same damping at the fundamental and the third harmonic frequencies. The impedance angles of the receiving end and the sending end systems are selected to be 80 degrees. This is likely to be more representative in the case of resonance at low frequencies [4] [7] [8].

During steady state, the rectifier is operating at a nominal firing angle of 18 degrees and the inverter at nominal firing angle of 142 degrees.

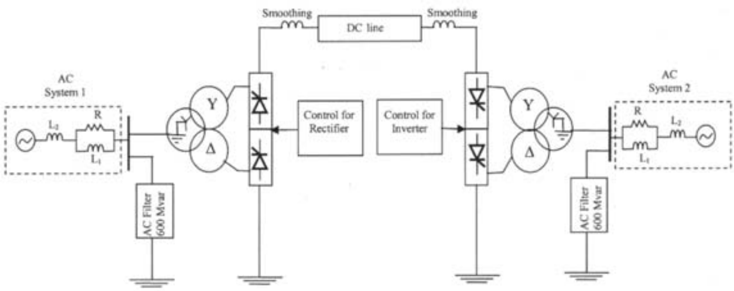



Figure 1. HVDC system

### 2.2. The converter transformers

The 1200 MVA converter transformer (Wye grounded/Wye/ Delta) is modeled with three-phase transformer (Three-Windings). The parameters adopted (based on AC rated conditions) are considered as typical for transformers found in HVDC installation such as leakage: X = j0.24 p.u.

### 2.3. The DC side of the system

The DC side of the converter system consists of a smoothing reactor (0.5 H) for the rectifier and the inverter bridges. The DC line is modeled in distributed parameter line model with lumped losses. This model is based on the Bergeronís traveling wave method used by the Electromagnetic Transient Program (EMTP) for a more realistic simulation.

### 2.4. AC filters and capacitor banks

On AC side of 12-pulse HVDC converter, current harmonics of the order of 11, 13, 25 and higher are generated. Filters are installed in order to limit the amount of harmonics to the level required by the network. In the conversion process the converter consumes reactive power which is compensated in part by the filter banks and the rest by capacitor banks of 600 Mvar on each side.

## 3. CONTROL SYSTEMS

HVDC transmission systems must transport very large amounts of electric power that can only be accomplished under tightly controlled conditions. DC current and voltage is precisely controlled to affect the desired power transfer. It is necessary therefore to continuously and precisely measure system quantities that include at each converter bridge, the DC current, its DC side voltage and the delay angle $\alpha$ and for an inverter, its extinction angle $\gamma$ [9] [10].

### 3.1 Inverter control system

The inverter is in constant extinction angle (CEA) control. An error signal is derived from the difference between the reference gamma and the measured gamma. This error is fed through a PI controller to produce an alpha-order signal, which controls the firing pulses to the converter thyristors.

### 3.2 Rectifier control system

The DC link current is maintained by using a current controller at the rectifier. This controller performs its task by generating a control voltage, which then controls the firing pulses, at some delay angle alpha, to the rectifier valves. The relationship between DC current Id and delay angle α is obtained by using the expression for the DC voltage at the rectifier, which is given by [4] [11]:

$$V_{dr} = V_{d0r}.\cos(\alpha) - R_{cr}.I_d \quad (1)$$

where $V_{dr}$ is DC line voltage, $V_{d0r}$ is open circuit rectifier DC voltage, and $R_{cr}$ is equivalent resistance of rectifier.

For constant $I_d$, and small changes in α

$$\frac{\Delta V_{dr}}{\Delta\alpha} = V_{d0r}.\sin(\alpha) \tag{2}$$

The relationship between DC current and alpha is given by:

$$I_d = \frac{V_{d0r}.\cos(\alpha) - V_{d0i}.\cos(\gamma)}{R_{dc} + R_{cr} - R_{ci}} \tag{3}$$

where $V_{d0i}$ is open circuit inverter DC voltage, α is rectifier firing (delay) angle, γ is inverter extinction angle, $R_{dc}$ is DC line resistance, and $R_{ci}$ is equivalent resistance of inverter.

The rectifier and inverter controls both have a voltage and a current regulator operating in parallel and calculating firing angles alpha. The effective angle is the minimum of these two angles. Both regulators are proportional and integral types with gains $K_p$ and $K_i$.

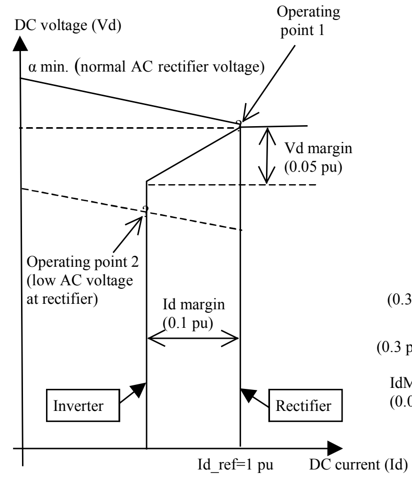



Figure 2. Rectifier and inverter operating characteristic.

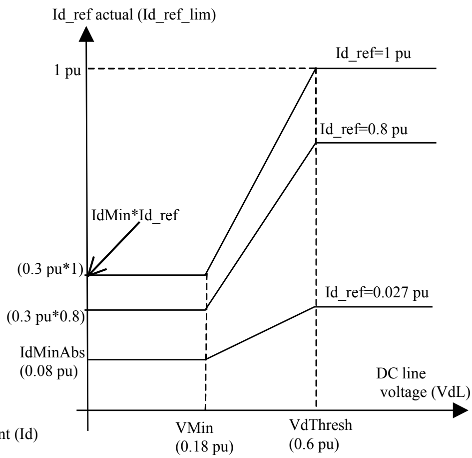



Figure 3. VDCOL characteristic.

Another particularity of the regulator is the linearization of the proportional gain. As $V_d$ generated by the rectifier and the inverter is proportional to $\cos(\alpha)$ (eq. 3), the variation in $V_d$ due to change in α is proportional to $\sin(\alpha)$ (eq. 2). With a constant $K_p$, the effective gain would therefore be proportional to sin(α). In order to keep a constant proportional gain, independent of α, the gain is linearized by multiplying $K_p$ with 1/sin(α). This linearization is applied for range of α defined by two limits (5∞≮ α <165∞for rectifier, and 92∞≮ α <165∞ for inverter).

**3.3 The VDCOL function**

In normal operation, the rectifier controls the current at the $I_{d\_ref}$ reference value whereas the inverter controls the voltage at the $V_{d\_ref}$ reference value. The $I_{d\_m\arg in}$ and $V_{d\_m\arg in}$ parameters are respectively 0.1 p.u. and 0.05 p.u. The system normally operates at point 1 as shown in figure 2. However, during a severe contingency producing a voltage drop on the AC system_1 feeding the rectifier, the operating point will move to point 2. The rectifier will therefore be forced to α minimum mode and the inverter will be in current control mode.

Another important control function is implemented to change the reference current according to the value of the DC voltage. This control named Voltage Dependent Current Order Limits (VDCOL) automatically reduces the reference current ($I_{d\_ref}$) set point when $V_{dL}$ ($V_d$ line) decreases (as for example, during a DC line fault or a severe AC fault). Reducing the Id reference currents also reduces the reactive power demand on AC network, helping to recover from fault [4]. The VDCOL parameters of the discrete 12-Pulse HVDC control are presented in figure 3.

The $I_{d\_ref}$ value starts to decrease when the $V_d$ line voltage falls bellow a threshold value $V_{dThresh}$ (0.6 p.u.). The actual reference current is named $I_{d\_ref}$-lim. $I_{d\_\min}$ Abs is the absolute minimum $I_{d\_ref}$ set at 0.08 p.u. When the DC line voltage falls bellow the $V_{dThresh}$ value, the VDCOL reduces instantaneously $I_{d\_ref}$. However, when the DC voltage recovers, VDCOL limits the $I_{d\_ref}$ rise time with a time constant [2] [7].

## 4. SIMULATION RESULTS

The behavior of the controllers in controlling the desired current for typical system disturbances was studied. In order to evaluate the system behavior after large disturbances, the system response for DC fault on the line and single phase AC fault on the inverter side were simulated.

**4.1 Step change in current reference**

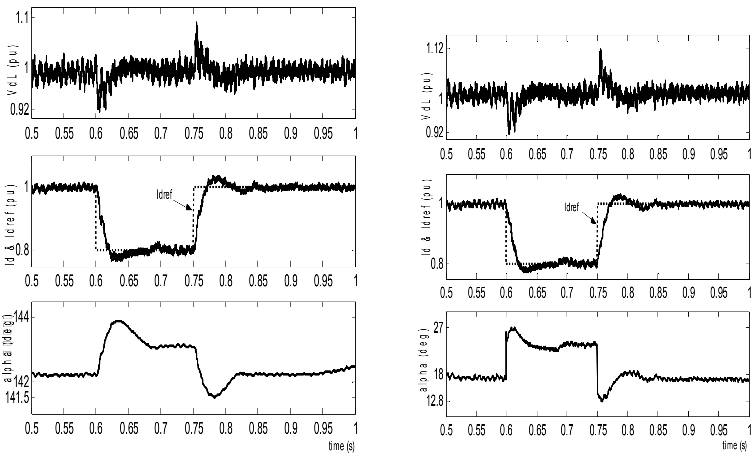
To simulate the response of the current command changes in an interval of time of 0.15 second for rectifier and inverter system, we should make the following steps:

- At $t = 0.6$ s, a 20% step is applied on the reference current (decrease from 1 p.u. to 0.8 p.u.).
- At $t = 0.75$ s, another step is applied to set the reference back to 1 p.u.

The figure 4 shows the response of the current regulator. The step change is effected in approximately 100 ms, and the step response is well controlled and stable.

### 4.2 DC Line fault

At fault application ($t = 0.6$ s), the DC current quickly increases to 2.3 p.u. and the DC voltage falls to zero at the rectifier. This DC voltages drop is seen by the Voltage Dependant Current Order Limiter (VDCOL), witch reduces the reference current to 0.3 p.u. at the rectifier (see figure 5). A DC current still continues to circulate in the fault. Then, at $t = 0.65$ s, the rectifier $\alpha$ firing angle is forced to 165 degrees. The rectifier now operates in inverter mode. The DC line voltage becomes negative and the energy stored in the line is returned to the AC network, causing rapid extinction of the fault current at its next zero-crossing. Then, $\alpha$ is released at t=0.7 s and the normal DC voltage and current recover in approximately 0.5 s when the fault is cleared.



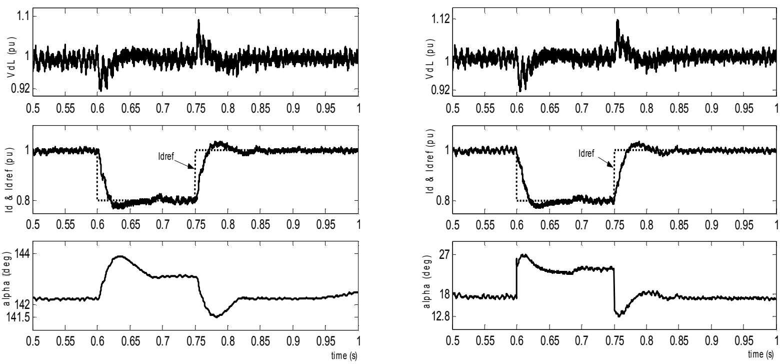

Rectifier Inverter

Figure 4. Response to 20% step of reference current

### 4.3 Single phase-ground fault at inverter

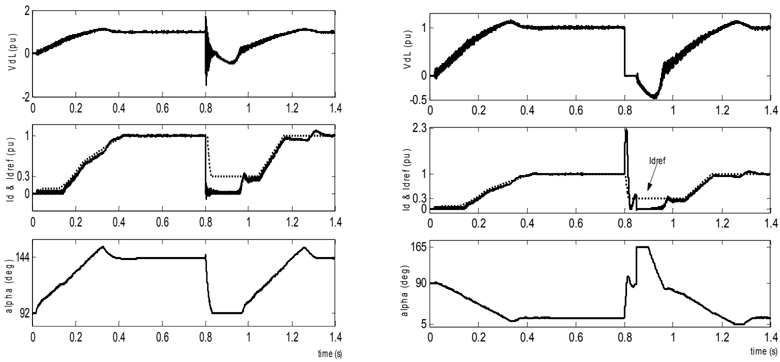
A single-phase-ground was applied to the A-phase of the inverter bus. The duration of the fault was 5 cycles. Results of this study are shown in figure

6.When this fault is applied at $t$ =0.6 s, the fault causes the DC voltage to collapse and the DC current to rise to 2 p.u. before the current controller action reduce it. The rectifier current controller attempts to reduce the current by increasing its firing angle and the rectifier therefore goes into the inverter region. The DC current decreases to a low average value as determined by VDCOL. When the fault is cleared at $t$ = 0.7 s, the VDCOL operates and rises the reference current to 1 p.u. The system recovers in approximately 0.3 s after fault clearing.




Rectifier Inverter

Figure 5. DC line fault on the rectifier side




Rectifier Inverter

Figure 6. Single-phase-ground fault at inverter

## 5. CONCLUSIONS

Digital studies of transient disturbances were carried out using the Simulink in Matlab. Two cases are used to demonstrate the performance of the system. From the results given above it can be seen that, in the case of DC fault, the voltage-dependent current order limits (VDCOL) function can have an important role in determining the DC system recovery from faults. Faults on the inverter end leads to a reduction in the receiving end voltage. This causes an initial overshoot in the DC current. The system however recovers after the fault is cleared. During normal operation, the rectifier is under current control mode and the inverter under extinction angle control mode. During faults, when the DC current reduces below the current reference of the inverter, the inverter takes control of current. After the fault is cleared, the current control is transferred back to rectifier. If VDCOL function is activated during an inverter AC system fault, the result will be to decrease the DC current and hence the inverter reactive power consumption, thus helping to support the AC system voltage. In the case of severe single-line-to-ground faults, the VDCOL may also help to recover normal commutation, and thus some power transfer can resume during the fault. Following fault clearing, the removal VDCOL function current limit may be delayed and ramped so as to maximize the recovery rate, while avoiding subsequent commutation failures.

### Appendix

Data for the system model are provided below :

- Rectifier end: The rectifier end AC system_1 (short circuit ratio=5) consists of one source with an equivalent impedance: $R$ = 26.07 Ω, $L_1$ = 48.86 mH, $L_2$ = 98.3 mH.
- Inverter end: The inverter end AC system_2 (short circuit ratio=10) consists of one source with an equivalent impedance of: $R$ = 6.205 Ω, $L_1$ = 13.96 mH, $L_2$ = 28 mH.
- DC line parameters: $R_{dc}$ = 0.015 Ω/Km, $L$ = 0.792 mH/km, $C$ = 14.4 nF/km.

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