Control strategy for ± 800 kV 6000 MW NER-Agra Multi-Terminal HVDC Project

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Abstract—The North East Region-Agra HVDC link is the world’s first Multi-Terminal Project at ±800 kV, linking rectifier stations at Biswanath-Chariali and Alipurduar, with inverter station at Agra. Multi Terminal HVDC (MTDC) systems require complex actions for their operation and control. Hence a comprehensive study of the entire system is necessary. The main aim of this paper is to analyze the basic operation of the North East-Agra MTDC scheme and suggest appropriate control measures for it. A simulation of the system is done in MATLAB-Simulink to understand how the system operates. Along with it, the details of the proposed controllers that can ensure proper control of each station of the HVDC link are also included. The results of the simulations show that the proposed controllers can be effectively incorporated in the system.

Index Terms—HVDC, Multi-terminal, HVDC Controller, NEA, MTDC, etc.

I. INTRODUCTION

With the rapid expansion of the electrical power network in India, grids are transitioning more and more towards an interconnected system of grids. There is a growing trend to integrate the distributed electrical networks based on Renewable Energy Sources. This calls for long distance power transfer links between the local generation centres and the grids. HVDC transmission, in this regard, is a great solution. Traditional HVDC lines implemented in India have 2 terminals: rectifier end and inverter end. MTDC links, on the other hand, enable power transfer between multiple links. They also help in reduction of transmission lines, flexible operation of connected systems, and have other benefits. Hence, MTDC systems are of great importance, and can improve the utilization of distributed resources.

One of the world’s first MTDC systems is the Sardinia-Corsica-Italy (SACOI) HVDC linking the Italian mainland with the islands of Sardinia and Corsica [3]–[5]. It is an LCC based monopole system rated at 200 MW, with a voltage rating of 200 kV. There are two principle control schemes of this system described in literature: Constant Power Control and Power/Frequency Control [3]. In the first method, a power order signal is used to derive operational setpoints for the main stations (local current orders for each station). The second method is similar to the first one, but with frequency control. There is no central controller for this system.

Another major MTDC system is the Quebec-New England HVDC link, connecting stations at Radisson, Nicolet and Sandy Pond [10]. It is a 2000 MW bipolar system with a DC voltage of ±450 kV. A master controller is used for overall system control functions, such as balancing of current and power orders for each station, power order ramping, etc. [6]. The basic control strategy of two terminal stations, with some modified functions, is implemented, wherein the Sandy Pond station is employed as Voltage Setting Terminal, and all other stations are operated in current control mode.

India’s first multi-terminal link is the North East Region (NER)-Agra HVDC link. The link connects terminal stations at Biswanath-Chariali (BNC) and Alipurduar (APD) to Agra. This link is the world’s first ever ±800 kV system using 12-pulse converters.

Usually, the design and analysis of point-point LCC HVDC links is discussed in the published literature. The control design and operation of three terminal systems though conducted throughly, is generally not available in the published literature. The paper attempts to design the control and observe operation of the three terminal NEA HVDC link. The control design proposed in this paper is based on the steady state equations and also uses sensitivity indices. The paper investigates and presents basic operating conditions of the link. The complex design approaches used for transfer function derivation have not been used in this paper, but, these may be required for in-depth analysis of system interactions and robust control design. The harmonic spectrum variation with operating conditions is also investigated. The harmonic spectrums are investigated, since, the filter parameters were derived from first principles and are not based on the actual values of the NEA link. Based on the control approach incorporated, associated results and discussions have been presented.

II. SYSTEM DESCRIPTION

The NER-Agra link is a bipolar LCC based system. Two rectifiers are situated at BNC and APD respectively, and two inverters are installed at Agra, with both the inverters connected to the same AC bus. The power transfer capacity of each rectifier/inverter is 3000 MW. 3000 MW power, transferred from BNC to APD, is added with 3000 MW power from APD rectifier, and the total 6000 MW power is
transferred to Agra through a 1296 km long ±800 kV DC transmission line. All the converters are connected to a 400 kV AC system. It is a joint project of Power Grid Corporation of India Ltd. (PGCIL), ABB and Bharat Heavy Electricals Ltd. (BHEL) [8], [9].

A. Configuration of the system

Fig. 1 shows the circuit diagram for NEA link [9]. The salient features of the HVDC link are listed below:
- Power Capacity : 6000 MW
- Voltage : ±800 kV
- Rectifiers : Biswanath-Chariali; Alipurduar, 3000 MW each
- Inverter : Agra, 6000 MW
- Total length : 1728 km

III. ASSUMPTION OF SYSTEM PARAMETERS

A. AC side filters

AC filters consist of one filter block at the BNC end, one at the APD end, and two at the Agra end. Assuming the total reactive power injection as 3600 MVAR (60% of the rated power), each of the four filter blocks have to supply 900 MVAR. Only 11th, 13th, 23rd and 25th harmonic filters, each of 225 MVAR, are considered. Assuming LC filters, and that the corresponding capacitor \( C_h \) provides the entire reactive power \( Q_c \) [1], [2], we get,

\[
V^2 \omega C_h = Q_c
\]

As the AC side is a 400 kV, 50 Hz system, \( C_h \) is calculated as 4.47 \( \mu \)F using equation 1. Now, inductances of the filters are calculated as,

\[
f_h = \frac{1}{2\pi \sqrt{L_h C_h}}
\]

which gives us \( L_{11} = 18.7 \) mH, \( L_{13} = 13.4 \) mH, \( L_{23} = 4.28 \) mH & \( L_{25} = 3.63 \) mH. The calculated filter parameters are listed in Table I.

<table>
<thead>
<tr>
<th>Filter Type (HP)</th>
<th>( C_h ) (( \mu )F)</th>
<th>( L_h ) (mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pass (HP-12)</td>
<td>( C_{11} )</td>
<td>( L_{11} )</td>
</tr>
<tr>
<td></td>
<td>( C_{13} )</td>
<td>( L_{13} )</td>
</tr>
<tr>
<td>4.47</td>
<td>18.7</td>
<td>4.47</td>
</tr>
<tr>
<td>4.47</td>
<td>13.4</td>
<td>4.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Pass (HP-24)</td>
<td>( C_{23} )</td>
<td>( L_{23} )</td>
</tr>
<tr>
<td></td>
<td>( C_{25} )</td>
<td>( L_{25} )</td>
</tr>
<tr>
<td>4.47</td>
<td>4.28</td>
<td>4.47</td>
</tr>
<tr>
<td>4.47</td>
<td>3.63</td>
<td></td>
</tr>
</tbody>
</table>

TABLE I

The filter schematic is shown in Fig. 2.

B. DC side filters

At rectifier end, total four 75 mH coils, two each at DC bus and neutral bus, are connected. At inverter end, two 75
Thus we have the transfer function

\[ L(s) = \frac{K_p s + K_i V_{co} \sin\alpha}{sL + R_{eq}} \]  

where, \( K_p \), \( K_i \) are PI constants. The characteristic equation of the closed loop system is

\[ s^2 + \left( \frac{R_{eq}}{L} + \frac{K_p V_{co} \sin\alpha}{L} \right)s + \frac{K_i V_{co} \sin\alpha}{L} = 0 \]  

Assuming the poles of the system to be \( p_1 \) and \( p_2 \), we have

\[ p_1 + p_2 = \frac{R_{eq}}{L} + \frac{K_p V_{co} \sin\alpha}{L} \]  

\[ p_1 \ast p_2 = \frac{K_i V_{co} \sin\alpha}{L} \]  

For this controller, the values of both the poles are chosen as -1200. Accordingly, the PI constants are calculated.

**B. Design of APD Rectifier Controller**

The preceding method is followed for designing the current controller for the APD rectifier as well. The values of the controller parameters are summarised at the end of this section.

**C. Design of Agra Inverter Controller**

In a similar manner, the system model considered for the inverter controller design is shown in Fig. 5. We have

\[ V_{di} = -V_{co} \cos\alpha + \frac{3X_{ci}}{\pi} i \]  

Here, \( V_{co} = \frac{3\sqrt{2}}{\pi} V_{l-1} \), \( X_{ci} \) = commutation reactance on inverter side, and \( \alpha \) = inverter firing angle. We get

\[ V_{di}(1 + \frac{3X_{ci}}{\pi R}) = -V_{co} \cos\alpha + \frac{3X_{ci} V_{dr}}{\pi R} \]  

\[ V_{di} = -\frac{V_{co} \cos\alpha}{1 + \frac{3X_{ci}}{\pi R} + \frac{3X_{ci} V_{dr}}{\pi R}} \]
For small perturbations around a stable operating point, taking Laplace Transform on both sides, we get the transfer function

\[
\frac{\Delta V_{di}(s)}{\Delta \alpha(s)} = \frac{V_{co} \sin \alpha}{1 + \frac{\Delta V_{di}}{\pi R}} = \frac{K}{s}
\]

where \( K \) is a constant. The corresponding control block diagram with a PI controller is shown in Fig. 6.

![Controller Inverter Diagram](image)

**Fig. 6. Inverter Controller**

The characteristic equation of the closed loop system is

\[
s^2 + K_0 K_p s + K K_i = 0
\]

where, \( K_0 \) and \( K_i \) are the PI constant. Both the poles were taken to be -200 for calculating the PI constants.

Hence, the calculated PI values of the controllers are:

1) BNC Rectifier Current Controller
   \[ K_p = 0.0984 \]
   \[ K_i = 59.23 \]
   Gain = 0.285 (Tuned by Trial and Error)

2) APD Rectifier Current Controller
   \[ K_p = 0.0738 \]
   \[ K_i = 44.42 \]
   Gain = 0.500 (Tuned by Trial and Error)

3) Inverter Voltage Controller
   \[ K_p = 0.0046 \]
   \[ K_i = 0.4581 \]
   Gain = 0.032 (Tuned by Trial and Error)

### C. Normal operation

In the normal operating mode, the inverter voltage controllers and current controllers regulate the respective control variables so that the system is able to operate at the desired operating point.

### VI. RESULTS AND DISCUSSIONS

The results obtained are shown in Fig. 7 and Fig. 8, respectively. As is seen in the results, the reference values, applied in steps, are tracked smoothly and negligible overshoot is observed. Also, the final required DC voltage of 760 kV and current of 1875 A is attained with sufficient accuracy.

The firing angles of the converters at BNC, APD and Agra stations are shown in Fig. 9. It is observed that the firing angles fluctuate roughly around 15° for the BNC rectifiers, 25° for the APD rectifiers, and 142° for the Agra inverters.

The harmonic analysis of the DC link current, and AC side currents at one of the rectifier stations, in this case APD station, and Agra station have been done for three separate instants: when just the BNC controller is operating (t = 0.6s), when both the BNC and APD controllers are operating (t = 1s), and when the voltage controller is activated as well along with the current controllers (t = 1.8s). The harmonic spectrum has been shown in Table II, III and IV, respectively. In the tables, \( h_i \) refers to \( i^{th} \) harmonic. As APD station is started after 0.7s, its harmonic spectrum is shown from 1.0s.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>DC LINK CURRENT HARMONICS</th>
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</thead>
<tbody>
<tr>
<td>time (s)</td>
<td>( h_6(%) )</td>
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<tr>
<td>0.6</td>
<td>3.22</td>
</tr>
<tr>
<td>1.0</td>
<td>1.25</td>
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<tr>
<td>1.8</td>
<td>1.34</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>APD AC SIDE CURRENT HARMONICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (s)</td>
<td>( h_5(%) )</td>
</tr>
<tr>
<td>1.0</td>
<td>2.09</td>
</tr>
<tr>
<td>1.8</td>
<td>0.77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>AGRA AC SIDE CURRENT HARMONICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (s)</td>
<td>( h_5(%) )</td>
</tr>
<tr>
<td>0.6</td>
<td>0.78</td>
</tr>
<tr>
<td>1.0</td>
<td>0.17</td>
</tr>
<tr>
<td>1.8</td>
<td>0.29</td>
</tr>
</tbody>
</table>
VII. CHALLENGES FACED

Some of the challenges faced in this project are:

- The design of the controller could not be done accurately due to insufficient data.
- AC side rectifier data was also not available. However the controllers could adequately track the reference values.
- Due to absence of filter and DC link line data, the controller design was roughly approximated. Hence, the output voltages and currents were observed to have large harmonic content.

VIII. CONCLUSION

The traditional two terminal control method has been applied to design independent controllers for this HVDC system.

IX. FUTURE SCOPE

The simulation results state the suitability of the designed controllers for implementation. With availability of proper data, a rigorous controller design can be done to ensure smoother operation.
the future scenarios can be done, and appropriate results can be obtained. Also contingency analysis can be done to study the effects of faults, failure of one or more converters, AC side voltage dips, and other such events on system performance. The results thus obtained can be used to evaluate the effectiveness of the controllers in emergency situations. Also, the mutual interaction between the controllers can be investigated by state space modelling of the system, which will ensure a coordinated design of the controller.

REFERENCES