Response of monopolar HVDC system in presence of single double-tuned dc filter

Soma Deb and H K Verma
Department of Electrical and Electronics Engineering
School of Engineering and Technology
Sharda University, Greater Noida, India
E-mail: soma.deb@sharda.ac.in

Abstract. Study of the response of an HVDC system to various conditions, types and locations of fault on the system is basic to developing suitable protection techniques and algorithms. This paper presents a study of the behaviour of monopolar HVDC system in the presence of a single double-tuned dc filter. CIGRE Benchmark model for monopolar HVDC system has been simulated on PSCAD/EMTDC for the study. Five different fault locations, viz. three dc line faults (two faults near the line ends and the third fault at the middle point of the line) and two ac side faults (one near the rectifier and the other near the inverter), and five different values of fault resistance (ranging from 0 to 2000 ohms) have been considered. It has been observed that incremental current and incremental power in the HVDC line can discriminate only mid-line dc faults from ac fault. Also, incremental current can discriminate between rectifier-side ac fault and inverter-side ak fault for all values of fault resistance, whereas incremental power can do so only for lower values of fault resistance (0 ohm and 10 ohms). Transient energy can discriminate dc line faults at all locations from ac faults with all values of fault resistance. However, transient energy can discriminate rectifier-side ac fault from inverter-side ac fault only for low values of fault resistance (0 ohm and 10 ohms) and not for high values. This study can be very effectively used in developing a protection algorithm/technique. The study can be further extended to analyze the performance of HVDC system in the presence of any type of the dc filter and for any length of the line.

1. Introduction
HVDC system is widely used these days for transporting bulk power over long distances. With rapid developments in the technology of line-commutated converter based high voltage direct current (HVDC) system, the reliability and sensitivity of the associated protection system are becoming increasingly important. For development of suitable protection techniques and algorithms, study of the response of the given HVDC system to various conditions, types and locations of fault is essential so as to determine the system variable to be used as the basis of protection. A survey of the literature on the development of protection techniques and algorithms for HVDC systems reveals that the following system variables have been used or recommended for protection of monopolar HVDC system by various researchers:

i. Current [1-5]
ii. Voltage [6]
iii. Power [1]
iv. Reactive Energy [7]

v. Transient Energy [1,8]

Study of the response of an HVDC system essentially requires its simulation under healthy and various fault conditions. This paper is aimed at evaluating the response of a monopolar HVDC system and choosing system variables suitable for designing a protection scheme. Soma Deb and Verma [1] reported a detailed performance evaluation of CIGRE benchmark model, wherein they concluded that change in current, power and transient energy are the best suited system variables for protection, while voltage, impedance etc. generally do not give the desired selectivity of the protection scheme. As such, this paper also evaluates the system performance only in respect of the change in current, power and transient energy.

In any HVDC system, dc filters are a major and important component and are used to serve two purposes, providing reactive power and reducing harmonic currents. DC filters are installed on the line side of the HVDC smoothing reactor and shunt with the dc line. The DC filters used, employ different configurations of reactors, capacitors and resistors to achieve single, double or triple tuning.

Commonly used types are cascaded double tuned filter [9], parallel double-tuned filter [8], triple tuned filter [10] and parallel triple tuned filter [4]. Type of dc filter installed affects the response of HVDC system to faults. Reference [1] reported the system response in the presence of cascaded double tuned dc filter while, this paper considers only one single double tuned dc filter. Parameters of the simulated HVDC System along with parameters of the dc filter are given in Section 2.

Simulation methodology and the results of the simulation study are given in Section 3 and Section 4 respectively, followed by discussion and conclusion.

2. Simulated HVDC System

HVDC system considered in this paper for simulation study is based on CIGRE benchmark model for monopolar HVDC system, which has been simulated using PSCAD/EMTDC [11].

| Parameters          | Values          |
|---------------------|-----------------|
| AC Source 1         | 345 kV, 50 Hz   |
| AC Source 2         | 230 kV, 50 Hz   |
| Rated Power         | 1000 MW         |
| Rated Voltage       | 500 kV          |
| Rated Current       | 2 kA            |
| DC line length      | 800 km          |

Table 1. Parameters of Simulated System

Figure 1 above shows a simplified diagram of monopolar LCC-HVDC system with two-end measurements. Here, v, i, represent the voltage and current measurements at sending end M, and v, i, represent at receiving end N. The assumed directions of currents and voltages are as shown. Table 1 above shows the parameters of the simulated HVDC system.

Configuration of a single double-tuned dc filter is shown in figure 2. It comprises of a series resonant circuit in series with a parallel resonant circuit. Filter parameters of the dc filter is given in Table 2.
Table 2. Parameters of DC Filter

| Parameter | Value     |
|-----------|-----------|
| C1        | 2 µF      |
| L1        | 11.71 mH  |
| C2        | 9.074 µF  |
| L2        | 5.874 mH  |
| Ld1       | 0.29 H    |

Figure 2. Single double-tuned dc filter.

3. Simulation Methodology
Simulation study has been carried for faults occurring at five different locations. Two three phase faults – one at the rectifier side (RF) and the other at the inverter side (IF), and three internal dc faults- sending end (DF1), mid-point (DF2) and receiving end (DF3) have been created. Every time the fault is created at 0.5 s. The data has been collected at a rate of 2 kHz.

4. Simulation Results
In this simulation study, system response has been obtained in terms of change in current (incremental current), change in power (incremental power) and transient energy. Five different values of fault resistance, viz, 0 ohm, 10 ohms, 100 ohms, 1000 ohms and 2000 ohms, are considered.

4.1. System Response in terms of incremental current
Variation of the incremental current with time for three internal fault locations (DF1, DF2 and DF3) is shown in figures 3 to 5 respectively, and for external fault locations (RF and IF) in figures 6 and 7 respectively.

4.1.1. Incremental-Current Response for Internal Faults (DF1, DF2 and DF3)
Response curves in terms of change in current for rectifier side dc fault DF1, are shown in figure 3. Separate curves are shown for five different values of fault resistance. In each case, a pair of curves is plotted, one for the sending end M and the other for the receiving end N. It may be noted that the scale is progressively amplified as the values of the incremental current are decreasing with the increase in the fault resistance. It is observed that on solid fault, the incremental current at the fault end ($\Delta I_M$) has huge oscillations and changes its polarity between positive and negative values for a few cycles of the fault inception. The incremental current at the other end ($\Delta I_N$) is almost zero with no oscillations. As the fault resistance increases, the magnitude and oscillations in the incremental current at the sending end reduce while it remains positive throughout.

Response curves in terms of change in current for mid-line dc fault DF2, are shown in a similar style in figure 4. It may be noted that for mid-line fault, the oscillations in the sending end current are less severe than for fault at the rectifier end DF1. Moreover, the incremental current at the other end is also more than that for DF.

Figure 5 shows the system response in terms of change in current for dc fault near the inverter end (DF3). It is observed that the oscillations are more severe in the incremental current at the fault end, i.e. $\Delta I$, and very little oscillations in the incremental current at the other end, i.e. $\Delta I$. 
4.1.2. Incremental-Current Response for External Faults (RF and IF)
Response curves in terms of change in current for rectifier side ac fault (RF) are shown in figure 6. It can be noted that both $\Delta I_M$ and $\Delta I_N$ are negative and free from oscillations. Moreover, their values reduce with increase in the fault resistance, as would be expected.
Response curves in terms of change in current for inverter side ac fault (IF) are shown in figure 7. It is noted that both $\Delta I_M$ and $\Delta I_N$ are positive (at least for a couple of cycles) and have no oscillations. As expected, their values reduce as the fault resistance is increased.

Figure 6. Response curves in terms of change in current for rectifier-side ac fault (RF).

Figure 7. Response curves in terms of change in current for inverter-side ac fault (IF).

4.2. System Response in terms of incremental power
Variation of incremental power for the same five locations of fault is shown in figures 8 to 12 respectively.

4.2.1. Incremental-Power Response for Internal Faults (DF1, DF2 and DF3)
Figure 8 shows the response curves in terms of change in power for DF1. As shown in the figure, for solid fault resistance and lower values of fault resistance, the incremental power at the fault end oscillates between positive and negative values, whereas the incremental power at the end is largely free from such oscillations.

Response curves in terms of change in power for rectifier side dc fault DF are shown in figure 9. The value of change in power $\Delta P_M$ is negative and that of $\Delta P_N$ is positive for this fault location. As expected, the magnitude of each incremental power reduces with increase in fault resistance.

Response curves shown in figure 10 show that for DF1, the incremental power at the fault end (which is the end N) has oscillations, like the oscillations in incremental power at the fault end M for DF.
Figure 8. Response curves in terms of change in power for rectifier-side dc fault (DF$_1$).

Figure 9. Response curves in terms of change in power for mid-line dc fault (DF$_2$).

Figure 10. Response curves in terms of change in power for inverter-side dc fault (DF$_3$).
4.2.2. Incremental-Power Response for External faults (RF and IF)

Change in power at both the ends \( \Delta P_M \) and \( \Delta P_N \) are positive for rectifier side ac fault RF as shown in figure 11. It may be observed that in this case too, the magnitudes reduce as the fault resistance increases.

As shown in figure 12, change in power \( \Delta P_M \) and \( \Delta P_N \) are both negative for inverter-side ac fault IF for lower values of fault resistance (0 and 10 ohms), whereas these values are positive, though the magnitudes are small, for higher values of fault resistance (100 ohms and above).

![Figure 11. Response curves in terms of change in power for rectifier-side ac fault (RF).](image1)

![Figure 12. Response curves in terms of change in power for inverter-side ac fault (IF).](image2)

4.3. System Response in terms of transient energy

Variation of transient energy with time for the same five locations of fault is shown in figures 13 to 17 respectively.

4.3.1. Response Curves for Internal Faults (DF1, DF2 and DF3)

The response curves in terms of transient energy at the two ends for the three locations of internal fault (dc fault), viz., DF1, DF2, and DF3, are shown in figures 13, 14 and 15 respectively. In each case, the transient energy \( \Delta E \) at rectifier side M remains negative whereas that for inverter side N remains positive. Their magnitudes reduce with increase in fault resistance, as expected.
**Figure 13.** Response curves in terms of transient energy for rectifier-side dc fault (DF1).

**Figure 14.** Response curves in terms of transient energy for mid-line dc fault (DF2).

**Figure 15.** Response curves in terms of transient energy for inverter-side dc fault (DF3).
### 4.3.2. Response Curves for External Faults (RF and IF)

Response curves in terms of transient energy for rectifier side ac fault RF are shown in figure 16, and those for inverter side ac fault IF in figure 17. It is observed from Figure 16, that the transient energy at each end is positive for RF; their values reduce with increase in fault resistance. The transient energy curves given in Figure 17 reveal a different type of response for IF. The transient energy at both the ends is negative for low values of fault resistance (0 ohm and 10 ohm) and it is positive for both the ends for high values of fault resistance, (1000 and 2000 ohms). For a middle value of fault resistance, \( \Delta E \) changes from initial positive value to some negative value whereas \( \Delta E \) remains negative throughout.

![Figure 16.](image1.png)  
![Figure 17.](image2.png)

### 5. Discussion and Conclusion

Monopolar HVDC system in presence of single double tuned dc filter has been simulated in this paper to analyze system response to dc and ac faults: three locations on dc line and two locations on ac side. Five different values of fault resistance (0 ohm, 10 ohms, 100 ohms, 1000 ohms and 2000 ohms) have been simulated. Incremental current, incremental power and transient energy are the system variables selected for the simulation study.

A critical analysis of the simulation results leads to the following significant observations:

(a) For line end dc faults, incremental current and incremental power at the fault end have oscillations whereas transient energy is free from any such oscillations.

(b) For mid-line dc faults, incremental current, incremental power and transient energy, all the three are free from oscillations.

(c) For external fault at the rectifier end, incremental current at both the ends remain negative for a minimum of two ac cycles whereas incremental power and transient energy remains positive. Similar trends are observed for all values of fault resistances.
(d) For external fault at the inverter end, incremental current and incremental power at both the ends remain positive for a minimum of two ac cycles for all values of fault resistances. However, transient energy at both the ends is negative only for lower values of fault resistances (0 ohm and 10 ohms). For 100 ohm fault resistance, transient energy at rectifier end is positive on fault inception and tends negative after a quarter of ac power cycle, whereas transient energy at inverter end is negative. For higher values of fault resistances (1000 ohms and 2000 ohms), transient energy at both the ends are positive.

Following proposals are made for extending the reported work in future:

i. On similar lines, system variables can be analyzed for any other dc filter.

ii. The actual system for which the relaying is to be designed can also be simulated.

iii. The line length taken in the present study is 800 km. However, the lines in several systems are much longer which may have an effect on reducing the magnitudes of the signals.

iv. Protection algorithm can be developed using the results of the simulation study such as reported or proposed above.

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