Modelling of HVDC Link for Power Quality Assessment

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Abstract. Conversion technique of HVDC has become a dominant technology for long distance bulk power transmission. The AC and DC system are interconnected by HVDC converter thus, it becomes the medium of the harmonic transfer. The presence of harmonic not only increases the losses, but it can also lead the system to collapse. In this study, the passive filter is used to mitigate the harmonics in both the AC and DC sides of the HVDC network by tuning it until satisfied with the harmonic standard. The test system of TNB-EGAT HVDC link is modelled using PSCAD software with AC voltage rating of 275 kV and 230 kV for rectifier and inverter side, respectively. The system is controlled by the control system that has been modelled according to CIGRE Benchmark. Comparison of the simulation results between before and after the implementation of passive filters in the system reveals that the harmonics have been mitigated effectively. The results show that the level of THD current at the AC side reduced to 0.2336% and 0.0154% at rectifier and inverter side, respectively.

1. Introduction

High Voltage Direct Current (HVDC) transmission system is being advantageous as it can transmit high power ratings with low electrical losses over very long distances [1]. This can be proved through the development of 110 km HVDC 300/600 MW project between Malaysia and Thailand to get power exchange between the two countries due to differences of daily peaks in consumption [2]. On the Malaysia side, the converter operated as a rectifier because the electrical power is transformed from AC power into DC power while on the Thailand side, the converter operated as an inverter due to the DC power is transformed back to AC power [3]. However, the switching actions of the thyristor valves contribute to the power quality problems such as harmonic.

Harmonic is one of the important power quality effects that should be a concern since it is unpredictable when and where it might happen [4]. The harmonic mechanism present within the HVDC network will reduce the operating life and contribute to the system failure [5]. Additionally, if the system has a high level of harmonic, the system can not work properly as the harmonics entering the mains and the DC line that can cause overheating of equipment. Therefore, the mitigation is needed which the passive filters are proposed to be installed in the system [6-8]. The passive filters are made up of passive elements such as resistor, inductor and capacitor. Typically, it is designed to provide a low impedance path to avoid harmonics from entering the system [9]. Several banks of different filter types are connected in parallel to achieve acceptable limits of harmonic distortion as suggested by IEC 1000-3-6 standard [10].

The purpose of this study is to perform the harmonic assessment on 275/230 kV TNB-EGAT HVDC link using PSCAD software. The complete model required two systems: electrical system and control system [11]. The electrical system consists of three elements: rectifier side circuit, inverter side...
circuit and DC connection. The condition of current and voltage harmonics will be observed on the AC side and DC side, respectively. Then, the passive filters will be connected in the system to mitigate the harmonic. In this study, the harmonic will be reduced until satisfied the harmonic standard.

This paper begins by describing the harmonics in the HVDC system that consist of AC current harmonics and DC voltage harmonics. Then, this paper emphasizes on the development of TNB-EGAT HVDC link that consists of 3 sub-modules. In the early stages, the test system is modeled without filter and for the next stage, the filters are included. In the last part, this paper discusses the comparison of harmonic magnitude in the AC side and DC side which are before and after the filters are installed in the system.

2. Harmonic in HVDC System

The non-linear characteristic of HVDC converter generates harmonic currents and harmonic voltages on AC and DC sides, respectively [12]. The harmonics can be divided into characteristic and non-characteristic harmonics [13][14]. The orders of the characteristic harmonics can be determined by the pulse number which DC harmonic voltage in the order of \( h = 6n \) while AC harmonic current exists in the order of \( h = 6n + 1 \), where \( n \) is an integer [15][16].

2.1. AC Current Harmonics

For AC current harmonic, the current waveform for star-star connected converter transformer is shown in Figure 1.

![Figure 1. Current waveform for star-star connected converter transformer.](image)

As the absence of commutation reactance, the current waveform for star-star connected converter transformer in Figure 1 can be explained as follow:

\[
i = I_d \quad \text{for} \quad -\frac{\pi}{3} < \omega t < \frac{\pi}{3}
\]

\[
i = 0 \quad \text{for} \quad -\frac{2\pi}{3} < \omega t < -\frac{\pi}{3} \quad \text{and} \quad \frac{\pi}{3} < \omega t < \frac{2\pi}{3}
\]

\[
i = -I_d \quad \text{for} \quad -\pi < \omega t < -\frac{2\pi}{3} \quad \text{and} \quad \frac{2\pi}{3} < \omega t < \pi
\]

The Fourier series for the waveform is

\[
i = \frac{2\sqrt{3}}{\pi} I_d \left(\cos \omega t - \frac{1}{5} \cos 5\omega t + \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + \ldots\right)
\]

with harmonic orders determined from the expression

\[h = 6n \pm 1\]

The magnitude of the nth harmonic is

\[
I_n = \frac{\sqrt{6}}{\pi} I_d
\]

and that of the fundamental
\[ I_1 = \frac{\sqrt{6}}{\pi} I_d \]  

(7)

The Fourier series for the current waveform of star-delta or delta-star transformer connection in Figure 2 is described as in equation (8).

\[ i = \frac{2\sqrt{3}}{\pi} I_d (\cos\omega t + \frac{1}{5}\cos5\omega t - \frac{1}{7}\cos7\omega t + \frac{1}{11}\cos11\omega t - \ldots) \]

(8)

2.2. DC Voltage Harmonics

The order of voltage harmonics on the DC side is using a single three phase configuration of 6 pulses as a reference. The voltage crossings are derived as in equation (9) and the repetition interval is that used as a time reference.

\[ V_d = \sqrt{2}V_s \cos\left(\omega t + \frac{\pi}{6}\right) \text{ for } 0 < \omega t < \alpha \]

where, \( V_s \) is phase voltage in RMS

\[ V_d = \sqrt{2}V_s \cos\left(\omega t + \frac{\pi}{6}\right) + \frac{1}{2}\sqrt{2}V_s \sin\omega t = \frac{\sqrt{6}}{2}V_s \cos\omega t \text{ for } \alpha < \omega t < \alpha + \mu \]

(10)

\[ V_d = \sqrt{2}V_s \cos\left(\omega t - \frac{\pi}{6}\right) \text{ for } \alpha + \mu < \omega t < \frac{\pi}{3} \]

(11)

The magnitude of harmonic voltages is derived from the equation

\[ V_n = \frac{V_n}{\sqrt{2(n^2-1)}} \left[ (n-1)^2 \cos^2 \left( \frac{(n+1)\mu}{2} \right) + (n-1)^2 \cos^2 \left( \frac{(n-1)\mu}{2} \right) + 2(n-1)(n+1) \right]^{\frac{1}{2}} \]

(12)

where, \( V_n = \frac{3\sqrt{2}}{\pi} V_s \)

3. Modelling of TNB-EGAT HVDC System

The HVDC network consists of rectifier station, inverter station and DC transmission line as shown in Figure 3 [17]. The AC system 1 at rectifier station is referred from TNB side with the voltage rating of 275 kV while the AC system 2 at inverter station is referred from EGAT side with voltage rating 230 kV. The converter station at Gurun will be constructed for bidirectional 300 MW with monopolar operation [18].

Figure 3. TNB-EGAT AC-HVDC network schematic overview.
busbar (Thailand side) based on the short circuit method and the parameters are shown in Table 1. The data are obtained from Tenaga Nasional Berhad, R&D Department (TNBR).

| Parameters | TNB       | EGAT      |
|------------|-----------|-----------|
| R1         | 0.1059Ω   | 1.7765Ω   |
| R2         | 6.9925Ω   | 11.777Ω   |
| L1         | 52.25mH   | 117.99mH  |
| C1         | 50.905μF  | 22.026μF  |

The modelling of TNB-EGAT AC-HVDC link by using PSCAD software consists of 3 sub-modules: electrical system, rectifier controller and inverter controller as shown in Figure 4. The load flow parameters also been calculated using equations (1) until (13) and used as input data for the circuit construction.

![Figure 4. Overview of TNB-EGAT network in PSCAD software.](image)

### 3.1 Electrical System

The electrical system consists of the rectifier and inverter side networks that linked by DC transmission line with the smoothing reactor as shown in Figure 5. The DC passive filter group also installed on the DC lines to suppress the harmonics voltage that occur at 12th and 24th orders of harmonic.
Figure 5. Electrical system circuit in PSCAD software.

For the rectifier side, the value of reactive power, $Q_{fr}$ is 120 MVAr as the data is obtained from TNBR. So, two AC filters with 60 MVAr each and three capacitor sub-banks with 60 MVAr each are connected to 275 kV AC busbar. The two AC filters are a tuned filter to reduce harmonic order of 11th and a high pass filter to reduce the 23rd. Then, for the inverter side, three AC filters as well as three capacitor sub-banks, are connected to 230 kV AC busbar. As the value of $Q_{fi}$ is 168 MVAr, one of the AC filters is rated at 84 MVAr while the other two are 42 MVAr. Then, the three capacitor sub-banks are rated at 84 MVAr each.

3.2 Rectifier Constant Current Controller

The rectifier side current controller block diagram used in CIGRE benchmark model is applicable for TNB-EGAT HVDC interconnection network [19][20]. In the rectifier side, constant current control plays the most important role in adjusting abnormal DC current fluctuations quickly and efficiently. The parameters for the PI controller are given in Table 2.

Table 2. PI controller parameters of rectifier current controller.

| Parameter         | Value      |
|-------------------|------------|
| Proportional gain | 1.0989     |
| Integral time constant | 0.01092 sec |
| Maximum limit     | 3.054      |
| Minimum limit     | 0.52       |
| Initial output    | 1.57       |

3.3 Inverter Current and Constant Extinction Angle (CEA) Controller

The inverter current controller is coupled with VDCOL to minimize the maximum current order during the disturbance. The function is to generate an alpha order from a PI controller acting from the error between current orders and measured current. Besides, it also produces a gamma error signal, DGE which increases the required gamma in the controls of the valve group when the current is less than the current order. The parameters of the PI controllers are given in Table 3, respectively.
Table 3. PI controller parameters for inverter current controller and CEA controller.

| Parameter               | Current Controller | CEA controller |
|-------------------------|--------------------|----------------|
| Proportional gain       | 0.63               | 0.7506         |
| Integral time constant  | 0.01524 sec        | 0.0544 sec     |
| Maximum limit           | 1.92               | 1.57           |
| Minimum limit           | 0.52               | 0.52           |
| Initial output          | 1.92               | 1.57           |

4. Result and Analysis

Through the observation from the simulation in PSCAD software, it is noted that the waveforms of current and voltage are distorted due to the presence of harmonic. The harmonic level also exceeds the compatibility limit. This is because, in the first stage, the circuit is not completed with the filtering component to see the difference in magnitude current and voltage for each of the harmonic component. Then, to mitigate the harmonic, the passive filter is connected to the AC and DC side. The load flow analysis is performed for TNB and EGAT side as the input. The testing for validation is in two cases: 1) harmonic current in AC side and 2) harmonic voltage in DC side.

Case 1: Harmonic Current in AC side

In the AC side, the orders of 11th, 13th, 23rd and 25th have a high magnitude of harmonic current rather than 12th and 24th which can be assumed as zero as shown in Figure 6 and Figure 7. This is because the harmonic AC current exists at orders of $h = 6n + 1$, where $n$ is an integer. From the observation, the unfiltered circuit of both rectifier and inverter sides contains harmonic which 11th order has the highest magnitude as it exceeds more than 0.02 p.u and followed by the 13th, 23rd and 25th orders. After the filter is connected to the circuit, the harmonic level is reduced until below than 0.002 p.u, which the passive filter mitigates the harmonic by suppressing the dominant orders. The THD level also reducing from 5.30298% to 0.2336% for the rectifier side and 4.27928% to 0.0154% for the inverter side, which has satisfied the IEC 1000-3-6 standard.

![Figure 6](image-url) Figure 6. Magnitude of Harmonic Current at Rectifier Side.
Figure 7. Magnitude of Harmonic Current at Inverter Side.

Case 2: Harmonic Voltage in DC side

The simulation results for the DC side voltage are presented in Figure 8 and Figure 9 which can be stated that 11th, 13th, 23rd and 25th components value does not exist since the DC harmonics voltage exist in the order of $h = 6n$. For the unfiltered circuit, the component of 12th contains the highest level of harmonic ad followed by 24th order. After the filtering component has connected to the system, the passive filter tuned the harmonics until the magnitude reduced under 9 p.u. The THD value also decreasing and satisfied the IEC 1000-3-6 standard.

Figure 8. Magnitude of Harmonic Voltage at Rectifier Side.

Figure 9. Magnitude of Harmonic Voltage at Inverter Side.
5. Conclusions
The mitigation of harmonic in TNB-EGAT link using passive filter has been successful in this research. The results from the experiment are compared in graphs between the circuit without and with passive filters for the AC side and DC side. From the finding discussed, by connecting the filters in the system, the line voltage and current waveforms can maintain in sinusoidal. Besides, the mitigation method using passive filters have improved the HVDC system as the THD of current and voltage harmonics have reduced until below 3% that satisfied with IEC 1000-3-6 standard. As this project only covered on the steady state operating, passive filter suitable to eliminate the current and voltage harmonics in HVDC link from the effects of harmonic.

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