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Scientific Research

New Concept for Calculating DC Harmonic Voltages and Currents in BTB HVDC Converters

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Abstract

This paper deals with a new concept for calculating DC harmonic voltages and currents of line-commutated HVDC systems. In contrast to the conventional method, this method is useful for BTB (Back-To-Back) HVDC systems without smoothing reactors or PTP (Point-To-Point) with very short transmission line. This method proposes a new direction for HVDC system design and analysis. The proposed method is applied to a 50 Hz/60 Hz BTB test system and a synchronized BTB test system. After simulation and verification, the new results are introduced.

Keywords

HVDC, BTB (Back-To-Back), PTP (Point-To-Point)

1. Introduction

This conventional line-commutated HVDC converter with cable or overhead lines acts in the AC side as current sources for characteristic currents independently. That is, an inverter is considered as only an ideal current source or voltage source in the viewpoint of a rectifier and inverter is on the contrary. So, in the cases of the harmonic calculation on the DC side and the design of smoothing reactors, considering the other side is meaningless. However, with respect to HVDC without a transmission line (cable or overhead line) such as a BTB system, because the rectifier and inverter in a BTB HVDC system are strongly coupled each other, the influence of the second converter cannot be disregarded. This paper proposes extended HVDC equations considering the coupling effects between rectifiers and inverters. The proposed methods are more suitable than a separated current source model in case of the harmonic current/voltage and minimum DC current calculations.

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1.1. Fundamental Equations of DC Harmonic Voltage

The definition of currents and voltages used for the calculation are shown in **Figure 1**. In this case, the characteristic 12-pulse DC harmonics voltages for an HVDC converter station will be calculated. The magnitude will be calculated according to the following equations [1]:

$$V_{d1h} = V_{d10}\sqrt{A_1^2 + B_1^2 - 2A_1B_1\cos(2\alpha_1 + \mu_1)} \tag{1}$$

$$V_{d2h} = V_{d20}\sqrt{A_2^2 + B_2^2 - 2A_2B_2\cos(2\alpha_2 + \mu_2)} \tag{2}$$

where,

V_{d1h}, V_{d2h} = DC harmonic voltages of rectifier and inverter in harmonic order (h),

V_{d10}, V_{d20} = No-load dc voltages of rectifier and inverter.

$$A_1 = \cos\left[(h-1)\cdot\mu_1/2\right]/(h-1),\ \ B_1 = \cos\left[(h+1)\cdot\mu_1/2\right]/(h+1)$$

$$A_2 = \cos\left[(h-1)\cdot\mu_2/2\right]/(h-1),\ \ B_2 = \cos\left[(h+1)\cdot\mu_2/2\right]/(h+1)$$

α_1, α_2 = firing angles of rectifier/inverter, μ_1, μ_2 = overlap angles of rectifier/inverter,

h = 12, 24, 36, 48 ··· etc. (12-pulse, integer).

The resulting harmonic voltages in the DC circuit will be calculated according to the following equation [2].

$$V_{dh} = |V_{d1h}| + |V_{d2h}|\cdot\exp(-j\varphi_0) \tag{3}$$

$$V_{dh} = |V_{d1h}| + |V_{d2h}| \quad \text{if } \varphi_0 = 0^\circ$$

$$V_{dh} = \sqrt{|V_{d1h}|^2 + |V_{d2h}|^2} \quad \text{if } \varphi_0 = \pm 90^\circ$$

$$V_{dh} = |V_{d1h}| + |V_{d2h}| \quad \text{if } \varphi_0 = \pm 180^\circ$$

The resulting source voltage comprising both rectifier and inverter harmonics depends on the phase angle φ_0 between both AC systems. In general, this value is based on both system configurations and load flow conditions and will therefore not be a constant value. As an average usually a value of φ_0 = 90˚ will be assumed for system and design studies.

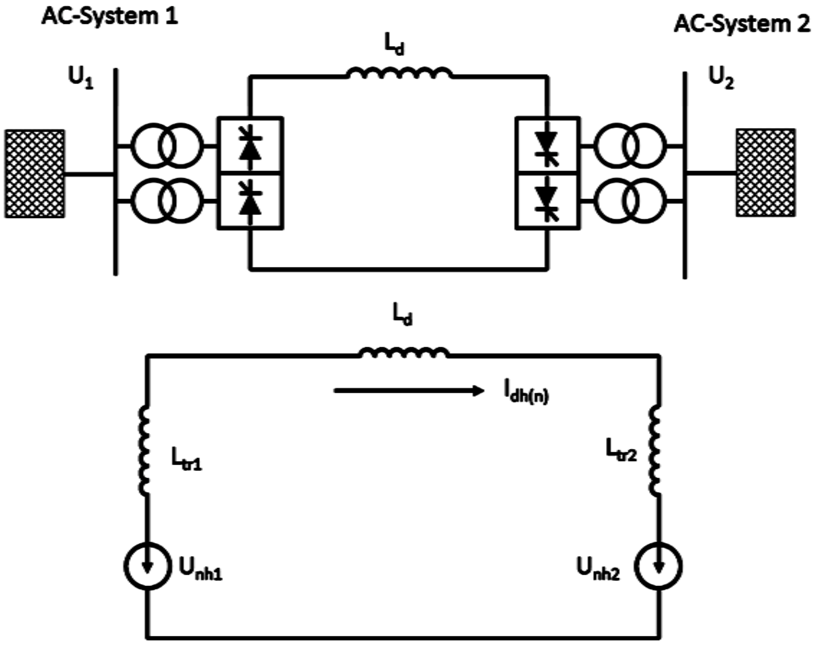


Figure 1. Circuit for calculation of 12th harmonic DC Voltage and Current.

1.2. Modeling the DC Current Ripple for the Calculation of DC Harmonics

The DC current consists of two parts as indicated in **Figure 2** and in Equation (4).

$$Id_{\text{total}} = Id_{\text{ripple}} + Id_{\text{offset}} \tag{4}$$

where Id_{total} = mean value of the DC current obtained assuming hypothetical infinite inductance on the DC side of the circuit, Id_{ripple} = mean value of the DC ripple, Id_{offset} = part of the Id current not related to the DC current ripple.

The existence of DC current discontinuities depends on the operating conditions, converter configurations, and system frequencies. Normally, Id_{total} at minimum power is selected to give a positive value of Id_{offset}.

The classical expression for calculating the maximum Id_{ripple} due to the influence of a single 12-pulse converter is found in [3].

$$Id_{\min} > Id_{\text{ripple}} = \frac{3}{\pi} \cdot \frac{E_{LL\max pk}}{\omega} \cdot L_{T\min} \cdot \left(0.023 \cdot \sin\alpha_{\max}\right) \quad \left(\text{Rectifier or Inverter}\right) \tag{5}$$

where, $\alpha \le \omega t \le \alpha + 30^\circ$: interval where the expression is defined, Id_{ripple}: maximum operating DC current ripple, $E_{LL\max pk}$: maximum valve winding voltage, peak, 6-pulse converter, $L_{T\min} = 4 \cdot \left(L_{cr} + L_{ci}\right)$: minimum value of the total inductance of the DC circuit, L_{cr} and L_{ci}: 6-pulse commutating reactances of the rectifier and inverter, respectively.

The expression above is calculated by assuming no overlap. For this particular analysis, where Id is at its minimum level, the overlap is normally very small and the approximation is quite acceptable. Since for BTB converters the influence of the second converter cannot be disregarded, Equation (5) can be extended to:

$$\begin{aligned} Id_{\min} &> \frac{3 \times 2}{\pi} \cdot 0.023 \cdot \left[A + B\right] \\ A &= \frac{2 \cdot E_{LLr\max pk}}{\omega_r \cdot L_{T\min}} \cdot \left(\sin\alpha_r\right) \\ B &= \frac{2 \cdot E_{LLr\max pk}}{\omega_r \cdot L_{T\min}} \cdot \left(\sin\alpha_i\right) \end{aligned} \tag{6}$$

where, α_r = Firing angle of the rectifier, α_i = Firing angle of the inverter.

On the inverter side, α_i is defined as:

$$\alpha_i = \pi - \left(\mu_i + \gamma_i\right) \tag{7}$$

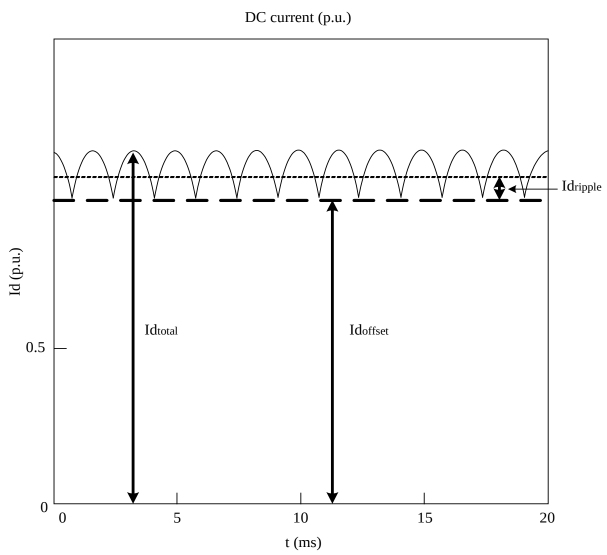


Figure 2. Id_{total}, Id_{ripple}, Id_{offset}.

where, μ_i = Overlap angle of the inverter, γ_i = Gamma angle of the inverter.

Since the overlap angle is assumed to be zero, $\sin(\alpha_i) = \sin(\pi - \gamma_i) = \sin(\gamma_i)$, and Equation (6) can be rewritten as:

$$
\begin{aligned}
&Id_{\min}(\text{both converter}) > \frac{3\times 2}{\pi}\cdot 0.023\cdot[A+B] \\
&A = \frac{2\cdot E_{LLr\max pk}}{\omega_r\cdot L_{T\min}}\cdot(\sin\alpha r) \\
&B = \frac{2\cdot E_{LLr\max pk}}{\omega_r\cdot L_{T\min}}\cdot(\sin\gamma i)
\end{aligned}
\tag{8}
$$

The equations presented until now describe the mean value of the DC current, but are not sufficient to explain the nature of the current ripple in HVDC schemes in the time and frequency domains. The time domain contribution due to a single 6-pulse converter is calculated in [3]. For BTB 12-pulse converters, the ripple can be split into two contributions: one due to the rectifier and the other due to the inverter. Each individual contribution can be expressed in the range $\alpha \le \omega t \le \alpha + 30^\circ$ using the following expressions for the rectifier and inverter, respectively:

$$
\begin{aligned}
&idr(t) = \pi\cdot\left(\frac{3}{\pi}\cdot E_{LLr}\cdot\frac{1}{L_T}\right)\cdot\frac{\frac{\pi}{6}\cdot[A-B]}{\omega r} \\
&A = 4\cdot\cos\left(\frac{\pi}{12}\right)\cdot\sin\left(t\cdot\omega_r - \frac{\pi}{12}\right) \\
&B = 4\cdot\cos\left(\frac{\pi}{12}\right)\cdot\sin\left(\alpha r - \frac{\pi}{12}\right)
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
&idi(t) = \pi\cdot\left(\frac{3}{\pi}\cdot E_{LLi}\cdot\frac{1}{L_T}\right)\cdot\frac{\frac{\pi}{6}\cdot[A-B]}{\omega i} \\
&A = 4\cdot\cos\left(\frac{\pi}{12}\right)\cdot\sin\left(t\cdot\omega_i - \frac{\pi}{12}\right) \\
&B = 4\cdot\cos\left(\frac{\pi}{12}\right)\cdot\sin\left(\gamma i - \frac{\pi}{12}\right)
\end{aligned}
\tag{10}
$$

Equation (9) and Equation (10) represent the individual contributions to $id_{\text{ripple}}(t)$ considering a single pulse from each converter side. Switching functions are required to completely describe $id_{\text{ripple}}(t)$ for any time period.

2. Simulation and Verification

2.1. 50 Hz/60 Hz BTB System without Smoothing Reactor

Before starting, we assume the following: firstly, for this analysis the AC system voltage assumed at the commutation busbar is the positive sequence fundamental frequency voltage. This is a reasonable assumption for the dominant harmonics since the harmonic filter design will ensure that the harmonic content at the commutation busbar is minimal.

Secondly, assuming that $\alpha + \mu$ is limited to 45˚ during steady-state operation, the equations above also represent a good approximation of the maximum harmonic ripple along the full power range. This is based on the well-known behavior of the DC side ideal harmonic voltage source that varies as a function of the firing angle and overlap as indicated in [3].

As shown in **Figure 3**, the 12th harmonic of the ideal voltage DC source is calculated as a function of the overlap variation considering different alpha values. From **Figure 3**, the maximum harmonic occurs for the case with minimum overlap and maximum firing angle.

Figure 4 shows an example of the $id_{\text{ripple}}(t)$ and related DC quantities based on the time domain switching

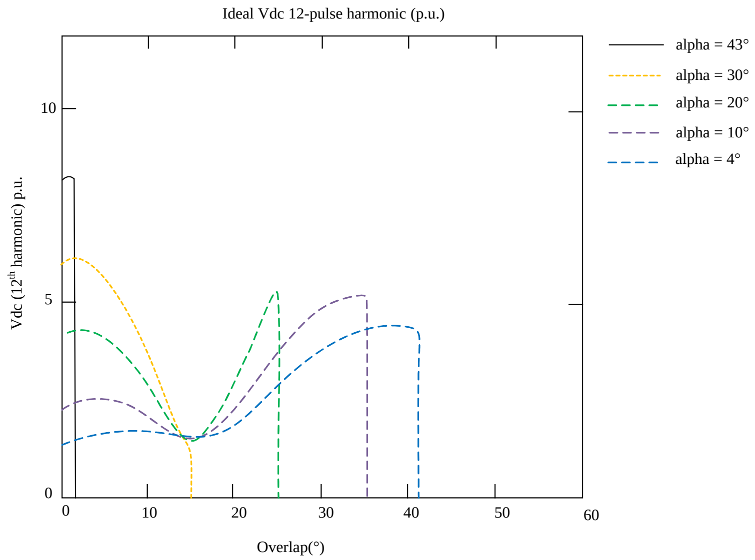


Figure 3. 12th harmonic DC voltage.

functions. This example is for a BTB system connecting a 50 Hz system to a 60 Hz system. The plots in shown in **Figure 4** are not to scale and are presented for facilitating the understanding of the relationship between different electrical quantities. **Figure 4** presents a diagram where the electrical quantities of **Figure 5** are identified in the circuit.

For calculating *idr*(*t*) and *idi*(*t*) in **Figure 5**, the DC total resistance, R_{HV}, is assumed zero. *idr*(*t*) and *idi*(*t*) are defined in Equation (9) and Equation (10), respectively, and *vt*(*t*) is defined in Equation (11). This test example assumes that the rectifier is at 50 Hz, and the inverter is at 60 Hz.

Figure 4 shows the simulation results of the proposed method. In **Figure 4**, DC voltage, A, and DC current ripple, B, show differences between the asynchronous BTB system (50 Hz/60 Hz) and synchronous BTB system (60 Hz/60 Hz).

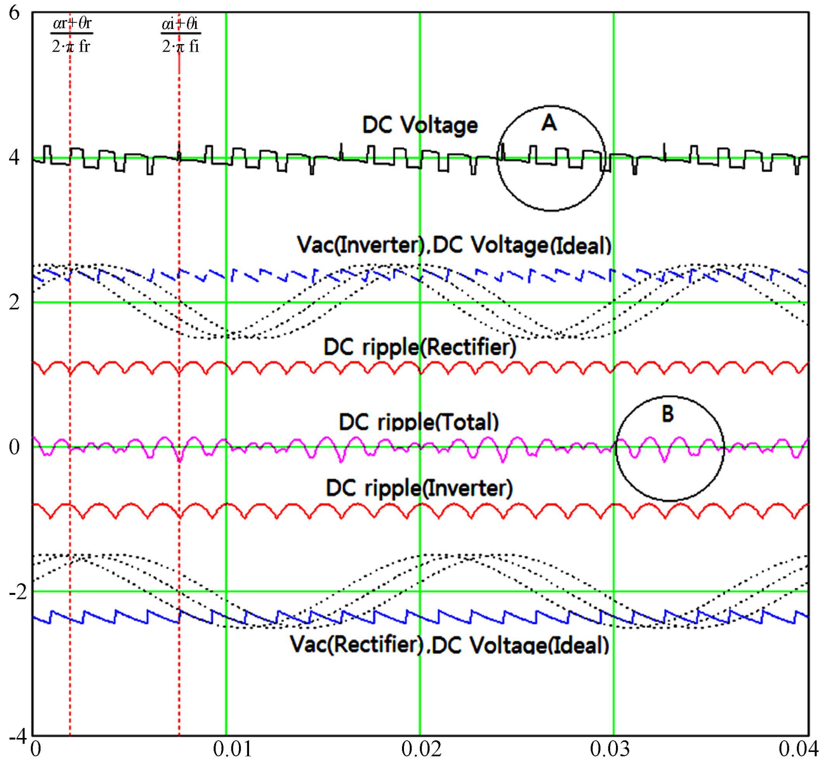
This difference originates from the fact that the rectifier and inverter in the BTB HVDC system are strongly coupled to each other. Therefore, because DC harmonics calculation and the smoothing reactor design are incorrect in the classical method [2], the coupling influences between the rectifier and inverter have to be considered to calculate more detailed results.

The DC voltage shown in **Figure 4** and **Figure 5** is calculated by the following expression.

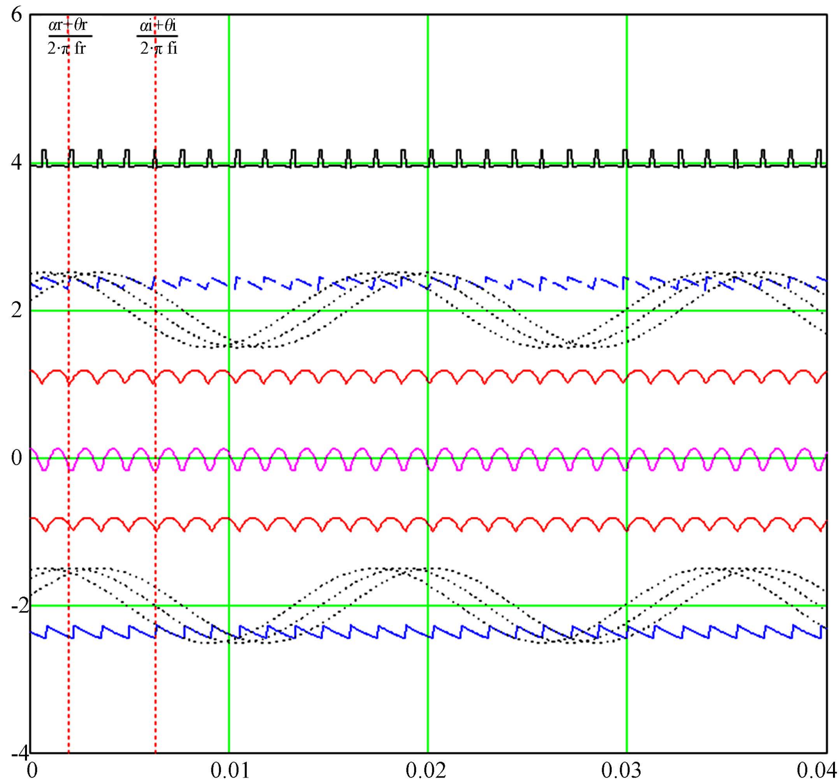
$$\begin{aligned} vt(t)_{p.g} &= vr(t)_{p.g} \cdot \frac{L_{ci}}{L_{cr}+L_{ci}} - vi(t)_{g.p} \cdot \frac{L_{cr}}{L_{cr}+L_{ci}} \\ vt(t)_{p.g} &= \frac{3\sqrt{2}}{\pi} \cdot E_{LL(\text{Rectifier})} \cdot \cos(\alpha r + \theta_r) \\ vi(t)_{g.p} &= \frac{3\sqrt{2}}{\pi} \cdot E_{LL(\text{Inverter})} \cdot \cos(\alpha i + \theta_i) \end{aligned} \tag{11}$$

where, $vr(t)_{p.g}$ = ideal 12-pulse DC voltage for the rectifier (pole to ground), $vi(t)_{g.p}$ = ideal 12-pulse DC voltage for the inverter (ground to pole), and θ_r and θ_i are the AC system phase voltage angles of the equivalent independent sources at the rectifier and the inverter, respectively.

Figure 6 shows the frequency analysis results of a typical Fast Fourier Transform (FFT) of DC current ripple, $id_{\text{ripple}}(t)$, for the 50 Hz/60 Hz case shown in **Figure 4(a)**. In **Figure 6**, the contribution from the 50 Hz side has frequencies at 600 Hz (12th) and 1200 Hz (24th), and the contribution from the 60 Hz side has frequencies at 720 Hz (12th) and 1440 Hz (24th). Therefore the total DC current ripple, $id_{\text{ripple}}(t)$, which appears on the DC side as shown in **Figure 6(a)**, is overlapped by the characteristic harmonic due to the 50 Hz AC source with a characteristic harmonic due to the 60 Hz AC source. **Figure 7** shows the magnified waveform portion B in **Figure 4(a)**,



(a)



(b)

Figure 4. DC quantities related to the $id_{\text{ripple}}(t)$ calculation. (a) Waveforms in case of asynchronous interconnection (Rectifier: 50 Hz, Inverter : 60 Hz); (b) Waveforms in case of synchronous interconnection (Rectifier: 60 Hz, Inverter : 60 Hz).

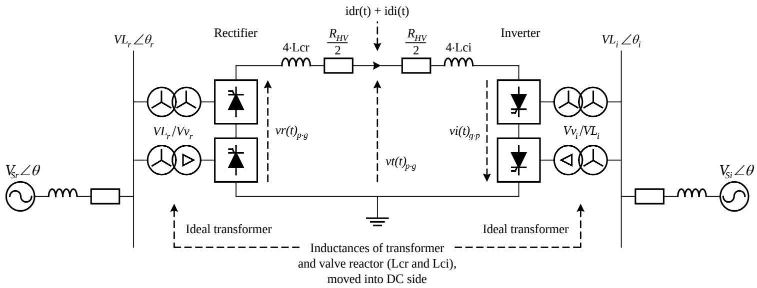
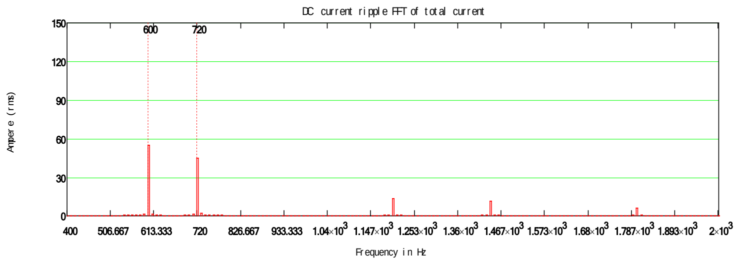
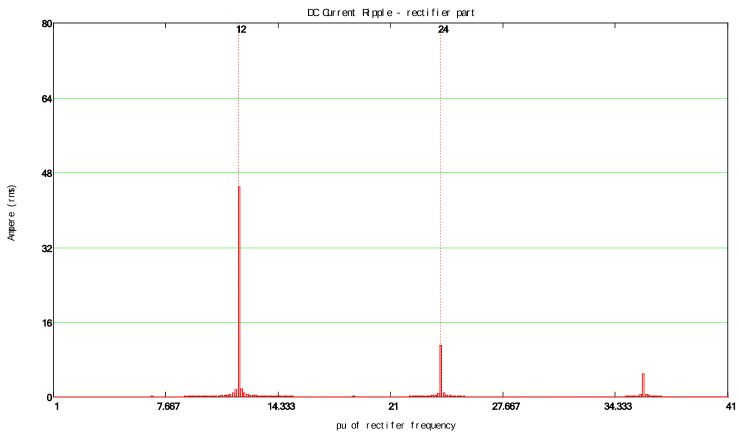


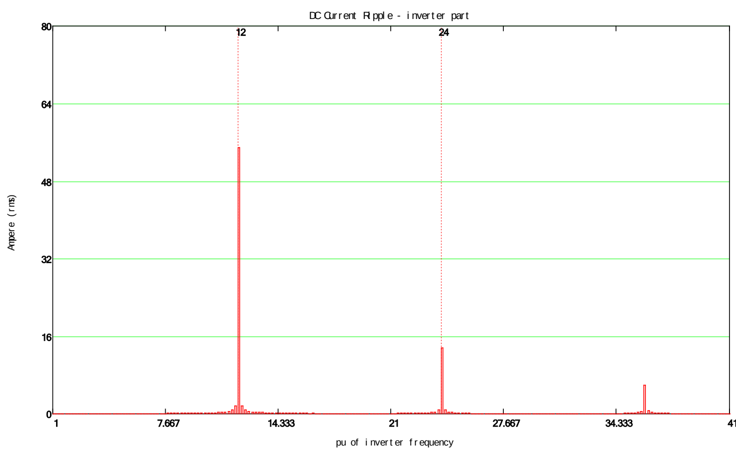
Figure 5. DC circuit related to the electrical quantities of **Figure 3**.



(a)



(b)



(c)

Figure 6. Typical frequency spectrum for $id_{\text{ripple}}(t)$. (a) Total DC current ripple; (b) DC current ripple on Rectifier side; (c) DC current ripple on Inverter side.

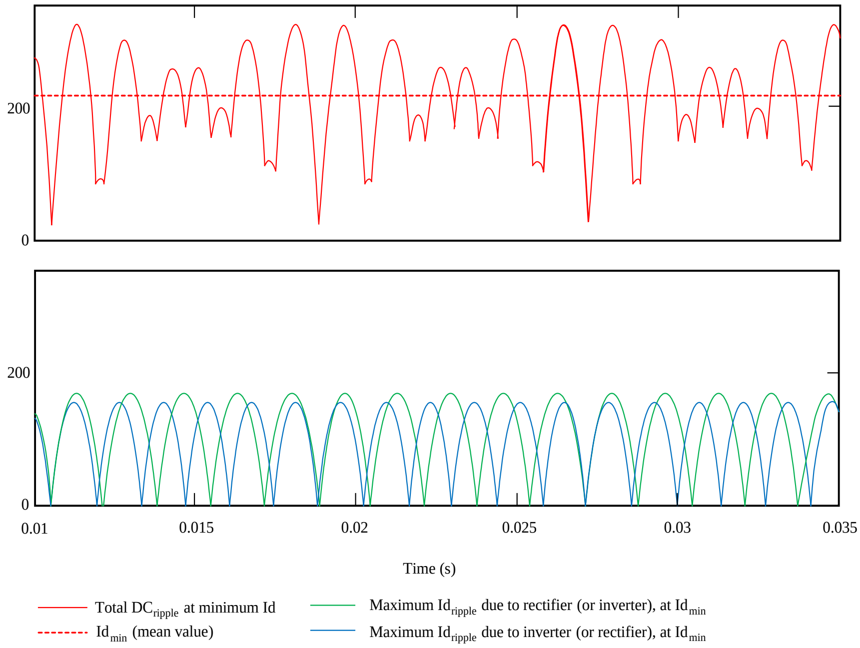


Figure 7. Typical $id_{\text{ripple}}(t)$ waveshape for 50/60 Hz systems.

and the overlapped waveforms are shown as mentioned.

In a BTB HVDC system, except for the overlap effect of frequencies, the difference between the AC system phase voltage angles, $(\theta_r - \theta_i)$, can impact themaximum and minimum amplitudes of $id_{\text{ripple}}(t)$. The $(\theta_r - \theta_i)$ values that will generate the extreme values of $id_{\text{ripple}}(t)$ are not so easy to predict, because the AC voltage angle is always varied according to AC load conditions.

From Equation (11), for converters with identical frequencies (synchronous connection, 60 Hz/60 Hz BTB), the AC voltage system angles will impact the harmonics on $id_{\text{ripple}}(t)$ as follows:

-For $(\theta_r - \theta_i) = 0$, if we assume perfect symmetry between the two sides, the harmonic spectra generated by the rectifier and inverter will have the same phase angle and will add in phase.

-For $(\theta_r - \theta_i) = 7.5^\circ$, if we assume perfect symmetry between the two sides, the harmonic spectrum generated by the rectifier will be phase shifted by 7.5˚. For the 24th harmonic current, the period is 360˚/24 = 15˚. So if the rectifier and inverter contributions are phase shifted by 7.5˚ at the 24th harmonic, they will cancel out when added.

For $(\theta_r - \theta_i) = 15^\circ$, if we assume perfect symmetry between the two sides, the harmonic spectrum generated by the rectifier will be phase shifted by 15˚. For the 12th harmonic current, the period is 360˚/12 = 30˚. So if the rectifier and inverter contributions are phase shifted by 15˚ at the 12th harmonic, they will cancel out when added.

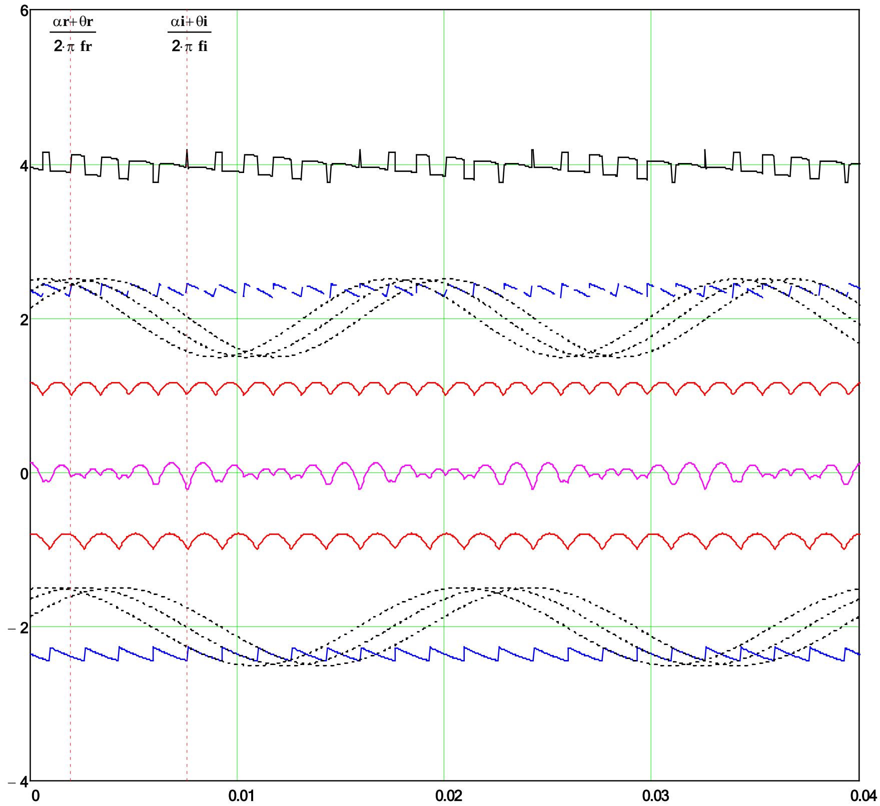
2.2. BTB System with Each Different Smoothing Reactor

Similar to **Figure 4**, **Figure 8** shows the waveforms of the DC side in case of asynchronous interconnection between the rectifier at 60 Hz and the inverter at 50 Hz. However, this case is with different smoothing reactors on the rectifier side and inverter side. Firstly, as **Figure 8** shows, the reductions in DC harmonic currents are worthy of close attention.

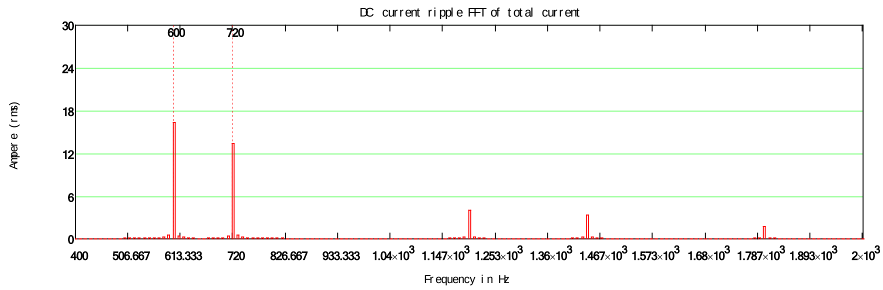
From these results, we can verify that the optimal smoothing reactor to reduce the DC harmonic current can be calculated considering the different frequency conditions and the difference in angles, $(\theta_r - \theta_i)$.

Also, in **Figure 8**, an impressive fact is found that the characteristic harmonic magnitude (600 Hz, 12th) of the 50 Hz frequency side is always greater than that of the 60 Hz frequency side. That is, the characteristic harmonic of the lower AC frequency side is always greater whether the lower frequency side has a rectifier or not, and is not related to the values of the smoothing reactor.

Figure 9 shows the simulated comparisons between the asynchronous interconnection (50 Hz/60 Hz) and the



(a)



(b)

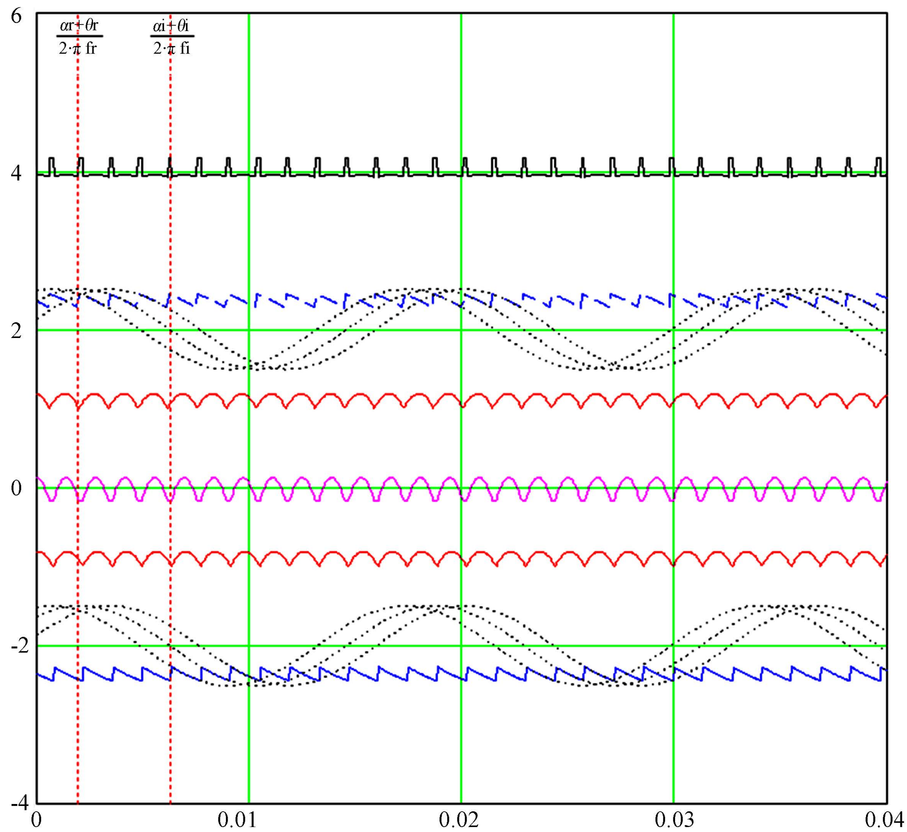
Figure 8. Asynchronous interconnection (Rectifier: 50 Hz, Inverter: 60 Hz). (a) DC quantities related to the $id_{\text{ripple}}(t)$; (b) Typical frequency spectrum for $id_{\text{ripple}}(t)$.

synchronous interconnection (60 Hz).

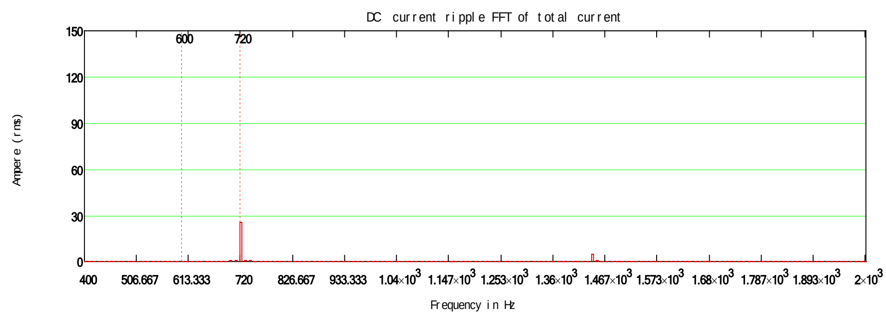
3. Conclusion

Because the rectifier and inverter in a BTB HVDC system are strongly coupled to each other, a new coupled analysis model is needed. The conclusions of analysis by the method proposed in this paper are as follows.

- The total DC current ripple, $id_{\text{ripple}}(t)$, which appeared on the DC side, overlapped the characteristic harmonic due to the 50 Hz AC source with the characteristic harmonic due to the 60 Hz AC source.
- The characteristic harmonic of the lower AC frequency side is always greater whether the lower frequency side is a rectifier or not, and is not related to the values of the smoothing reactor.
- For $(\theta_r - \theta_i) = 0$, $id_{\text{ripple}}(t)$ is maximum.
- For $(\theta_r - \theta_i) = 7.5^\circ$, the 24th harmonic will be minimal or zero.
- For $(\theta_r - \theta_i) = 15^\circ$, the 12th harmonic will be minimal or zero.



(a)



(b)

Figure 9. Synchronous interconnection (Rectifier: 60 Hz, Inverter: 60 Hz); (a) DC quantities related to the $id_{\text{ripple}}(t)$; (b) Typical frequency spectrum for $id_{\text{ripple}}(t)$.

Acknowledgements

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