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Analysis of Commutation Failure in LCC-HVDC System During Unbalanced Conditions Using Sequence Components

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Introduction

Commutation Failure (CF) in LCC-HVDC is the phenomenon that the valve which is supposed to turn off continues to conduct without transferring it's current to the next valve in the firing sequence. The occurrence of CF in the system can trigger serious transient events that might jeopardize the stability of the system. Commutation failure is caused by voltage drop, phase shift and DC rise, the previous works has focused more on analyzing and preventing commutation failure caused by voltage drop and DC rise, therefore, we will analyze CF considering phase shift and try to implement some prevention mechanism, using sequence components.

Mathematical Model

A. Commutating Voltages

For more accurate representation for the system during unbalanced conditions, the system can be represented using sequence components. When unbalanced faults occur on the system, there is two types of phase shift that might take place, phase shift due to voltage drop and the phase shift a combined with fault. The term of total phase shift can be used to describe the combination of those two types. Since the negative sequence component is related to the degree of unbalance on the system, the ratio of the negative sequence to the positive sequence components can be used to describe the degree of unbalance on the system. The line to line commutation voltages between thyristor 1 & 3 can be described as:

$$\left.\begin{aligned} V_{ba} &= \sqrt{3}V_p K_{ba}\sin(\omega t+\delta_{ba}^{'}) \\ K_{ba} &= \sqrt{1+r^2+2r\cos\theta_{ba}},\quad \theta_{ba}=\varphi-\pi/3 \\ \delta_{ba}^{'} &= \arctan\left(\frac{\sin(\varphi_p)+r\sin(\varphi_n-\pi/3)}{\cos(\varphi_p)+r\cos(\varphi_n-\pi/3)}\right) \end{aligned}\right\} \qquad (1)$$

$$r = V_n / V_p,\quad \varphi = \varphi_n - \varphi_p$$

Where r represents the unbalance degree on the system and φ represents the amount of phase angle sequence difference between negative and positive sequence components.

The unbalance ratio is the ratio between the negative and the positive sequence components and it represent the amount of the negative sequence component exist in the system, it reflects to what degree the system is unbalanced. It can be used quantitively to indicate the occurrence of CF in the inverter, without consideration of which valves will experience CF. The valve which will experience CF can be identified using commutation voltage sequence angle.

B. Phase Shift

When the system is unbalanced, the zero-crossing point of the line voltages will change with respect to the sequence component. Therefore, the phase shift can be obtained accurately by finding the difference between the reference angle as:

$$\phi = \delta_{ba} - \delta_{ba}^{'} \qquad (2)$$

$\delta_{ba}, \delta_{ba}^{'}$ represents the crossing between phase a and b during normal and abnormal conditions respectively.

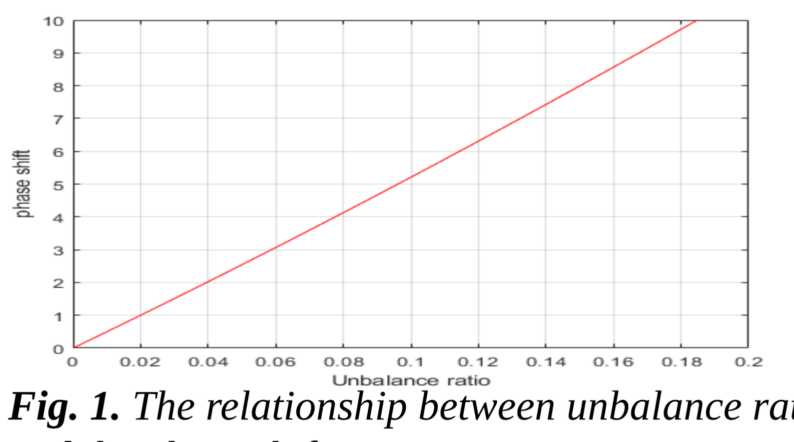

Fig. 1. The relationship between unbalance ratio and the phase shift

Commutation Voltage Time Area

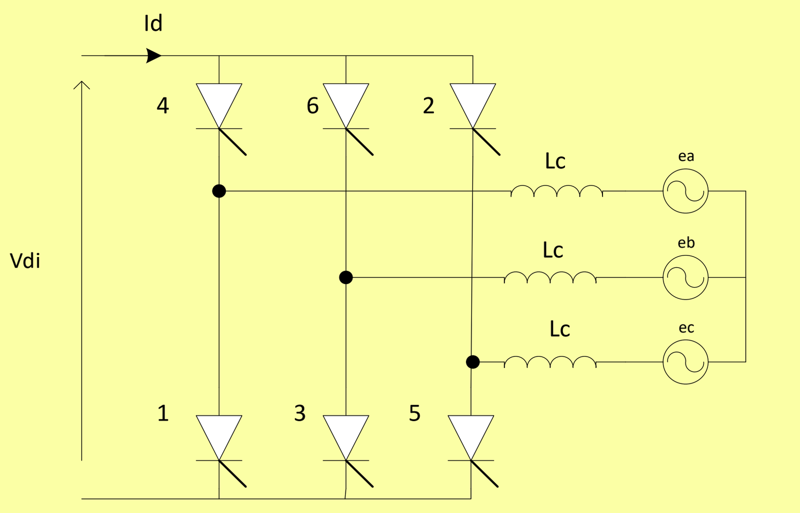

Fig. 2. The inverter terminal of LCC-HVDC

For the commutation process between valve 1 & 3, the commutation process can be described as:

$$V_{ba} = L_c\left(\frac{di_b}{dt}-\frac{di_a}{dt}\right) \qquad (3)$$

Commutation failure will take place on the system when the extinction angle is less than the minimum extinction angle. By integrating the commutation area:

$$\int_{\frac{\pi-\beta}{\omega}}^{\frac{\pi-(\gamma+\phi)}{\omega}}\frac{di_b}{dt}-\int_{\frac{\pi-\beta}{\omega}}^{\frac{\pi-(\gamma+\phi)}{\omega}}\frac{di_a}{dt}=\int_{\frac{\pi-\beta}{\omega}}^{\frac{\pi-(\gamma+\phi)}{\omega}}V_{ba}dt \qquad (4)$$

Which yields:

$$2X_c I_d^{'} = \sqrt{3}K_{ba}V_p\left(\cos\gamma_{\min}-\cos(\beta-\phi)\right) \qquad (5)$$

During normal operating conditions, the current can be described as:

$$I_d = \frac{\sqrt{2}E}{2X_c K_t}(\cos\gamma-\cos\beta) \qquad (6)$$

From the above two equations, the unbalance ratio can be obtained from:

$$\sqrt{1+r^2+2r\cos\theta_{ba}} = \frac{I_d^{'}}{I_d}*\frac{\cos\gamma-\cos\beta}{\cos\gamma_{\min}-\cos(\beta-\phi)} \qquad (7)$$

Results and Discussion

CIGRE benchmark model built in PSCAD/EMTDC is used to verify the validity of the proposed model. Numerous number of simulations were performed in PSCAD to find out the amount of the unbalance degree that would cause CF, for certain operating conditions, the results are compared with the proposed model. Then the probability of commutation failure with unbalance ratio is obtained for different types of faults.

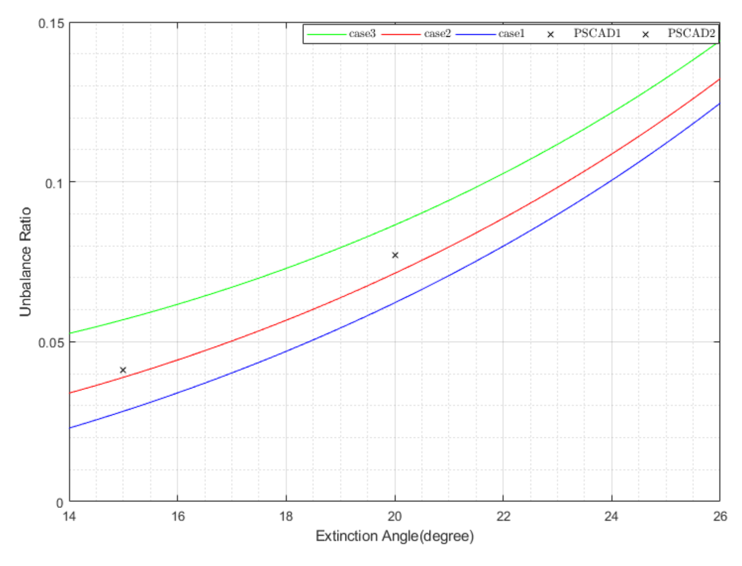

Fig. 3. The amount of unbalance ratio that will take place at any specified extinction angle for SLGF

Figure 3 shows the curves of a single-phase fault applied on the benchmark model. The theoretical curves are obtained from the numerical solution of unbalance ratio equation (7). The curves describe the amount of unbalance degree that will take place at any specified extinction angle. On the figure several cases are considered, case 1 is with no phase shift associated with the fault, case 2 is with a phase shift of 2°, case 3 is with phase shift of 5°. The cross points shown on the above figure represents the amount of unbalance degree that will result in CF at specified extinction angle.

Different values for the phase shift are assumed to test the contribution of the phase shift on the unbalance that took place on the system.

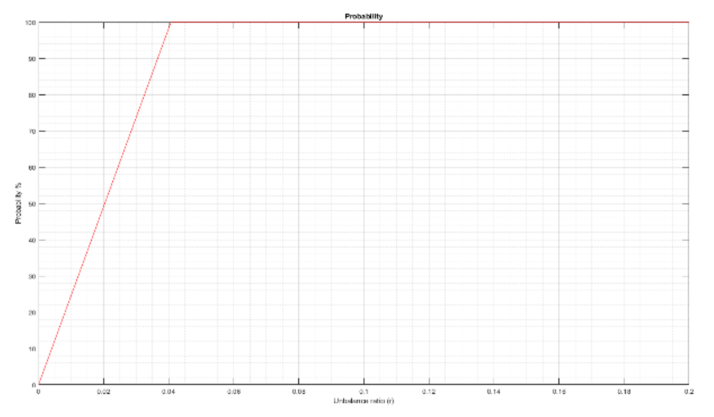

Fig. 4. The probability of CF due to unbalance ratio in case of SLGF

Figure (4) shows the probability curve for the occurrence of CF due to phase shift, represented with respect to the unbalance ratio. The steady increase of the curve shows the higher the unbalance ratio, the higher the probability that CF will take place. If the value of the unbalance ratio exceeds this value that means CF will take place in the system.

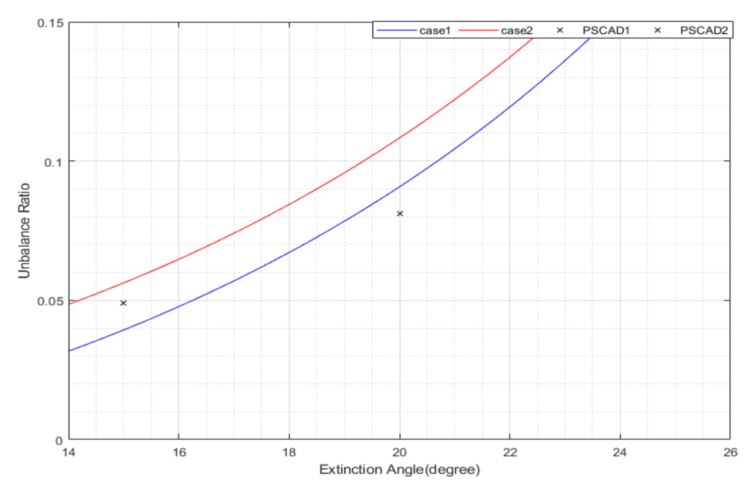

Fig. 5. The amount of unbalance ratio that will take place at any specified extinction angle in case of DLF.

Figure 5 shows the curves of a DLF applied on the benchmark model on the inverter side. The theoretical curves are obtained from the numerical solution of equation (7) of unbalance ratio. The curves describe the amount of unbalance degree that will take place at any specified extinction angle. Two cases are considered, case 1 is with no phase shift considered and case 2 is with 2° phase shift.

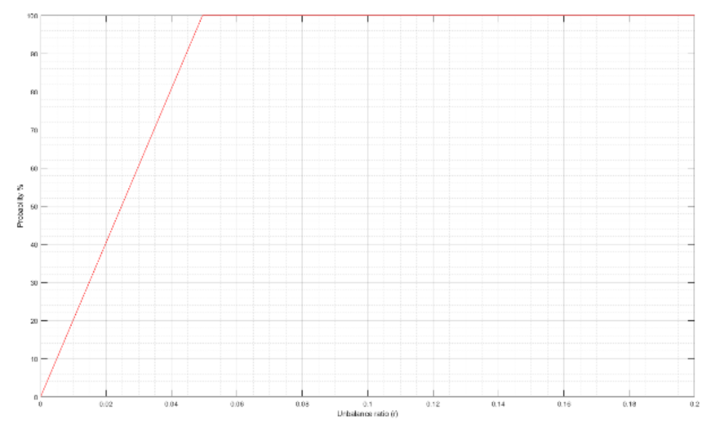

Fig. 6. Probability of CF due to unbalance ratio in case of DLF

Figure 6 shows the probability of CF with respect to unbalance ratio, it's obvious that the amount of unbalance degree required to produce onset of CF is less than SLGF. That can be justified by the amount of voltage drop that take place in each case, since the voltage drop is more significant in case of LLF that means the critical unbalance ratio is less than the case of SLGF.

Conclusion

The relationship between CF and total phase shift is analyzed, based on sequence components, by considering different types of unbalance faults that exist in the system. It's found that the larger the phase shift accompanied with the fault, the more probable CF would take place. The effect of this phase shift is quantified using sequence components.

In addition, a new mathematical model is proposed to identify CF in case of unbalanced conditions, by quantifying the amount of the negative sequence component that exist in the system.

References

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