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Estimation of multi-infeed HVDC inter converter direct current interaction in close electric proximity

Bilawal Rehman [a], Atiq Ur Rehman [b,*], Waqar Ahmad Khan [c], Jan Muhammad [d], Syed Mudassir Hussain [e]

[a] *Department of Electrical Engineering Technology, National Skills University, Islamabad, Pakistan*

[b] *Department of Electrical Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan*

[c] *PENTA-H Pvt. Ltd. Lahore, Punjab, Pakistan*

[d] *Department of Computer Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan*

[e] *Department of Electronic Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan*

[*] Corresponding author: Atiq Ur Rehman, Email: atiq_marwat99@yahoo.com

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KEYWORDS

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Multi-Infeed Interaction Factor

DC-DC Interaction

Power Flow Study

ABSTRACT

This paper aims at investigating the direct current interaction between various converters of High Voltage Direct Current (HVDC) system, which lie in close electric proximity within the multi-infeed configuration. The interaction between converters in multi-infeed DC system are highly possible events which need to be evaluated in order to avoid the adverse operational results. The various indices such as multi-infeed interaction factor (MIIF) considering AC busbar voltages, local and concurrent commutation failures (CF) in converter stations under different AC disturbances, influence of AC system's strength on fault recovery time (FRT), transient over-voltage (TOV) under permanent DC faults, voltage and power stability of multi-infeed DC system are comprehensively illustrated in literatures. However, there is lack of literature regarding the investigation of current interaction in multi-infeed DC system. Therefore, in this paper, a power flow approach is adopted to estimate the inter converter direct current interaction. An index, multi-infeed current interaction factor (MICIF) is proposed that can effectively depicts the interaction between converters. The MICIF index is verified through electromagnetic transient simulations of dual infeed HVDC system developed in PSCAD/EMTDC. The results show that MICIF index can accurately assess the interaction between different converter stations of HVDC system under steady and transient states.

1. Introduction

Multi-Infeed HVDC system has become allure topic of research since the HVDC links are observed in close electric proximity, especially the industrial remote area where the demand of power is increasing than the capacity of single HVDC link. Such situations have made numerous HVDC links to lie in close proximity of each other's AC network or even on the same AC busbar [1]–[6]. The operation and challenges (such as voltage and power instability and their allied problems) of single infeed HVDC system with low short circuit ratio (SCR) are briefly discussed in [7]–[9]. The multi-infeed steady state and transient phenomena have also been reported since first concept of HVDC links in close proximity [10]–[12]. Since then, a vast research has been conducted to analyze the behavior of multi-infeed HVDC system as described in the CIGRE report [13]. The performance of HVDC system is mainly influenced by the system's strength of AC network. Strong AC network has proven to be less problematic than weak and experience less voltage fluctuations during various fault conditions. The inter converter voltage interaction in multi-infeed HVDC system disturbs the quality of operation and consequently reduces the maximum achievable power, prolongs fault recovery time, increases the cascaded commutation failure and causes the stability issues. If the dynamic behavior between converters is properly analyzed, then various strategies can be developed to mitigate the malfunctions. In [1] and [3], the voltage stability factor (VSF) and maximum available power (MAP) of single infeed system are extended to quantify the voltage and power stability of multi-infeed HVDC systems.

The multi-infeed interaction factor (MIIF) is proposed in order to estimate the degree of voltage interaction between converters of multi-infeed DC system [13]. The MIIF_{21} can be calculated by simply taking the ratio of voltage drop at bus 2 (linked to converter 2) to bus 1 (linked to converter 1) in response of fault causing 1% voltage drop at bus1. MIIF varies between 0 to 1 indicating the strength of closeness and it is suggested that MIIF less than 0.15 can be ignored to assume the two DC systems operating as single infeed.

In [14] and [15], the multi-infeed commutation failure (CF) analysis is given describing the inter converter interaction which leads to the local and concurrent CF in converter stations. The analysis explains that local CF depends on the local Effective Short Circuit Ratio (ESCR), while concurrent CF largely depends on MIIF. As the ESCR increases, immunity to local CF increases and as MIIF approaches to zero, the chance of concurrent CF reduces to zero.

The AC-DC interaction and associated problems are dependent on system's strength of AC network allied to the DC link. The lower AC system's strength causes high transient over voltage (TOV) in converter station under permanent DC faults. During contingency, when converter stops absorbing reactive power then the excessive reactive power by shunt capacitors and AC filters results in high TOV. Usually, a 30% overvoltage in HVDC system is considered as very high and protection equipment is recommended to prevent insulation damage and to protect thyristors at converter bus. Studies have shown that ESCR index can accurately assess the steady state and transient phenomena such as MAP, harmonics interaction and TOV of single infeed HVDC system.

But for multi-infeed systems, an index termed as Multi-Infeed Effective Short Circuit Ratio (MIESCR) is suggested in [2][16]. This novel index for multi-infeed system incorporates the influence of nearby converter *j* in the strength of converter *i* and provides similar information about system as ESCR for single infeed. In [17] and [18], the apparent increase in short circuit ratio (AISCR) is proposed for hybrid dual infeed consisting of LCC and VSC converters. The hybrid scheme increases MAP, reduces CF and TOV.

Many achievements have been done on specific phenomena of multi-infeed HVDC system. The two phenomena which have lack of literature are: i) Multi-infeed (current) interaction factor, and ii) AC multi-infeed HVDC power flow. The AC/DC multi-infeed power flow studies are similar to single infeed HVDC system with any of approach either its simultaneous or sequential [19]. But the difference is to traverse all dc systems connected to the network. During the extensively used control i.e. extinction angle control at inverter, the interaction between converters not only affects the voltage of nearby converter but it also affects the direct current. The first definition and an attempt to model the dc interaction is given in [20] but it doesn't provide any procedure or results and behavior of dc interaction with MIIF is also not explained. A brief discussion about bus voltage and direct current variation in response of fault is presented in [21]. But it doesn't reflect any mutual relation between direct current of multi-infeed HVDC system.

Thus, the main purpose of this paper is to analytically investigate the DC interaction between converters of multi-infeed HVDC system. In addition, a multi-infeed current interaction factor (MICIF) index to evaluate the direct current interaction is developed which incorporates the MIIF.

This work is organized in the following sections: Section 2 analytically develops the basic concepts to model the DC interaction. Section 3 describes DC interaction, DC interaction factor and influence of MIIF. Simulation results are given in section 4.

2. Multi-infeed HVDC System Model

2.1 Study System

The dual converter multi-infeed HVDC system is shown in Fig. 1. The topology under study will reflect more practical and accurate results because both converters are assumed to feed into the same ac busbar. The advantage of this configuration is that the system will observe significant inter-converter interaction which will lead to a future multi-infeed scenario, where the MIIF>0.4 and converters would be much close to each other. A network impedance is connected between each bus to make system stable using eigenvalue based approach [1][3]. Both converters are assumed in constant extinction angle control mode and considered as load to network by inverting signs of real and reactive power. The converter buses are taken as PQ buses while source bus is slack bus for Newton Raphson power flow studies. The converters are rated as 1000MW and 500kV each.

The real and reactive power is denoted by Pdi and Q_{di}, while I_{di} and U_{di} are the direct current and voltage of converter i respectively. The converter tap position and saturation reactance are denoted by T_i and X_{Ti}, while Q_{ci} represents the total reactive power supplied by installed filters and synchronous condensers/shunt capacitors at converter i. The γ_i and V_i are inverter extinction angle and AC bus voltage at converter bus i respectively.

The control structure at inverter's side of multi-infeed HVDC system is shown in Fig.2. The constant DC current control and constant extinction angle control mechanism can be adopted at inverter's end of multi-infeed HVDC system [18].

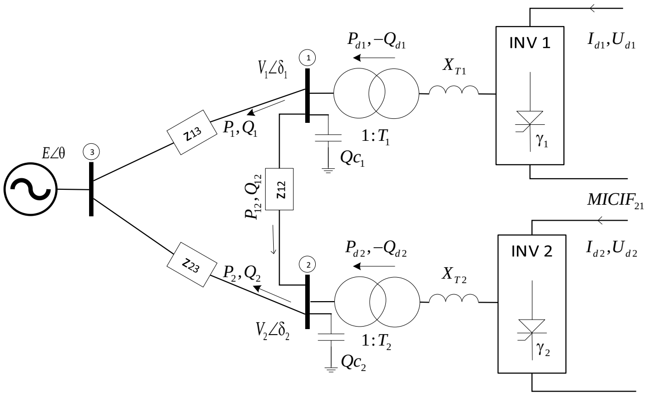

Fig. 1. Schematic diagram of multi-infeed HVDC topology

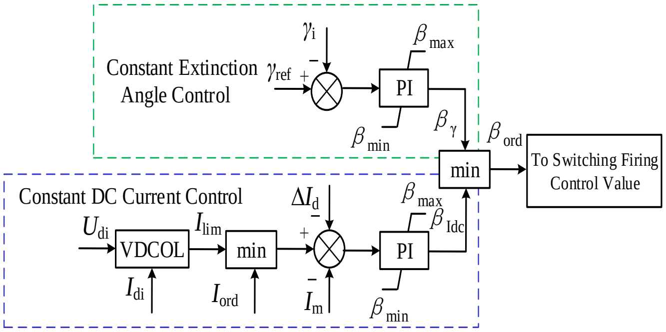

Fig. 2. Control structure at inverter's end of multi-infeed HVDC system

2.2 Power Flow Study

The power flow Jacobian matrix can be written as (1)

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_{P\delta} & J_{PV}\\ J_{Q\delta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \tag{1}$$

Where $[\Delta P\ \Delta Q]^t$ is power residual matrix determined by incremental real and reactive power and $[\Delta\delta\ \Delta V]^t$ is matrix of state variables where $\Delta\delta$ and ΔV denotes bus voltage angle and magnitude respectively. The $J_{P\delta}$, J_{PV}, $J_{Q\delta}$ and J_{QV} are elements of Jacobian matrix J which are partial derivatives of real and reactive power. Solving (1) for ΔQ gives Eq. 2 as

$$\Delta Q = J_{Q\delta}J_{P\delta}^{-1}\Delta P+\left(J_{QV}-J_{Q\delta}J_{P\delta}^{-1}J_{PV}\right)\Delta V \tag{2}$$

Let's assume that the active power variation is zero (ΔP=0) as in [20], the (1) will then result ΔQ as Eq. 3.

$$\Delta Q = J_Q\Delta V \tag{3}$$

Where the $J_Q = J_{QV} - J_{Q\delta}\, J_{P\delta}^{-1} J_{PV}$ is reduced Jacobian matrix of J.

Substituting JQ into Eq. 2, we can get Eq. 4 as

$$\Delta Q = J_{Q\delta}J_{P\delta}^{-1}\Delta P + J_Q\Delta V \tag{4}$$

The relation formed in Eq. 4 provides basic concept to investigate *V-Q* stability index by incorporating both active and reactive power contrary to [1] and [3], where the stability analysis was done by assuming the reduced Jacobian such as Eq.(3). However, the studies have shown that both active and reactive power influences the stability of multi-infeed system [22]. Thus, Eq. 4 can be used to conduct stability analysis of multi-infeed HVDC system by incorporating both active and reactive power. Another significance of Eq. 4 is that the existing reduced Jacobian based methods can also be employed for analysis. Rearranging the Eq. 4 results as

$$\Delta V = J_Q^{-1}\left(\Delta Q - J_{Q\delta}J_{P\delta}^{-1}\Delta P\right) \tag{5}$$

Introducing $\Delta Q^{net} = (\Delta Q - J_{Q\delta}J_{P\delta}^{-1}\Delta P)$,

$$\Delta V = J_Q^{-1}\Delta Q^{net} \tag{6}$$

The quantity ΔQ^{net} describes instantaneous net power injection at converter bus.

3. Proposed Multi-infeed Current Interaction Factor (MICIF)

The MIIF explains the interaction between voltages of converter AC buses in response to reactive power variation at any of ac-dc bus. A lot of work has been done to mathematical model the MIIF [23,27], but the outstanding problem is behavior of converter j direct current in response of variation in converter i direct current. The interaction of single infeed direct current with ac bus voltage is discussed in [28], where the step decreases in direct current increase ac bus voltage. This supports the theory presented in this paper. This section mathematically models the interaction between DC quantities of dual infeed HVDC system.

Eq. 5 clearly relates active and reactive power to bus voltage. Let's say the system observes no reactive power variation i.e. ΔQ=0, the Eq. 5 reduces to Eq. 7 as

$$\Delta V = -J_Q^{-1}\left(J_{Q\delta}J_{P\delta}^{-1}\Delta P\right) \tag{7}$$

If the converters are assumed lossless (i.e. $P_{ac}=P_{dc}$) and the dc voltage is considered to be constant then,

$$\Delta V_{bus} = -J_Q^{-1}\left(J_{Q\delta}J_{P\delta}^{-1}\Delta P_{dc}\right) \tag{8}$$

$$\left[\Delta V_{bus}\right] = -J_Q^{-1}\left[J_{Q\delta}J_{P\delta}^{-1}\right]\left[U_d\right]\left[\Delta I_d\right]^t$$

(9)

The Eq. 9 can also be simplified in terms of eigenvalues of reduced Jacobian matrix as Eq. 10 using modal analysis [29]. Here, the minimum eigenvalue is taken to ensure the stability limit as described in [1] and [3].

$$\left[\Delta V_{bus}\right] = -\frac{1}{\min(\lambda_{J_Q})}\left[J_{Q\delta}J_{P\delta}^{-1}\right]\left[U_d\right]\left[\Delta I_d\right]^t \tag{10}$$

The relation between converter bus voltages Vbus and Id is given by Eq. 11. Here *B*, *T* and U_{d0} are no. of bridges, transformer ratio and ideal no-load voltage of converter.

$$I_d = \frac{\pi}{3X_cB}\left(U_{d0}\cos(\gamma) - U_d\right) \tag{11}$$

Where $U_{d0} = \frac{3\sqrt{2}}{\pi}BTV_{bus}$

An index Multi-Infeed Current Interaction Factor (MICIF) is formulated as Eq. 12 which is analogous to MIIF. MICIF is the ratio of change in I_{dj} to change in I_{di} with ΔV_d=0 and ΔQ=0. Another relation of MICIF is produced in Eq. 13 heuristically by seeing the behavior of system.

$$MICIF_{ji} = \frac{\Delta I_{d_j}}{\Delta I_{d_i}} \tag{12}$$

$$MICIF_{ji} = \frac{\Delta I_{d_j}}{\Delta I_{d_i}} = \frac{\Delta V_{bus_i}}{\Delta I_{d_i}} \times MIIF_{ji} \times \frac{\Delta I_{d_j}}{\Delta V_{bus_j}} \tag{13}$$

The Eq. 13 explains inter converter flow of MICIF. Therefore, the abnormal conditions such as AC/DC side faults, commutation failure or reactive power variation at converter bus not only cause converter bus voltage to change but also yield MIIF and MICIF between converters. Like MIIF, MICIF always exists between two converters but varies from ±1 to 0. Following are steps to calculate $MICIF_{ji}$.

Procedure steps

i. Calculate I_{d_j} for $\Delta I_{d_i} = 0$
ii. $I_{d_i} \pm \Delta I_{d_i}$, $\Delta I_{d_i} \neq 0$
iii. Calculate V_{bus_i}
iv. Calculate V_{bus_j}
v. Calculate I_{d_j} for $\Delta I_{d_i} \neq 0$
vi. Calculate $\Delta I_{d_j} = I_{d_j}(\Delta I_{d_i} \neq 0) - I_{d_j}(\Delta I_{d_i} = 0)$
vii. Calculate $MICIF_{ji} = \frac{\Delta I_{d_j}}{\Delta I_{d_i}}$

There is no direct relation between I_{d1} and I_{d2} found. The only indirect way which is observed is illustrated in Fig. 3. The Eq. (9) and (10) explain that variation in Id will cause change in bus voltage and vice-versa. Suppose I_{d1} is slightly increased, the bus voltages V_1 will decrease and V_2 will also be affected due to V_1 because of $MIIF_{21}$.

The variation in bus voltages are actually caused due to active power change. As I_{d1} increases, active power of bus 1 increases ($\Delta P_1=V_{dc}\times\Delta I_{d1}$). Increase in P_1 consequently results $Q_1<Q_{1req}$ because $\Delta Q_1=0$.

Since the system is supposed to work in stable region; thus, the decrease in reactive power in fact decreases the bus voltage and vice-versa. A flow chart is shown in Fig. 4 for better understanding. The graph in Fig. 4 shows relation between various quantities. With step increase in direct current (I_{d1}), the bus voltage of converter 1 decreases due to lack of sufficient reactive power. This reduction in V_1 voltage directly influence the bus voltage of nearby converter (V_2) because of inter-converter interaction.

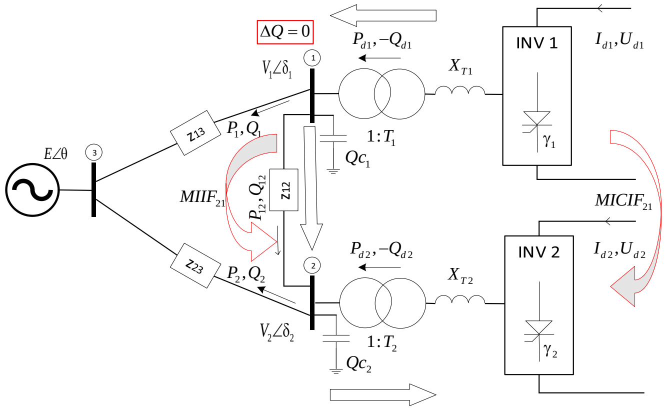

Fig. 3. Flow process of MICIF

The reduction in V_2 cuts the direct current (I_{d2}) as per Eq. 11. So, this I_{d2} indirectly relates to direct current Id1 as explained in Fig. 6 where the increase in I_{d1} reduces the I_{d2} of nearby converter in proximity.

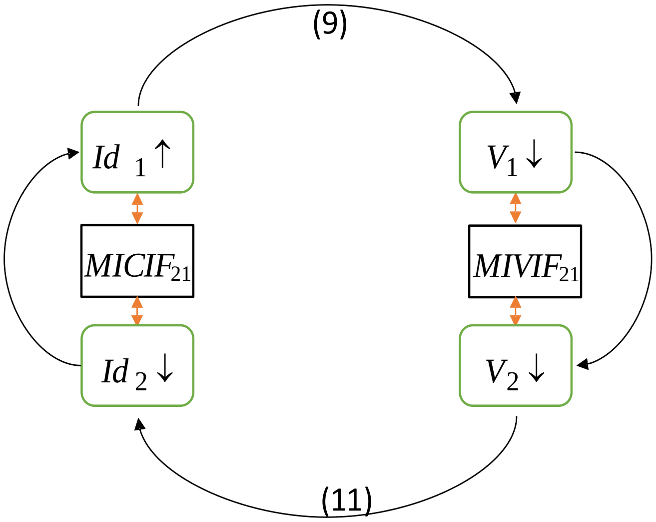

Fig. 4. I_{d1} vs I_{d2} flow chart

4. Simulations

4.1 Characteristic Analysis

Suppose converters in Fig. 1 are both working in stable region with constant extinction angle control mode. The variation of ΔV_1 and ΔV_2 w.r.t ΔI_{d1} is shown in Fig. 5. The graph shows larger influence on V_1 in response of ΔI_{d1}. The effect on V_2 mainly depends on MIIF. The significant voltage reduction is confirmation of lack of reactive power due to increase in direct current. Here, the network impedances are $z_{23}=z_{13}=2.5$ and $z_{12}=40$. The $P_1=P_2=1000$ MW, $Q_{c1}=Q_{c2}=0.6\times1000$ MVAR and $E=1.05$ p.u.

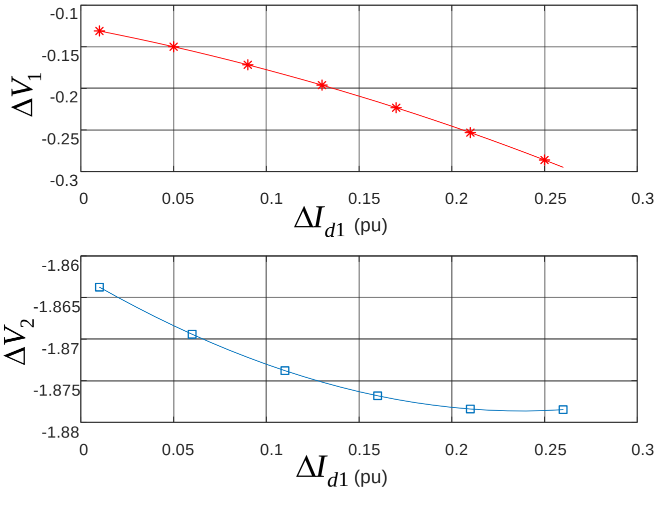

Fig. 5. Behavior of $\Delta V_{1,2}$ vs ΔI_{d1}

The change in bus voltage of nearby converter in close electric proximity is also occurred due to reactive power flow. If I_{d1} of inverter 1 is increased, $I_{d1}+\Delta I_{d1}$, then lack of reactive power at bus 1 cause reactive power to flow from bus 2 to 1 consequently Vbus2 decreases.

Decrease in bus voltage decreases converter current as observed from Eq. 11. Fig. 6 illustrates variation in converter current as V_{bus2} reduces due to injection of ΔI_{d1}. Coupling impedance (z_{12}) between converters also influences MICIF because as $z_{12}\rightarrow\infty$, $MIIF_{21}\rightarrow 0$ thus $MICIF_{21}\rightarrow 0$ as (13).

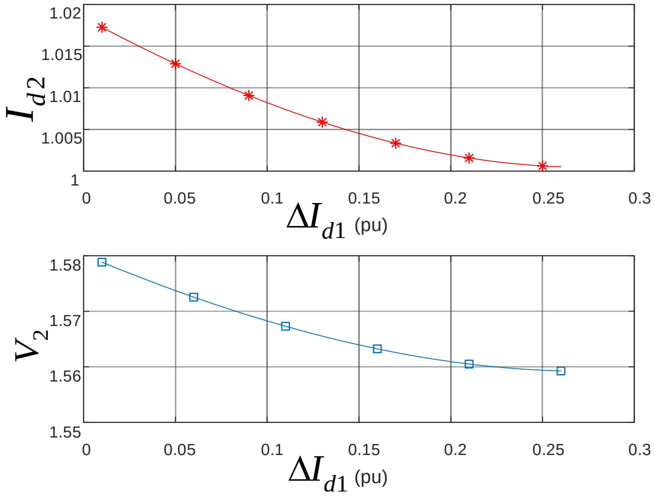

Fig. 6. I_{d2} and V_{bus2} vs ΔI_{d1}

Fig. 7 shows behavior of $MI(V)IF_{21}$ and $MICIF_{21}$. Since V_{bus1} and V_{bus2} are both decreasing with increase in I_{d1} so $\Delta V_2/\Delta V_1$ is positive while $\Delta I_{d2}/\Delta I_{d1}$ is negative due to anti-phase relation between DC quantities.

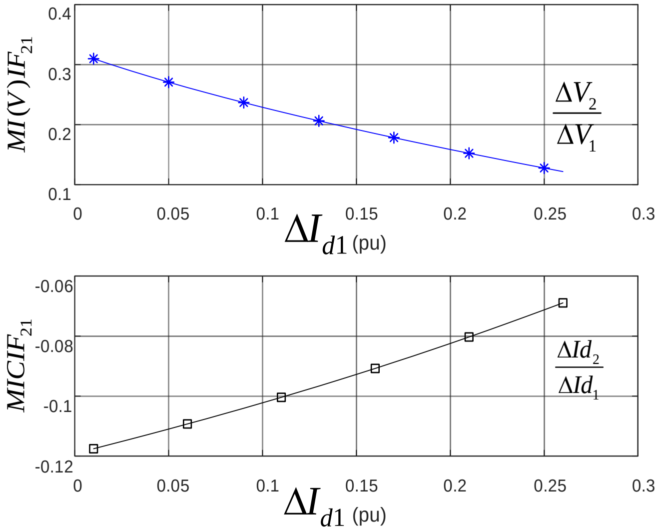

Fig. 7. $MIIF_{21}$ and $MICIF_{21}$ vs ΔI_{d1}

The Eq. 10 also depicts dependency of bus voltage variation on eigenvalues. Assuming constant ΔI_{d1}, the ΔV_{bus1} and ΔV_{bus2} show spikes with $\lambda_{min}\rightarrow 0$. An influence of λ_{min} on local and remote converter in close electric proximity is shown in Fig. 8 for $\Delta I_{d1}=0.05$ p.u. The reason behind this abrupt change is singularity of Jacobian matrix which occurs when λ_{min} becomes 0.

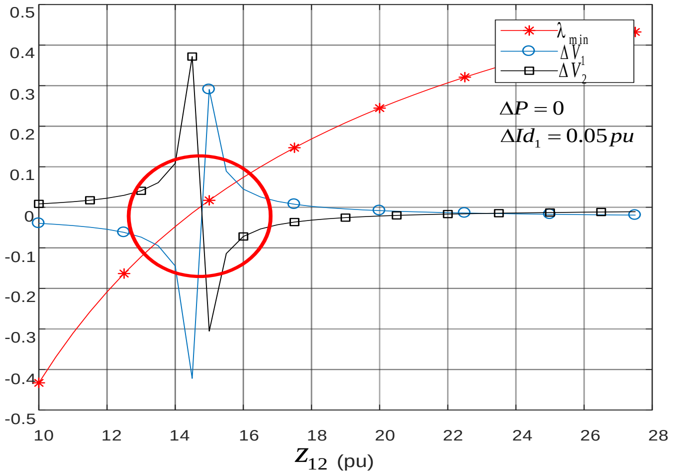

Fig. 8. z_{12} vs ΔV_{bus1} and ΔV_{bus2}

4.2 Influence of Coupling Impedance (z_{12}) on $MICIF_{21}$

To verify the proposed MICIF, a multi-infeed model is developed in PSCAD/EMTDC with parameters given in Table 1. Commutating bus voltage and direct current of both inverters are observed by varying the coupling impedance with normal and step increase of $\Delta I_{d1}=0.05$ at inverter 1. The graph in Fig. 9 shows behavior of $MICIF_{21}$ with z_{12}.With increase in coupling impedance the MIIF reduces which cause MICIF to reduce as Eq. 13.

The DC interaction is very important phenomenon because the CF of converters in close electric proximity directly depends on this factor. The MIIF only gives the relation of voltage interaction while the CF is also occurred due to increase in dc current.

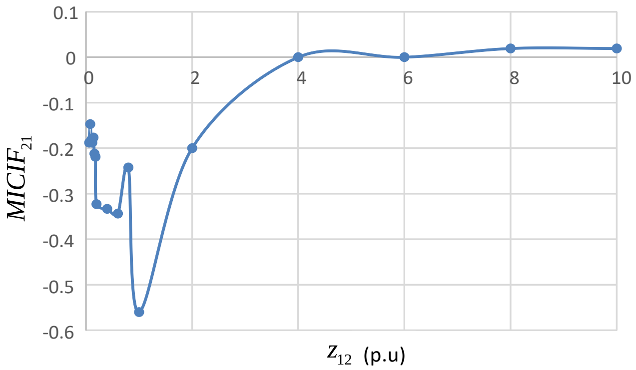

Fig. 9. $MICIF_{21}$ vs z_{12}

The index MICIF relates the dc current of both converters; particularly for the converters which observe high MIIF. With low coupling impedances, high MIIF, direct current of nearby converter drops which supports concurrent CF immunity following by a local increase in dc current. Practically, it is also observed that MIIF>0 allows reactive power support to flow from nearby remote converters to local converter. In parallel multiple

HVDC links, the MICIF can estimate influence of one converter's dc current on another converter in proximity during temporary or permanent blocking of converter. This can elaborate how the remote converter observed the change in local converter.

4.3 Correlation Analysis

A correlation analysis is also made between r(I_{d1},I_{d2}), r(I_{d1},V_1), r(I_{d1},V_2), r(V_1,V_2) and r(MIIF_{21},MICIF_{21}). The analysis tells how closely the two variables move; either they are positively related, inversely related or uncorrelated. The r is correlation coefficient which ranges between 0↔±1.

The |r|→1 means strong relation between variables while positive and negative signs implies that variables are positively or inversely related respectively. Positively related means variable 1 increases with increase in variable 2 while negative or inversely related corresponds to decrease in variable 2 with increase in variable 1 and vice-versa. The correlation analysis also explains the interaction of DC quantities with each other as in Table 2.

Table 1

Multi-Infeed HVDC parameters

<table>
<tr><td colspan="3">Rectifier Side parameters (each) 500 kV, 1000 MW, 50Hz</td></tr>
<tr><td>AC System</td><td>Reactive support (Capacitor Banks+ Filters)</td><td>Transformers (each)</td></tr>
<tr><td>382.87 kV
Impedance
47.655∠84°</td><td>626 MVAR</td><td>603.7 MVA
X_t=0.18 p.u.
345/213.5 kV</td></tr>
<tr><td colspan="3">Inverter Side parameters (each) 500 kV, 1000 MW, 50Hz</td></tr>
<tr><td>AC System (Shared)</td><td>Reactive support (Capacitor Banks+ Filters)</td><td>Transformers (each)</td></tr>
<tr><td>215.05 kV
Impedance
10.69∠75°</td><td>626 MVAR</td><td>591.8 MVA
X_t=0.18 p.u.
230/209.2 kV</td></tr>
<tr><td colspan="3">R(line) =5Ω, L (line) =1.2H, Coupling transformer X_t=0.01-10 p.u.</td></tr>
</table>

Table 2

Correlation Analysis

Var. 1	Var. 2	r	Relation	Strength
I_{d1}	I_{d2}	-0.979	Inversely	Strong
I_{d1}	V_1	-0.996	Inversely	Strong
I_{d1}	V_2	-0.978	Inversely	Strong
V_1	V_2	+0.956	Positively	Strong
MIIF_{21}	MICIF_{21}	-0.997	Inversely	Strong

5. Conclusion

In this paper, an in-depth analysis of inter converter direct current interaction for multi-infeed HVDC system is discussed. It is examined that a direct current interaction between converters of multi-infeed HVDC system always exists. Power flow equations are used to model a complete analytical framework for direct current interaction. An index, multi-infeed current interaction factor (MICIF), is developed to assess the interactions among converters of multi-infeed HVDC system. It is observed that MICIF may have negative value due to anti-phase relation between direct current of converters unlike multi-infeed interaction factor (MIIF). The influence of coupling impedance is evident; as $z_{12}\to\infty$ the $\mathrm{MIIF}_{21}\to 0$ then the $\mathrm{MICIF}_{21}\to 0$. The MICIF has significance due to the fact that it can accurately depict the effect on remote converters in response of change at local converters in the multi-infeed HVDC system.

In future, a systematic analysis can be made to model local and concurrent commutation failure of converters in close electric proximity particularly with high interactions.

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