Small power tapping limit on dc-link of VSC HVDC transmission system

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***Abstract*—Power tapping from HVDC transmission corridor to serve rural areas has been the focus of many researchers and network planners. The tapping stations are to be of small power ratings so that it will not interfere with the main control and stability of the HVDC network. Several research works have assumed tap-off of different percentages of the main HVDC terminal rating without justification. This paper therefore proposes a simple analytical technique used to determine power tapping limit on DC-link of a VSC HVDC network. Effect of power tapping below and above the analytical tap limit is illustrated by results from simulation carried out in Matlab/Simulink, hence validating the proposed technique.**

Keywords—VSC HVDC; Power tapping; Transmission

I. INTRODUCTION

The technological trend in point-to-point HVDC transmission system has created a need to tap-off a small amount of power at some locations along the DC transmission corridor to serve rural areas. Methods of these power tap-offs are based on power electronics interface between the HVDC line and dispersed local loads. Two possible ways to approach power tapping are series and parallel tapping methods as reported in [1], [2], but none of the authors gave any quantitative investigation to establish which method of tap-off is superior. However, the prospect of having multiple power tap-offs makes parallel tapping methods economically feasible. The main requirements for small tapping stations are [3] –[4]:

1. Reduced fixed cost of tapping station
2. Negligible impact of tapping station on the reliability of the main HVDC system. This implies that any fault in the tap must not be able to shut down the whole system.
3. Sufficiently small rating and its control not to interfere with the main HVDC system control i.e. the tap control system has to be strictly local.

Although tapping of small amounts of power from HVDC transmission lines has been the focus of many researchers [4]-[9], until now, all of the published researches in this area of small power tapping from HVDC transmission lines have considered different percentages of power taping in order not interfere with the main HVDC link control. For example, [10]-[11] assumed a small taps having ratings less than 10% of the main terminal rating, [12] considered a shunt-tapped off for power ratings over 20% of the main stations, [13] considered a tapping station to have a fairly small power rating of the order of 2 – 5 % of the power rating of the main HVDC line. However, none has actually tried to quantify the limit of power tap-off on the transmission corridor before violation of voltage limits and stability margins on the DC transmission link.

In this paper, an analytical technique using a principle of uniform loading to determine tap-off limit is proposed. This simple algebraic equation is a function of the HVDC transmission line parameters, point of tap-off and the control parameters of the main HVDC.

The rest of the paper is arranged as follows: section II deals with VSC HVDC link under small power tapping considering steady state modelling of VSC HVDC, tapping limit determination and the proposed analytical technique. Section III is the simulation and validation.

II. VSC HVDC LINK UNDER SMALL POWER TAPPING

Small power tap-off on the DC link of VSC HVDC transmission corridor will result in a radial multi-terminal system. However, certain factors that need to be considered before tapping off power on the DC-link of the VSC HVDC are short circuit ratio (SCR), voltage and power stability of the system especially when the HVDC converters are connected at AC system locations having low short circuit capacity.

Fig. 1 shows a simplified model of a two-terminal VSC HVDC System. Fig. 2 shows the equivalent circuit of the resulting 3-terminal VSC HVDC due to the tapping station on HVDC link.

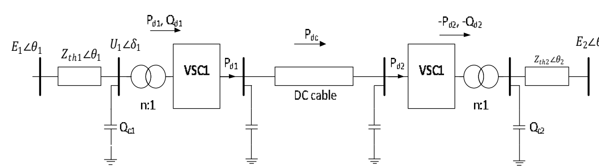

Figure 1. Simplified model of a VSC HVDC System

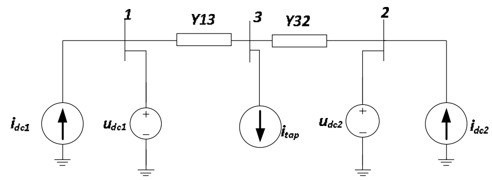

Fig. 2. Equivalent circuit of a VSC HVDC systems under power tapping

A. Steady state modelling

The DC-link of the two-terminal VSC HVDC consists of a large capacitor at converters stations and a DC cable as shown in Figure 2. Power injection and tapping at buses 1, 2 and 3 could be resolved generally using power flow studies.

Power flow studies are based on nodal voltage analysis of the power system. From figure 2, the nodal equation can be written directly.

However, in general for a system with r nodes, at node *n*, the current tapped/injected at node n, $\mathrm{i_n}$ is written as:

$$\left.\begin{aligned} i_n = Y_{n1}V_1 + Y_{n2}V_2 + \cdots + Y_{nn}V_n + \cdots \\ +Y_{nr}V_r = \textstyle\sum_{k=1}^{r} Y_{nk}V_k \end{aligned}\right\} \quad (1)$$

Where Y_{nn} = sum of all admittances connected to node n,

Y_{nk} = - (sum of all admittances connected between nodes n & k) = $\mathrm{Y_{kn}}$.

For the above three nodes,

$$\begin{bmatrix} i_{dc1} \\ i_{dc2} \\ i_{tap} \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix} \begin{bmatrix} u_{dc1} \\ u_{dc2} \\ u_{dc3} \end{bmatrix} \quad (2)$$

Where $\mathrm{y_{11}}$=$\mathrm{Y_{13}}$;$\mathrm{y_{12} = y_{21} = 0}$;$\mathrm{y_{13} = y_{31} = -Y_{13}}$;$\mathrm{y_{22} = Y_{32}}$; $\mathrm{y_{23} = y_{32} = -Y_{32}}$; $\mathrm{y_{33} = Y_{13} + Y_{32}}$

From the Jacobian matrix, $\mathrm{i_{dc1} = u_{dc1}Y_{13} - u_{dc3}Y_{13}}$

The active power injected/tapped off at bus 1, 2 & 3 respectively for a monopolar DC grid can be written as:

$$\left.\begin{aligned} \mathrm{P_{dc1}} &= \mathrm{u_{dc1}i_{dc1}} \\ \mathrm{P_{dc2}} = \mathrm{u_{dc2}i_{dc2}} &= \mathrm{u_{dc2}(i_{dc1} - i_{tap})} \\ \mathrm{P_{tap}} &= \mathrm{u_{dc3}(i_{dc1} - i_{tap})} \end{aligned}\right\} \quad (3)$$

i_{tap} should be very small so that $\mathrm{P_{dc2}}$ will not decrease appreciably below acceptable limits.

Firstly, making initial estimates of all variables $\mathrm{u^o_{dc1}, u^o_{dc2}, i^o_{dc1}, i^o_{tap}}$ (where the superscript "o" indicates number of iteration cycles completed), the power at each bus can be calculated from (3). These values are compared with the specified values to give a power error for bus 1, 2, and 3 respectively as:

$$\left.\begin{aligned} \mathrm{\Delta P^o_{dc1}} &= \mathrm{P_{dc1} - u^o_{dc1}i^o_{dc1}} \\ \mathrm{\Delta P^o_{dc2}} &= \mathrm{P_{dc2} - u^o_{dc1}(i^o_{dc1} - i^o_{tap})} \\ \mathrm{\Delta P^o_{tap}} &= \mathrm{P_{tap} - u^o_{dc3}(i^o_{dc1} - i^o_{tap})} \end{aligned}\right\} \quad (4)$$

The power errors at each node are related to the errors in the dc voltage and current magnitudes $\mathrm{\Delta u^o_{dc1}}$, $\mathrm{\Delta i^o_{dc1}}$, $\mathrm{\Delta i^o_{tapp}}$ by the first order approximation:

$$\begin{bmatrix} \mathrm{\Delta P^o_{dc1}} \\ \mathrm{\Delta P^o_{dc2}} \\ \mathrm{\Delta P^o_{tapp}} \end{bmatrix} = \begin{bmatrix} \frac{\partial \mathrm{P_{dc1}}}{\partial \mathrm{u_{dc1}}} & \frac{\partial \mathrm{P_{dc1}}}{\partial \mathrm{i_{dc2}}} & \frac{\partial \mathrm{P_{dc1}}}{\partial \mathrm{i_{tap}}} \\ \frac{\partial \mathrm{P_{dc2}}}{\partial \mathrm{u_{dc1}}} & \frac{\partial \mathrm{P_{dc2}}}{\partial \mathrm{i_{dc1}}} & \frac{\partial \mathrm{P_{dc2}}}{\partial \mathrm{i_{tap}}} \\ \frac{\partial \mathrm{P_{tap}}}{\partial \mathrm{u_{dc1}}} & \frac{\partial \mathrm{P_{tap}}}{\partial \mathrm{i_{dc1}}} & \frac{\partial \mathrm{P_{tap}}}{\partial \mathrm{i_{tap}}} \end{bmatrix} \begin{bmatrix} \mathrm{\Delta u^o_{dc1}} \\ \mathrm{\Delta i^o_{dc1}} \\ \mathrm{\Delta i^o_{tap}} \end{bmatrix} \quad (5)$$

From (5), one can easily compute the expected small changes in U_{dc} and I_{dc} for changes in P_{dc} and P_{tap}. The Jacobian matrix is a 3x3 because we have only two power controlled buses.

B. Tapping limit determination

Continuous power tapping on the dc line of the VSC HVDC link should have a limit otherwise it leads to instability of the system.

In this study, power sensitivity technique [14-16] is utilized to demonstrate tapping-off level limit criteria on DC-link of a VSC HVDC transmission system. This is based on maximum available power idea, which was first introduced by Ainsworth et al in [17] for a single-feed classical HVDC and extended to multi-infeed classical HVDC by [14]. In this case, this concept is adopted for power tapping on VSC HVDC.

From Fig. 2, supposing that the maximum available dc power (MAP) VSC1 can deliver to the dc bus 2 when there is no power tap-off is known which corresponds to $\mathrm{i_{dc1MAP}}$. If Power is tapped from bus 3, power delivered to VSC2 will be controlled by the converter. However as current tapping I_{tap} continues to increase, it will get to a point such that MAP of VSC2 will begin to decrease appreciably and at such point, the system becomes unstable. Such a phenomenon corresponds with unstable system behaviour, thus MAP of VSC2 condition determines the power stability and tap-off limit of this radial multi-terminal VSC HVDC systems.

Mathematically this point corresponds to the condition that

$$\frac{\mathrm{dP_{dc2}}}{\mathrm{dI_{tap}}} = 0 \quad (6)$$

From (5) two approaches to analyse power stability of the system may be derived. The first approach is to focus on the equation:

$$\frac{\Delta P^{o}_{dc2}}{\Delta i^{o}_{tap}} = \Delta u^{o}_{dc1}\frac{\partial P_{dc2}}{\partial u_{dc1}} + \Delta i^{o}_{dc1}\frac{\partial P_{dc2}}{\partial i_{dc1}} + \Delta i^{o}_{tap}\frac{\partial P_{dc2}}{\partial i_{tap}} \quad (7)$$

When $\Delta i^{o}_{tap}\frac{\partial P_{dc2}}{\partial i_{tap}}$ becomes zero, it will be seen that the radial multi-terminal VSC HVDC system reaches a condition similar to the MAP of VSC2 condition defined in (6). This yields power stability boundary of this system and hence maximum tapping limit on the system. From the power flow solution, i_{tap_limit} will be determined.

C. *Proposed Analytical method for tapping limit determination*

From the previous section, it could be observed that the power flow solution will be used to determine the tapping limit. However, in this section, the analytical method which was first proposed in [18] for power injection limit is hereby adopted and extended for power tapping limit determination.

Fig. 3 shows a VSC HVDC with a long DC link AB of length L, VSC1 as rectifier and VSC2 as inverter, with power tapping at bus 3. Without introduction of the power tapping, Pdc1 flows into bus 2 and gives rise to a voltage drop between bus 1 and bus 2.

The introduction of power tap on bus 3 and increasing its power will create more voltage drop at the tapping point. As power tap-off continues, it could reach an extent (tapping limit) that the direction of flow of power Pdc2 could begin to be reversed. This taping limit, using the principle of uniform loading [18-19], is analytically derived as shown below.

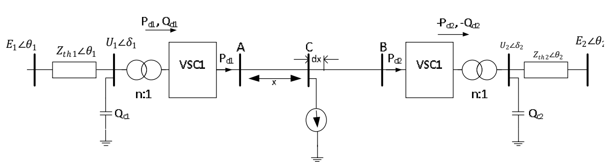

Fig. 3. Simplified model of radial Three-terminal VSC HVDC System

Consider Fig. 4, utilizing the principle of uniform loading, whereby power is being tapped-off per unit length of the DC-link transmission corridor,

Let

i_{tap} be current tapped per unit length,

i_{dc1} – The dc current from the inverter to bus 1,

L – The total length of the HVDC link,

r – Resistance per unit length of the link.

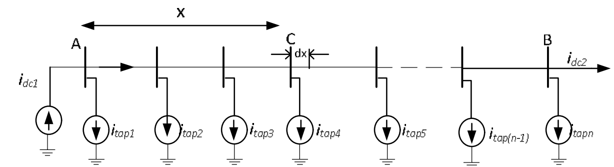

Fig. 4 Uniformly tapping stations on DC-link of VSC HVDC transmission system

At any point,

$$i_{dc2} = i_{dc1} - \sum_{j=1}^{n} i_{tapj} \quad (8)$$

As power tap-off increases, the voltage drop along the line increases. Now, let us find the voltage drop at point C which is at a distance *x* units from A.

Consider a small section of length *dx* near point C, its resistance is *rdx*; hence voltage drop over length *dx* is

$$dv = i(L - x)rdx = (iLr - ixr)dx \quad (9)$$

The total drop up to the point *x* is given by integrating the above quantity between proper limits

$$\int_0^V dv = \int_0^x (iLr - ixr)dx \quad (10)$$

$$V_{x\_drop} = iLrx - \frac{1}{2}irx^2 = ir\left(Lx - \frac{x^2}{2}\right) \quad (11)$$

The drop at point B can be obtained by putting x = L in the expression so that

$$V_{B\_drop} = ir\left(L^2 - \frac{L^2}{2}\right) = \frac{irL^2}{2} = \frac{iL \times rL}{2} = \frac{1}{2}IR_{Line} \quad (12)$$

Equation (11) shows that the voltage drop of a uniformly tapping points up to point x on the DC-link is a parabola. Equation (12) shows that the total voltage drop is equal to that produced by the whole of the tapping stations assumed connected at the middle point. Therefore, it is significant that in the worst case – the whole tapping is installed at the end of the link (B) and in this case the length will be assumed to be doubled. Therefore, at this point B i.e. length 2L, if the maximum power from VSC1 is Pdc1, then at point x, the power transfer will be

$$\frac{x}{2L}P_{dc1} \quad (13)$$

At this point x,

$$\frac{V_1 - V_3}{rx} - i_{tap} = \frac{V_3 - V_2}{r(L-x)} = \frac{x}{2L}\frac{P_{dc1}}{V_3} \quad (14)$$

$$V_3 i_{tap} = P_{tap} = \frac{V_3(V_1 - V_3)}{rx} - \frac{x}{2L}P_{dc1} \quad (15)$$

$$P_{tap} = \frac{-V_3(V_3 - V_1)}{rx} - \frac{x}{2L}P_{dc1} \quad (16)$$

But neglecting inverter losses,

$$P_{dc1} = U_{dc1}I_{dc1} = P_{ac1} = \frac{U_1 1}{X_{th}}\sin\delta \quad (17)$$

$$P_{tap} = \frac{-V_3(V_3 - V_1)}{rx} - \frac{x}{2L} U_{dc1} I_{dc1} \quad (18)$$

With V_3 being the voltage regulation limit on the dc link and V_1 being the setpoint or reference voltage and all values in per unit,

$$P_{tap\_max} = \frac{-U_{dcmin}(U_{dcmin} - U_{dcref})}{rx} - \frac{x}{2L} U_{dc1} I_{dc1} \quad (19)$$

Where

P_{tap_max} = Maximum power tapping for unity reference power of the main control:

U_{dcmin} = the lower voltage regulation limit in p.u specified in the control

U_{dcref} = the reference voltage in p.u

r = resistance per unit length of the line

x = distance of tapping station from bus 1

L = Total length of the DC-link

U_2 = converter AC output voltage

E_2 = AC bus voltage

X_{th} = the thevenin equivalent reactance of the ac system

U_{dc1} = upper voltage regulation (limit in p.u specified in the inverter control)

$I_{dc1} = I_{rated}$ = p.u current reference limit (current set point specified in the rectifier control)

This equation shows that the power tap-off limit depends on the length of the transmission link, point of tap-off, and control parameter settings of the HVDC.

III. SIMULATION

A. *Analytical technique*

In order to validate the proposed technique and to observe the performance of HVDC under tapping power below and above limit, Matlab/Simulink is used for the simulation model. Table 1 shows the parameter of the model used, which is the parameter of Namibia/Zambia Caprivi link VSC HVDC [20]. The classical vector control [21] was used for the model. From control setting parameters of VSC HVDC transmission system in Simulink with Dc-link of 950 km overhead line, the following parameters were used: $U_{dcmin} = 0.94$ p.u; $U_{dcref} = 0.95$; $U_{dc1} = 1.05$ pu ; $I_{dc1} = 1$pu; r = 0.0139 pu of km.

Table 1 Simulation parameter

Data	Parameters
Power rating	300 MW
Overload rating in monopolar mode	350 MW
No of poles	1
AC voltage	Gerus: 400 kV; Zambezi: 330 kV
DC voltage	350 kV
Coupling transformer on both sides (Gerus and Zambezi)	315 MVA
Length of overhead DC line	950 km
Switching frequency of converter valve	1150 kHz
Main reason for choosing HVDC	Long distance weak networks

From (19), substituting the control and dc-link parameters, the DC power tapping limit is calculated thus:

$$P_{tap_{max}} = \frac{0.94(0.94 - 1.05)}{1.39 \times 10^{-2} \times 475} - \frac{475}{2x950} \times 1.05 \times 1$$

$$= -0.0156 - 0.2625 = -0.278 \text{ p.u}$$

Therefore the tapping power limit for this VSC HVDC system is 27.8 % of the total capacity of the main HVDC

This value is for unity reference power of the control setting, but in the simulation, the reference power is 0.63, therefore the power tapping limit at this reference power is $P_{tap\ limit} = 0.63 \times 0.278 = 0.175$ p.u (17.5%).

B. *Effect of increasing power tapping*

Fig. 5 shows the effect of increase in power tapping on power flow of the main system. It could be seen that as power tapping increases, the commanded power on station 1 (Pdc1) remained constant whereas Pdc2 reduces and starts to reduce appreciably at tapping power of 0.18 p.u.

Fig. 6 shows the voltages at the three buses as power tapping increases and it could be seen that the tap voltage begins to drop substantially at tapping power of 0.17 pu, however, this would have been taken care of if the tapping station had its local control. Vdc2 remained constant because station 2 was responsible for the DC-bus voltage control. Therefore, it could be established that the tapping limit is 0.18 p.u which validates the analytical technique.

Fig. 7 shows the results of the power flow when the power tapping is below and above limit. At 0.18 s, a tapping station of power 37 MW (0.12 pu) is switched in and at 2.5 s the tapping power is increased to 64 MW (0.21 p.u). Pdc1 remained constant and Pdc2 decreased but more significantly at 2.5 s when tapping power is above limit.

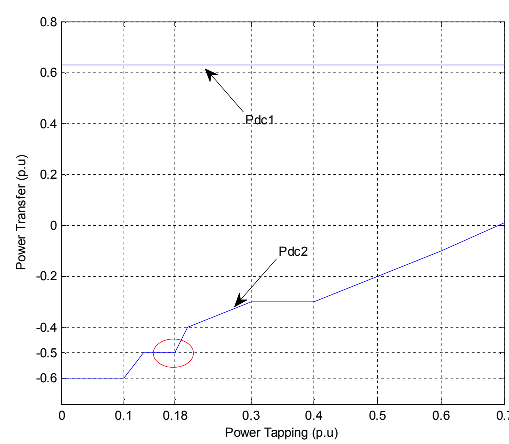

Fig. 5 Effect of increase in power tapping on system power flow

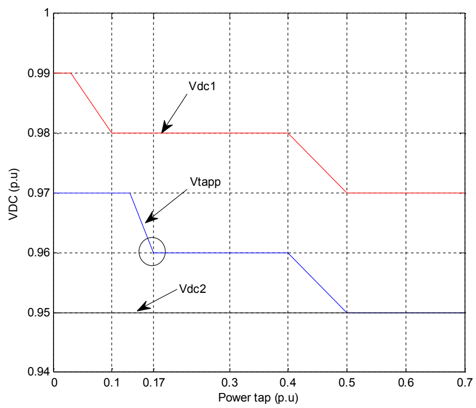

Fig. 6 Effect of increase in power tapping on bus voltages

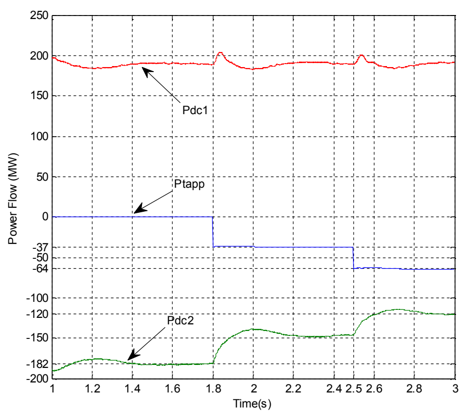

Fig. 7. Tapping power below and above tapping limit

IV. CONCLUSION

In this paper, an analytical method for determination of small power tapping limit on VSC HVDC transmission corridor is proposed. Simulation was carried out in order to validate the proposed analytical method. From the technique and simulation results, it could be concluded that the small power tapping limit from HVDC link depends on the following:

1. the control parameters of the main HVDC
2. the length of the HVDC link
3. the resistance of the line
4. the point of tap-off along the line

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