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POWER FLOW STUDIES IN HVAC AND HVDC TRANSMISSION LINES

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ABSTRACT
The choice of increasing the capacity of transmission infrastructure due to an increasing load demand needs careful evaluation and analysis. For a single HVAC transmission line, its capacity can be increased by using FACTS devices, adding another HVAC line in parallel to it, replacing the HVAC line by a HVDC line or by connecting HVAC and HVDC transmission lines in parallel. This paper investigates these alternatives by establishing three case studies. For the first, a double HVAC transmission line is used, for the second case, an HVDC transmission line is used, and for the third case, a parallel HVAC/HVDC lines are used. In each of these cases, power flow analysis is carried out to determine the most suitable way of increasing the capacity of transmission lines. The simulation results show that the best way to increase the capacity of the transmission line is to use Parallel HVAC/HVDC for transmission

KEY WORDS
HVDC transmission line, HVAC/HVDC transmission, power flow, power angle

1. Introduction

The continual increasing demand on the power system network in South Africa owing to growth and development in all sectors of the economy contributes to the overloading of existing transmission lines.
Most of the existing transmission lines in the country are AC transmission lines which are used for short and long distance transmissions.

Within the last half century, DC lines have been a preference over AC lines worldwide for long distance transmission because of the following reasons.

A. It is a more economical mode of power transfer as compared to High Voltage Alternating Current (HVAC) over long distances exceeding 500Km [1].
B. HVDC transmission lines (i.e. submarine, underground and overhead transmission lines) do not make use of the three phase cables used in HVAC transmission therefore, the power losses incurred in the DC lines are lower than that of AC lines.
C. HVDC can be used to interconnect asynchronous systems. Examples of such connections are in North America, between the south-west power pool (SPP) also between Quebec and its neighbors (New England and the Maritimes) [2].

Although, HVDC has become a preference over HVAC in long distance transmission and offers more controllability, it is important to evaluate the power flow in both HVAC and High Voltage Direct Current (HVDC) transmission to determine when to use HVAC, HVDC or both in parallel for power transmission. In addition to that, the rapid rate of increasing load demand plays an important role in planning transmission infrastructures.

As a result, the three cases; double circuit HVAC, HVDC and HVAC/HVDC transmission are simulated using DigSILENT. In the simulations, a 35% increase in load demand is considered to determine which of the cases will best supply the increased demand putting the change in power flow, rotor angle, loading and reactive power compensation into consideration.

2. An Overview of HVAC Transmission

In AC transmission, the direction of active power flow depends on the angular displacement of the voltage between the sending and receiving end of the power system [3]. Figure 1 depicts a HVAC transmission line model between the sending and receiving ends of a power system.

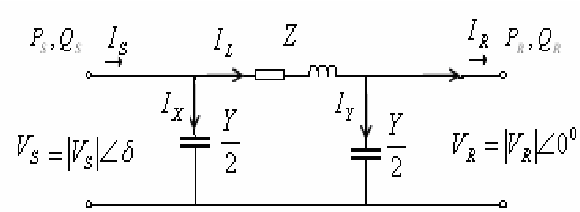

Figure 1. Equivalent model of AC Transmission Line
P = Active power Q = Reactive Power S = Apparent Power V = Voltage

The subscript R, refers to the receiving end while the subscript S, refers to the sending end of the transmission line [4].

From figure 1 the following apparent, real and reactive power at the sending end can be derived:

$$S_S = V_S I^* \tag{1}$$

$$= V_S \angle\delta \left(\frac{V_S \angle\delta - V_R \angle 0}{Z\angle\theta_Z} \right)^* \tag{2}$$

$$S_S = \frac{|V_S|^2}{Z} \angle\theta_Z - \frac{V_S V_R}{Z} \angle(\theta_Z + \delta) \tag{3}$$

$$P_S = \frac{|V_S|^2}{Z} \cos\theta_Z - \frac{|V_S| \cdot |V_R|}{Z} \cos(\theta_Z + \delta) \tag{4}$$

$$Q_S = \frac{|V_S|^2}{Z} \sin\theta_Z - \frac{|V_S| \cdot |V_R|}{Z} \sin(\theta_Z + \delta) \tag{5}$$

Similarly, the apparent, real and reactive power at the receiving end can be derived:

$$S_R = \frac{|V_R| \cdot |V_s|}{Z} \angle(\theta_z - \delta) - \frac{|V_R|^2}{Z} \angle\theta_z \tag{6}$$

$$P_R = \frac{|V_R| \cdot |V_S|}{Z} \cos(\theta_Z - \delta) - \frac{|V_R|^2}{Z} \cos\theta_Z \tag{7}$$

$$Q_R = \frac{|V_R| \cdot |V_S|}{Z} \sin(\theta_Z - \delta) - \frac{|V_R|^2}{Z} \sin\theta_Z \tag{8}$$

Assuming the HVAC line is lossless, i.e., R = 0 and θ = 90^0 and the shunt admittance is neglected, the maximum power will be sent to the receiving end when δ = 90^0 is,

$$P_S = \frac{V_S V_R}{X} \sin\delta \tag{9}$$

$$Q_S = \frac{{V_S}^2}{X} - \frac{V_S V_R}{X} \cos\delta \tag{10}$$

And the received real and reactive power at the receiving end is:

$$P_R = \frac{V_S V_R}{X} \sin\delta \tag{11}$$

$$Q_R = \frac{V_S V_R}{X} \cos\delta - \frac{{V_S}^2}{X} \tag{12}$$

Under normal operating conditions, δ is not allowed to reach 90^0 but restrained to 35^0[4].

3. An overview of HVDC Transmission

In HVDC transmission, AC power is filtered and fed through the rectifier transformer into the rectifier. The rectifier with a firing angle α, converts the AC power into DC power. The DC power goes through the DC filter to remove the unwanted harmonic that may have passed through the rectifier. The filtered DC power is then transmitted through a conducting medium which could either be an overhead transmission line, an under-ground cable or a sub-marine cable. The receiving end of the DC transmission line is connected to an inverter which has an angle of advance β which converts the power back to AC. At this point, transformers are used to step up or down the voltage level as necessary.

Figure 2 shows a typical HVDC transmission line, the rectifier station and the inverter station.

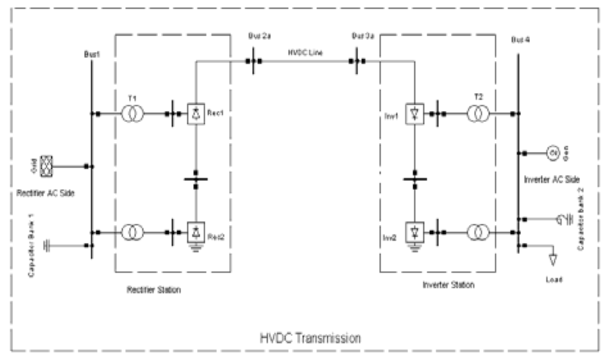

Figure 2. HVDC Transmission

In modern AC to DC conversion for HVDC transmission the line, twelve pulse converter is used which is made up of two series connected six pulse converters shown in figure 2.

Assuming the magnitude of the input line-to-line RMS AC voltage is V_S and V_A, V_B, V_C are the phase voltages,

$$V_A = V_S \cos(\theta + 60^0) \tag{13}$$

$$V_B = V_S \cos(\theta - 60^0) \tag{14}$$

$$V_C = V_S \cos(\theta - 180^0) \tag{15}$$

Then, the line-to-line voltage between phase A and C is:

$$V_{AC} = V_A - V_C = \sqrt{3} V_S \cos(\theta + 30^0) \tag{16}$$

V_{BA} and V_{CB} can be derived similarly.

Since the conversion is a full wave three phase rectification, a full cycle of 360^0 has six pulses separated by 60^0 each. By integrating V_{AC} over a 60^0 period, the average DC voltage V_{DC} is obtained and considering the delay angle α at the rectifier

$$V_{DC} = \frac{3}{\pi} \int_{-(60^0 - \alpha)}^{\alpha} V_{AC} \, d\theta \tag{17}$$

after integrating and neglecting commutation overlap and considering the number of converter bridges as well as the transformer turns ratio,

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_S BT \cos\alpha \tag{19}$$

where: B = Number of converter bridges and T = Transformer turns ratio

$$V_{DC(R)} = \frac{3\sqrt{2}}{\pi} V_{SR} BT \cos\alpha \tag{20}$$

$$V_{DC(I)} = \frac{3\sqrt{2}}{\pi} V_{SI} BT \cos\gamma \tag{21}$$

$$I_{DC} = \frac{V_{DC(R)} - V_{DC(I)}}{R_R + R_L - R_I} \tag{22}$$

where: $V_{DC(R)}$ = Rectifier DC voltage
V_{SR} = Rectifier AC Voltage
$V_{DC(I)}$ = Inverter DC voltage
V_{SI} = Inverter AC Voltage
γ= Inverter extinction angle
R_R= Resistance of the Rectifier
R_I= Resistance of the Inverter
R_L= Resistance of the HVDC Line
I_{DC}= DC line current

Hence from (20) and (22), the DC power output from the rectifier is given as follows:

$$P_{DC} = V_{DC(R)} \cdot I_{DC} \tag{23}$$

$$Q_R = P_{DC} \cdot \tan(\alpha) \tag{24}$$

where: Q_R = Reactive power consumed by the rectifier

4. System Modeling

Three cases are developed to study the power flow in different configurations of HVAC and HVDC transmission lines under different loading conditions between the Deto and Delta substations.

The grid is connected to Bus 1 the slack at Deto substation. The grid has a maximum capacity of 7,000MVA. The synchronous generator connected to Bus 4 which is a PV bus at Delta substation is rated at 1600MVA. In this simulation, the active power generation at Delta substation is set to 500MW. The HVAC transmission line is rated at 1000MVA, 500kV. The reactance of the HVAC transmission line is 0.326Ω/Km, resistance is 0.029Ω/Km and the shunt subceptance is 5.22 µS/Km. The HVDC transmission line is rated at 1000MVA, 500kV. The reactance is 0.071Ω/Km, resistance is 0.028Ω/Km and the shunt subceptance is 0.314 µS/Km. The transmission lines are all 500Km in length [5,6,7,8,9].

In Case 1, a double circuit HVAC is used to supply a load of 1400+j1120 MVA connected to Delta substation.

In case 2, the double circuit HVAC transmission line between the two substations is replaced with a HVDC transmission line to supply the load connected to Delta substation.

In case 3, HVAC and HVDC transmission lines are connected in parallel to supply the load.

In each of these cases, the load connected to Delta substation is increased by 35% from 1400+j1120MVA to 1900+j1520MVA. The power angle at Bus 4 at Delta substation is observed with reference to Deto substation to determine how close each of the cases are to the set power angle limit of 35^0. Furthermore, the transmission line losses are compared in each of the cases. According to theory of HVDC, HVDC transmission has lower line loss as opposed to HVAC transmission [2]. The simulation results indicated that the losses incurred in case 2 and in 3 when HVDC was used for transmission is lower than the losses in case 1 where HVAC alone was used for transmission.

4.1 Case 1: Double Circuit HVAC transmission line

Figure 3 shows the transmission network in case 1. Transmission of power between Deto and Delta substation is achieved through a double circuit HVAC transmission line. Table 1 shows the bus voltages and the power angles. The rest of the results are in appendix 1.

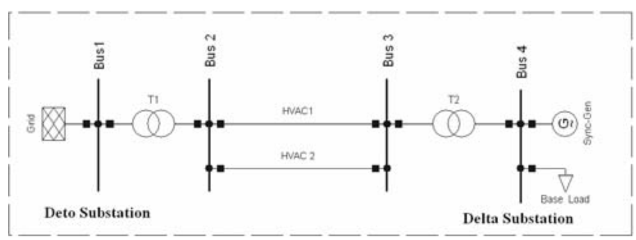

Figure 3. Double Circuit HVAC transmission with 1400+j1120 MVA load

Table 1
Bus voltages and power angles in Case 1

Element	Rated Voltage(kV)	Actual Voltage (kV)	Voltage (p.u)	Power angle (δ)
Bus 1	345	362.25	1.05	0.00
Bus 2	500	528.60	1.06	-0.96
Bus 3	500	505.02	1.01	-16.96
Bus 4	230	230.00	1.00	-17.97

At Deto substation, 923MW was transmitted with a loss of 23MW through the double circuit HVAC transmission lines to Delta substation at Bus 4 to compliment the 500MW generation at Delta. 902Mvar was generated by the HVAC lines due to their high Subceptance and 644Mvar from Delta substation. The excess 388Mvar is absorbed by the grid connected to Deto substation as indicated in appendix 1 which is not a good operating condition. According to [10], active power flows from Bus 1 at Deto substation to Bus 4 at Delta substation because the power angle at Bus 4 is more lagging with respect to Bus 1 as indicated in table 1. The power angle at Bus 4 is -17.97^0 while that of Bus 1 is at 0^0.

The power angle indicated that the system is capable of supplying the load without the generator rotor angle at Delta substation reaching its operational limit of 35^0.

When the load was increased by 35% from 1400+j1120MVA to 1900+j1520MVA, the power angle at Bus 4 of the Delta substation increased from -17.97^0 to -29.07^0. Because, the active power generation at Delta was set to 500MW, about 1458MW had to be transmitted from Deto to Delta to meet the load demand indicated. The loading of the generator at Delta increased from 59% to 87% and each of the transmission lines increased from 50% to 72%. Appendix 1 shows the active and reactive power at the substations and the transmission lines before and after the load was increased by 35%.

4.2 Case 2:HVDC Transmission

Figure 4 shows the transmission network in case 2. In this case, the Double circuit HVAC transmission line was replaced by a single HVDC transmission line. Table 2 shows the bus voltages and the power angles. The rest of the results are in appendix 2.

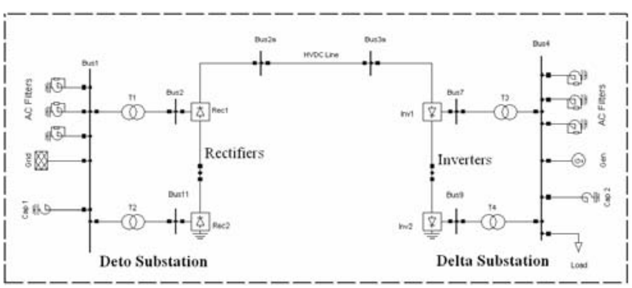

Figure 4. HVDC Transmission with 1400+j1120 MVA load

Table 2
Bus Voltages and power angles in Case 2

Element	Rated Voltage (kV)	Actual Voltage (kV)	Voltage (p.u)	Power angle (δ)
Bus 1	345	362.25	1.05	0
Bus 2a	500	530.46	1.06	0
Bus3a	500	515.46	1.03	0
Bus4	230	230	1.00	0

The real power flow in this case is similar to the case 1 where HVAC was used for transmission. This is because the generator at Delta substation is limited to 500MW although 441MW was generated. 1000MW was supplied from Deto substation via the HVDC transmission line from Bus 2a to Delta at bus 3a. Reactive power compensation in form of two capacitor banks and AC filters are used to provide more reactive power to both substations by connecting them to the AC side of the rectifier at Deto and the inverter at Delta. The AC filters are tuned for the 3^{rd}, 7^{th} and 11^{th} harmonics.

The total reactive power compensation from the two capacitor banks and the AC filters amounts to 1923 Mvar. The reactive power demand by the inverter is 849Mvar while that of the rectifier is 822Mvar. The generator at Delta substation supplied 768Mvar at 55% of its 1600MVA capacity while the grid supplied 4.4 Mvar.

In order to control the flow of active power through the HVDC transmission line from Deto substation to the Delta substation, current control is adopted at Deto substation [11]. From the results presented above in this case, the DC current was set to 1.89KA which is slightly below the 2KA rating of the HVDC line. By reducing the DC current at Deto from 1.89KA to 1.3KA, the active power transmitted via the HVDC line was reduced from 1000MW to 679MW. Consequently, the active power generation at Delta increased from 441MW to 768MW in order to meet the load demand, the reactive power generated decreased from 748 Mvar to 505 Mvar because the reactive power demand by the inverter reduced. Similarly, the reactive power demand by the rectifier reduced thereby forcing reactive power to be absorbed by the grid.

When the load was increased by 35% from 1400+j1120MVA to 1900+j1520MVA with the DC current at Deto substation set at 1.89KA, the voltage profile remained unchanged from Deto substation, across the HVDC transmission line and the Delta substation. Power generation increased from 441MW+j768Mvar to 941MW+j1167Mvar at Delta substation to meet the 35% increase in load demand while the DC current rating at Deto substation is at the default value of 1.89KA. In terms of the installed capacity at Delta, the 35% increase in demand made the generator at Delta run at 93% of its rated 1600MVA from 55%. To relieve the loading on the generator at Delta substation; the DC current at Deto substation can be increased to allow more power flow via the HVDC line between Deto and Delta. The Bus voltages are given in appendix 2.

4.3 Case 3:HVAC/HVDC Transmission in parallel

Figure 5 shows the circuit configuration for case 3.

Transmission of power between Deto and Delta substation is achieved through a parallel hybrid connection of a HVAC and HVDC transmission line.

The simulation results in table 3 and appendix 3 indicates that, with the current control at Deto substation set at 1.89KA and the active power of the generator at Delta substation set at 500MW, the HVDC transmission line transmits 1000MW from Bus 2a at Deto substation to

Bus 3a at Delta substations. It is noted that 58MW is transmitted in the opposite direction (i.e. from Bus 3a at Delta substation bus 2a at Deto substation) with 30MW absorbed by the AC filters at both substations. This is because the HVDC line is set at 1000MW and Bus 4 is a PV bus generating 500MW, hence the remaining excess MW is transmitted via the HVAC line in a reverse direction Furthermore, it should be noted that the power angle at Delta substation with reference to Deto substation is at 1.28º which is 16º lower than case 1 where the double circuit HVAC line was used for transmission.

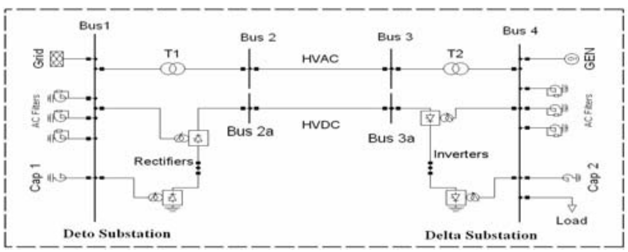

Figure 5. Parallel HVAC/HVDC Transmission with a 1400+j1120 MVA load

Table 3
Bus Voltages and power angles in Case 3

Element	Rated Voltage(kV)	Actual Voltage (kV)	Voltage (p.u)	Power angle (δ)
Bus 1	345	362.25	1.05	0
Bus 2	500	529.33	1.06	0.05
Bus3	500	506.92	1.01	1.28
Bus 2a	500	529.21	1.06	0
Bus3a	500	515.04	1.03	0
Bus4	230	230	1.00	1.36

The reverse in power flow on the HVAC transmission line is because of the following reason. Deto substation is set to 1.89KA (direct current) which transmits 1000MW and also Bus 4 at the Delta substation is a PV bus set to 500MW. This gives a total active power of 1500MW, since the load is 1400MW and the total AC filter demands at both substations is 30MW, and as such, the only way by which the excess active power at Delta power station will be dispatched is to the lower the grid supply at Deto substation and then transmit the excess MW to meet the need of the AC filter at Deto via the HVAC transmission line.

To reverse this power flow on the HVAC line, the scheduled power generation at Delta power station can be reduced. Since the reactive power demand by the converter varies with the amount of DC transmitted, dynamic reactive power compensation should be adopted [12,13].

When the load was increased by 35% from 1400+j1120MVA to 1900+j1520MVA, the direction of power flow in the HVAC line changed. 447MW was transmitted from Deto substation to Delta substation to meet the increased load demand. The power angle Delta substation with respect to Deto substation is 8.53º which is about 7º higher than the power angle before the load was increased. Appendix 3 shows all the bus voltages and power transfer

As the DC current from Deto substation is reduced more power flows via the HVAC transmission line and less via the HVDC transmission line thereby increasing the power angle at Delta substation. This observed phenomenon is shown in figure 6.

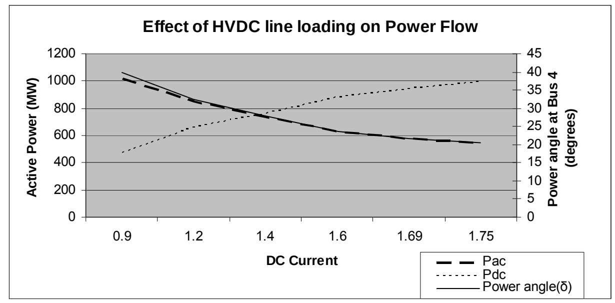

Figure 6. Active Power flow and power angle due to DC current control

5. Conclusion

From the power flow analysis, the following conclusions can be made. In case 1, the double circuit HVAC transmission line is capable of supplying the base load of 1400+j1120MVA and the increase of 35% in load demand. When the load was increased, the power angle at Delta substation increased from -17.97^0 to -29.07^0. The losses in transmission were found to be 60MW, the generator, transformers and transmission lines were all within 0.7 pu to 0.85 pu loading.

In case 2, the HVDC transmission supplied the base load with the generator at the Delta substation and transmission line within 0.5 pu and 0.85 pu loading. When the load was increased by 35%, the generator loading increased to 0.95 pu which was higher than case 1. DC current control at Deto Substation can be used to increase the power transferred via the HVDC line. The losses in transmission were found to be 27MW.

In case 3, the parallel connection of HVAC/HVDC supplied the base load. The power angle at the Delta substation was 1.36^0 which is very small as compared to case 1 where the power angle was at -17.97^0. The loading on the HVAC lines where are 0.5 pu each and the HVDC line was at 0.9 pu. Since the direct current at Deto substation was set to 1.89KA initially to supply the base load, only 57MW was transmitted via the HVAC transmission line. In case 3, it is necessary to control the power flow via the HVDC line in order to avoid a reversal of power flow in the HVAC line as observed. Current control used to solve the reversal of power flow problem in this case. Current control is one of the many forms of power control in HVDC lines and it was employed in this simulations. The losses in this case from the HVAC and the HVDC line in total was 28MW. Furthermore, the simulation indicated that as the direct current limit was reduced at the rectifier in the Deto substation, more power was routed via the HVAC line and less via the HVDC line. The reverse was the case when the current limit at the rectifier was increased. Although the power angle at Delta substation increased as more power was routed via the HVAC line, it is an advantage over case 1 and 2 as the power angle and loading is generally lower that case 1 and 2. Finally it is concluded that using HVAC in parallel with HVAC is the most suitable method of increasing the transmission infrastructure.

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Appendix 1

A- Power Flow in case 1 with 1400+j1120MVA Load

Element	Active Power [MW]	Reactive Power [Mvar]
Grid	923	388 *
HVAC 1	461	451
HVAC 2	461	451
Gen	500	644
Load	1400	1120

**Grid absorbing reactive power.

B- Power Flow in case 1 with 1900+j1520MVA Load

Element	Active Power [MW]	Reactive Power [Mvar]
Grid	1458	203
HVAC 1	729	246
HVAC 2	729	246
Gen	500	1310
Load	1900	1520

Appendix 2

A- Power Flow in HVDC Transmission with 1400+j1120 MVA load

Element	Active Power [MW]	Reactive Power [Mvar]
Grid	1016	89 *
Gen	441	768
HVDC TX line	1000	0
Cap Bank 1 (Deto substation)	0	138
Cap Bank 2 (Delta substation)	0	500
AC Filters (Deto substation)	15**	774
AC Filters (Delta substation)	15**	701
Rectifier (Deto substation)	1000	822
Inverter (Delta substation)	973	849
Load	1400	1120

*Filter absorbed real power. **Grid absorbing reactive power.

B-Bus bar Voltages in HVDC Transmission with 1900+j1520 MVA load

Element	Voltage (rated)	Actual Voltage (kV)	Voltage (p.u)	Power angle (δ)
Bus 1	345	362.25	1.05	0
Bus 2a	500	529.21	1.06	0
Bus3a	500	515.04	1.03	0
Bus4	230	230.00	1.00	0

Appendix 3

A-Power Flow in HVAC/HVDC Transmission with 1400+j1120 MVA load

Element	Active Power [MW]	Reactive Power [Mvar]
Grid	958	543*
Gen	500	74
HVDC TX line	1000	0
HVAC TX	58	1160
Cap Bank 1 (Deto substation)	0	138
Cap Bank 2 (Delta substation)	0	500
AC Filters (Deto substation)	15**	774
AC Filters (Delta substation)	15**	701
Rectifier (Deto substation)	1000	822
Inverter (Delta substation)	973	848
Load	1400	1120

*Filter absorbed real power. **Grid absorbing reactive power.

B-Power Flow in HVAC/HVDC Transmission with the 35% increased load (1900+j1520 MVA)

Element	Active Power [MW]	Reactive Power [Mvar]
Grid	1463	551*
Gen	500	545
HVDC TX line	1000	0
HVAC TX	447	1103
Cap Bank 1 (Deto substation)	0	138
Cap Bank 2 (Delta substation)	0	500
AC Filters (Deto substation)	0	774
AC Filters (Delta substation)	0	701
Rectifier (Deto substation)	1000	822
Inverter (Delta substation)	973	848
Load	1900	1520

**Grid absorbing reactive power.