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SIMULATION & EVALUATION OF COMPOSITE AC-DC POWER TRANSMISSION

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Simulation & Evaluation of Composite AC-DC Power Transmission

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***Abstract* — The bottle-necks in EHVAC and UHVAC is high line reactance, susceptance which limits the thermal loadings on the line. Surge impedance loading (SIL) due to characteristic impedance limits the capacity since a trade-off need to be made between active power and receiving end voltages (reactive power). In addition, single pole switching in case of Single Line to Ground Fault limits the power by 2/3 of healthy line. For longer lines AC lines, transposition and line reactors comes into the picture to balance line currents and receiving end voltages respectively. The HVDC technology as a mere solution of enhancing the power transmission capability has dis-advantages of high material cost in terms of heavy heighted towers, increased insulation assembly string lengths to withstand increased voltages, and more right of the way requirements. In this paper, the feasibility study of conversion of existing double circuit 380kV existing ac line to composite AC–DC line without altering the original line conductors, tower structures, and insulator strings has been presented. The conductors are allowed to carry usual ac along with DC superimposed on it. The study results verify that super-imposed DC power flow does not cause transient instability beyond tolerable limits. The scheme comprises a twelve-pulse bridge rectifier, DC-links, pulse width modulated (PSW)-voltage sourced inverter (VSI) and converter transformers and along-with the master current controller can make this happen such that transmission line never exceeds its thermal criterion in most of the cases. A double circuit ac line hybrid into composite ac–DC power transmission line has the inherent advantages of HVDC; transient stability, localization of oscillations, voltage regulation and reactive power compensation for ac weak buses. Simulation and experimental studies using PSCAD are carried out.**

***Keywords* — Hybrid Transmission System - AC/DC Voltage level selection – AC/DC Super-imposition & Polarization-Enhanced Power Flows - Short Circuit Analysis - Single Pole Switching - Line Current Balancing - Transient Stability - DC Compensation - Energization Sequence - Surge Impedance Loading**

I. Introduction

Construction of new overhead lines require additional cost, corridor area and lead-times. Conversion of existing EHVAC transmission line of GCC system into Hybrid Transmission Lines will not only increase transmission capacities but have many other techno-commercial advantages. There are constraints known to all which limit convention AC power system's ability to transmit power. In this paper, hybrid AC DC line is proposed which requires no alterations of conductors, insulator strings and tower structures of the original EHV AC line. A comparative analysis of the power increase achieved through upgradation of existing network is demonstrated and further system stability of such configuration is also being ensured under various contingencies.

A line has to be insulated for overvoltage expected during faults, switching operations, etc. This insulation requirement can be met by insulation corresponding to an AC voltage of 2.5 to 3 times the normal rated voltage.

$$k_1 = \frac{AC \cdot insulation \cdot level}{rated \cdot AC \cdot voltage(E_p)} = 2.5$$

On the other hand with suitable convertor control the corresponding HVDC transmission ratio.

$$k_2 = \frac{DC \cdot insulation \cdot level}{rated \cdot DC \cdot voltage(V_p)} = 1.7$$

Thus for a DC pole to earth voltage V_d and AC phase to earth voltage E_p the relations exists as:

$$Insulation \cdot ratio = \frac{insulation \cdot length \cdot required \cdot for \cdot each \cdot AC \cdot phase}{insulation \cdot length \cdot required \cdot for \cdot each \cdot DC \cdot pole}$$

From the above equation, it implies:

$$Insulation \cdot ratio = \left(k\frac{k_1}{k_2}\right)\frac{E_p}{V_d}$$

For equal current and insulation level, it gives:

$$I_L = I_d$$

$$V_d = \left(k\frac{k_1}{k_2}\right)E_p$$

$$\frac{P_d}{P_a} = \frac{V_d}{E_p}\left(k\frac{k_1}{k_2}\right)$$

For the same values of k, k_1 and k_2 as above, the power transmitted by overhead lines can be increased to 147%, with the percentage line losses reduced to 68%. It can further be improved by using composite lines.

II. CONCEPT OF SIMULTANEOUS AC-DC TRANSMISSION

The circuit diagram in Fig.1 shows the PSCAD model for composite AC-DC overhead transmission line. AC power is converted into DC power through the rectifier bridge and superimposed to the typical 380kV Double circuit Transmission Line by injection through the neutral point of secondary of the zig-zag delta-star Transformer, and it is polarized back to AC DC by the delta-star zig-zag transformer & Inverter Bridge at the receiving end.

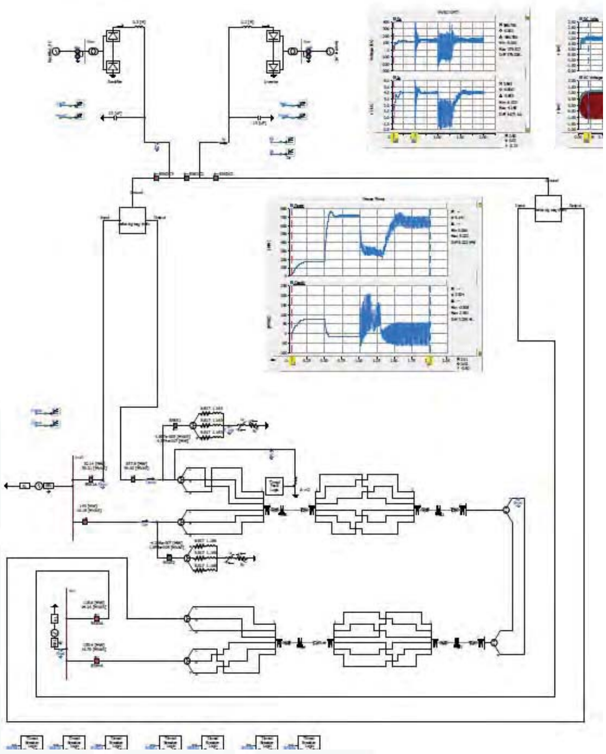

Fig. 1

12-pulse Rectifier Bridge is used for AC to DC rectification and is recovered back to AC again by the line commutated 12-pulse bridge inverter at the receiving end side. PSCAD model of rectifier is exhibited in following Fig. 2:

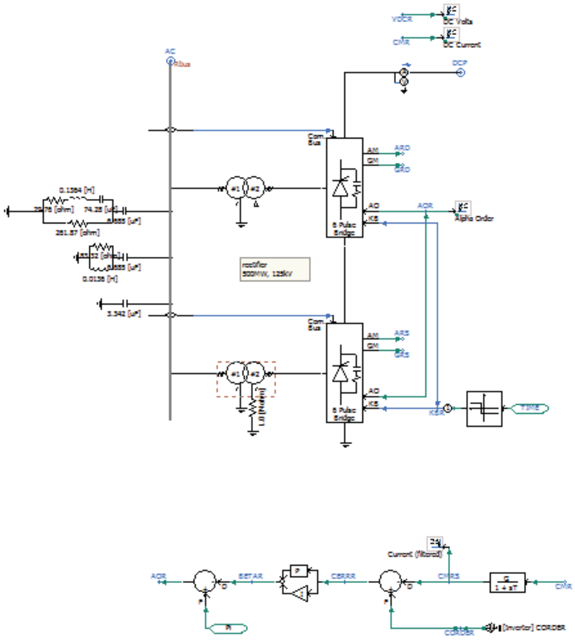

Fig.2

PSCAD model of Inverter is as follows in Fig.3:

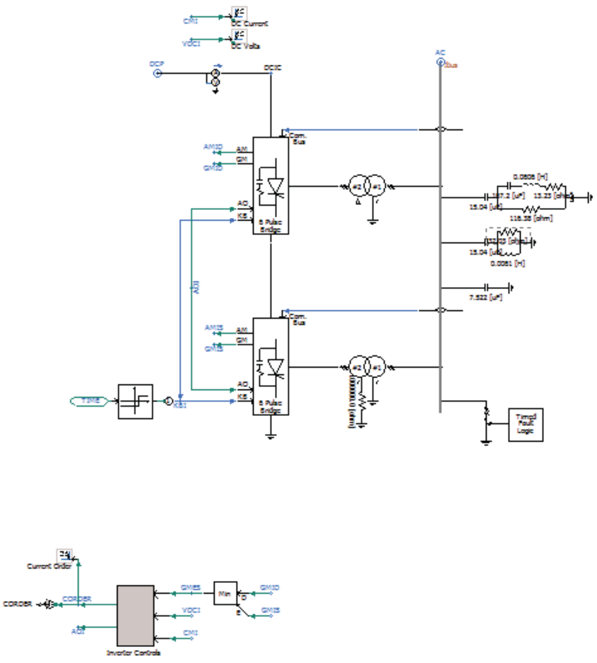

Fig.3

The double circuit AC transmission line carriers both three-phase AC and DC power on one circuit and AC power only on other circuit. Purpose of creating dis-similarity between two circuits is to make stability and flow analysis keeping worst scenario in view. Simulation results have shown that this asymmetric dual circuit transmission line is stable at most of the abnormal contingencies. So, it implies that symmetric double circuit transmission line will also be stable in all the studies cases. Normally, there are 4-sub-conductors in a bundle/phase for 380kV OHTL in KSA so each sub-conductor of transmission line carries ¼ of one third of the total DC current with AC current superimposed. Zig-zag serves the purpose of equal distribution of DC current in all the three phases since resistance is same in all the three windings of secondary winding (zig zag) of transformer. Owing to zig-zag nature of wound winding, saturation of transformer due to DC is avoided since the fluxes produced by the DC current flowing through each winding nullifies because of DC currents of equal magnitude following in opposite directions. As grounding transformer model is not available in PSCAD. Detailed modelling was performed using single phase units interconnected in Zigzag star formation. Modelled grounding transformer from single phase unit on PSCAD is shown as follows in Fig.4:

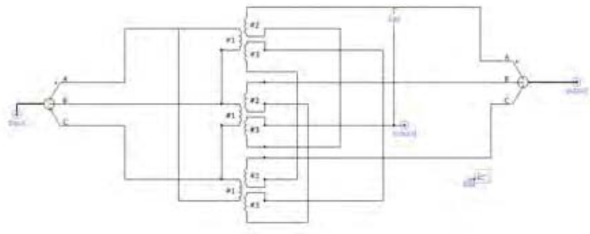

Fig.4

Smoothing reactors with higher values are employed to remove pulses due to harmonics in DC current. Due to delta-star winding DC current is obstructed to flow from secondary to primary winding of transformer and keeps flowing between conductors of the transmission line and secondary windings of zig-zag transformer. Owing to aforementioned conditions, negligible zero-sequence current flows through the ground. Equivalent circuit of the scheme under normal steady state operating condition is shown in Fig.5. The dotted line in the figure shows the path of AC return current only. Each phase of the line carries $1/3^{rd}$ of DC current along with the AC current per phase. The instantaneous phase-ground DC voltage say Vdc with a superimposed sinusoidally varying AC voltages say Vac having rms value Eph and the peak value being: Emax = Vdc + 1.414 Eph. Electric field formed by phase voltage possesses a DC component with sinusoidally varying AC component. If the instantaneous electric field polarity changes its sign twice in cycle which is possible if (Vdc/Eph) < 1.414 then higher creepage distance requirement for insulator assemblies for HVDC lines can be avoided. If each phase conductor is applied with Emax and the line to line voltage has no DC component then Ell(max) = 2.45 Eph. So, phase-phase separation distance will remain same as before DC superimposition. Comprehensive study of protective scheme, filter and instrumentation network required for the proposed scheme is beyond the scope of present work, but primary analysis exhibited below suggests that commonly used techniques in HVDC/AC system may be employed for this purpose. In case of fault in the transmission system, gate signals to all the SCRs are blocked that to the bypass SCRs are released to protect rectifier and inverter bridges. CBs are then tripped at both ends to isolate the complete system. As mentioned earlier, if (Vdc/Eph) <1.414, CBs connected at the two ends of transmission line interrupt current at natural current zeroes and no special DC CB is required. To ensure proper operation of transmission line CBs tripping signals to these CBs may only be given after sensing the zero crossing of current by zero crossing detectors. AC and DC filters used in HVDC system associated to the delta side and zigzag neutral filter out higher harmonics from DC and AC supplies. Conventional CVT's as employed in EHV AC lines used to monitor AC component of transmission line voltage can be used to measure superimposed DC voltage since it does not affect the functioning of CVT's.

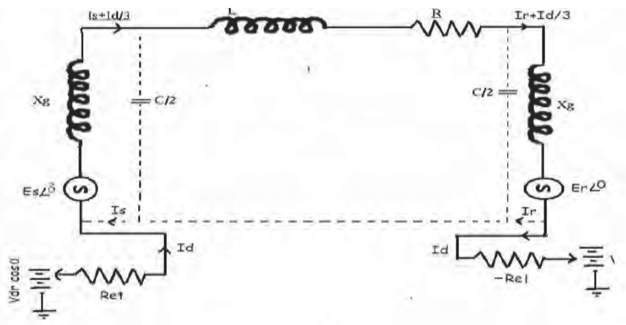

Fig. 5

Composite AC-DC transmission has a significant benefit over HVDC transmission due to its ability to utilize the Transmission Line capacitance available due to HVAC. In conventional HVDC system, capacitance of transmission line cannot be exploited to recompense inductive VAR, as the DC line voltage is continuous with time. The rectifier and inverter bridges consumes lagging VAR (about 50% to 60% that of active power) for their process. This VAR requirement is proportional to gate firing angles. In composite AC – DC power transmission, the superimposed AC-DC voltage has frequency and the transmission line capacitance performs as shunt admittance in parallel to the load.

III. MODELLING

Real life existing 380kV double circuit AC Transmission Line from Jouf to Hail of length 376.5km was employed to experiment the super-imposition on PSCAD. Line parameters, transposition details, Short Circuit values were taken from SEC planning department. Power flows & bus voltages were also taken from SEC planning department but not employed infact voltage and flows were adjusted so as to achieve maximum PQ flows and per unit voltage. Actual tower geometries were considered. Frequency dependent phase model of transmission line was considered with conductor and tower details as follows in Fig.6:

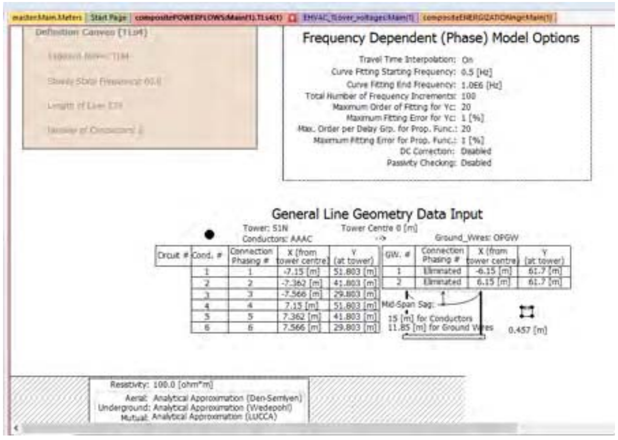

Fig. 6

Line reactors of 60MVAR and NGR data was taken from SEC planning department. But Line reactors and NGRs were resized so as to adjust for 230kV voltage level which is the selected voltage level for AC. Since, 230kV AC is also the available voltage level in KSA so it was selected. Simulations were performed so as to verify the sized Line Reactors and NGR. NGRs of value 40% were selected.

DC of 125kV was superimposed on AC of voltage level 230kV on a transmission line of 380kV Transmission Line. Detailed theoretical calculations and simulations were performed in selection of AC and DC voltage levels based on various techno-commercial factors. Zig-zag transformer composed of 3 numbers individual single phase 3-winding transformer were selected of minimum Percentage impedance so as to create worst scenario. Cigre Benchmark model has been employed for HVDC source. HVDC modelling has been performed so as to develop 125kV DC and 500MW monopole. Inverter and rectifier controls were adjusted so as to develop the aforementioned HVDC line characteristics as exhibited in following Fig.7

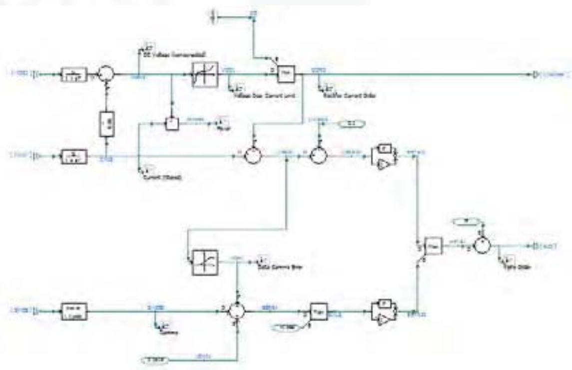

Fig. 7

As per SEC planning, for a typical 380kV, 4-1080 kcmil double circuit AC Transmission Line has the

MVA (Normal/Emergency) rating of 1645/1975 MVA. Impedance parameters provided are:

Z(+) = .000011 + j .000216 pu / km
Z(0) = .000109 + j .000643 pu / km
Charging = 0.00758 pu / km

While short circuit values provided by SEC are exhibited in Following Table. I:

Table. I

380 kV Substation	**Maximum Short Circuit Contributions**			
	3-Phase		**1- Phase**	
	kA	**X/R**	**kA**	**X/R**
A-Jouf	15.6	21.4	15.2	17.9
Al-Jouf 2	15.7	21.4	15.3	17.9
Arar	15.0	17.0	12.9	13.7
Tabarjal	19.4	24.7	17.0	14.2
Qurayyat	15.4	27.4	13.5	17.0

Actual data was modelled and matched and then modified so as to achieve worst permissible cases. Power angles were calculated so as to achieve maximum
power flow on AC Transmission Line without the violation of grid codes. Keeping all the aforementioned scenarios in view, 230kV AC line of length 376.5km with transmission line arrangement as that of 380kV Overhead Transmission Line can carry upto 171.727MW, 77.329MVAR as exhibited in Fig. 8 below:

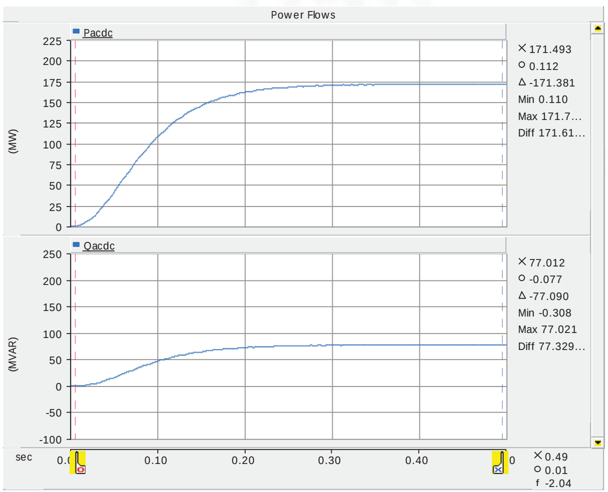

Fig. 8

125kV DC, 500MW HVDC link with all filters and smoothing reactors gives an output of 4.148kA DC as exhibited in Fig.9:

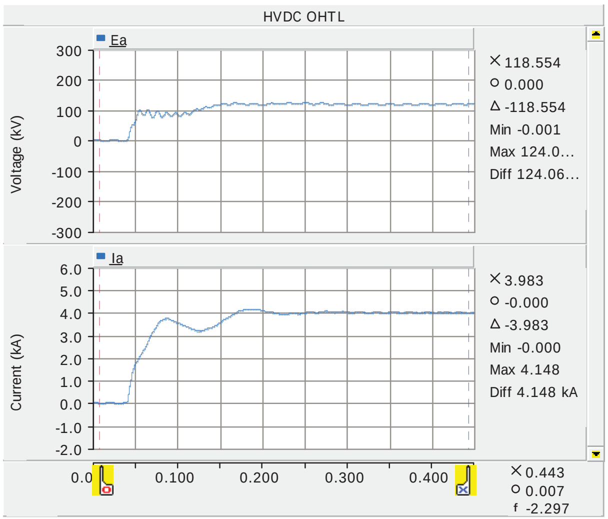

Fig. 9

Modelled 125kV, 500MW Rectifiers and inverters with feedback loops between them has input output voltages/currents in p.u as follows as exhibited in Fig. 10 and Fig. 11 with base voltage of 125kV and base current of 4kA:

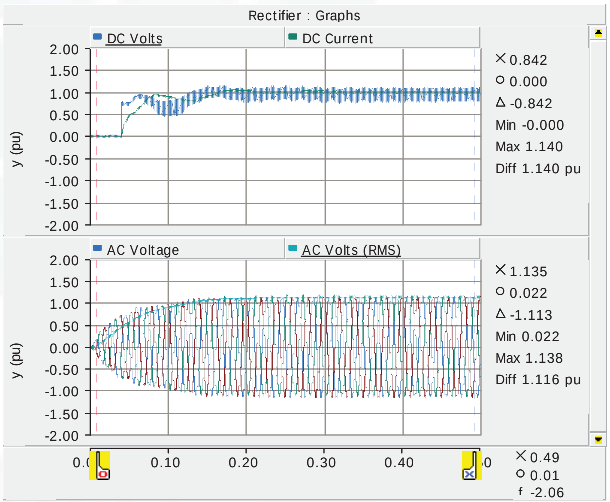

Fig.10

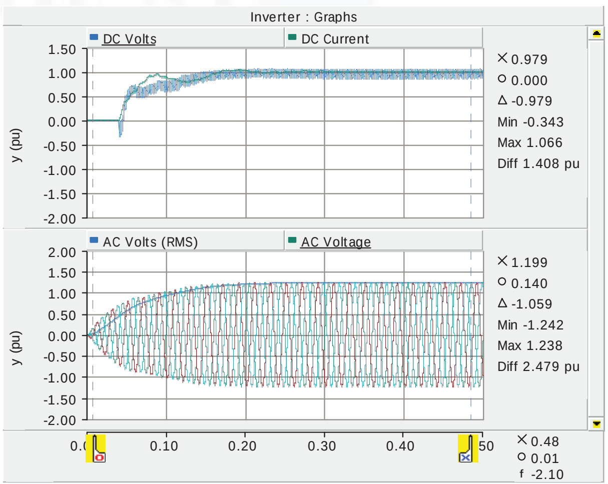

Fig.11

PSCAD model of HVDC arrangement as discussed aforementioned is as follows in Fig. 12:

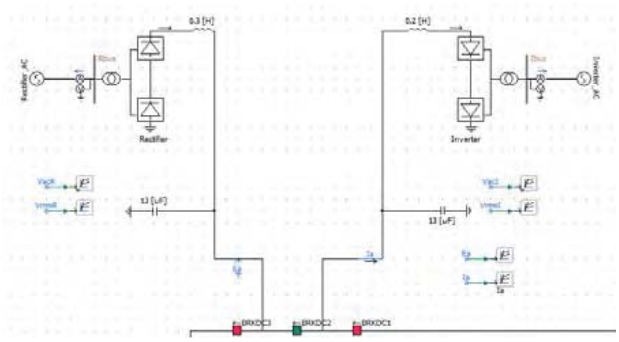

Fig. 12

PSCAD model of HVAC arrangement as discussed aforementioned is as follows in Fig. 13

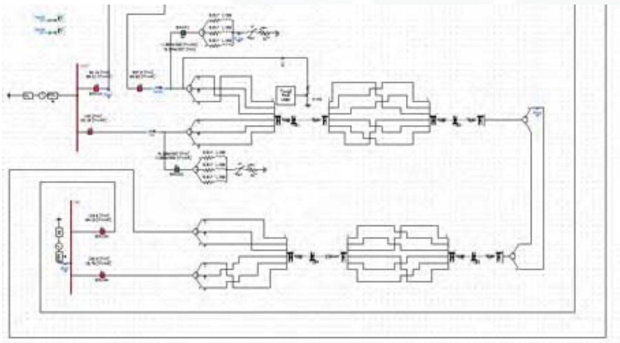

Fig. 13

IV. SIMULATION RESULTS AND DISCUSSION

Various cases were considered so as to make a check on the sustainability, durability and stability criteria. For the purpose of simplicity, only the decisive worst cases have been discussed. So as to experiment characteristics of composite line, a comprehensive case with different sequence of incidents happening at various time instances was developed. Deliberate dozens of discrete studies were performed and then all the decisive worst cases were compiled in single time line. Sequence of incidents in consolidated time line is elaborated in following table-II:

Table-II

Sr#	Event	Time
1	Normal operation of AC Line at maximum power and voltage	t=0 to 0.5s
2	125kV DC Voltage injection	t=0.5 to 1s
3	Single line to ground fault	t=1 to 1.3s
4	Single Pole Switching	t=1.3 to 2s

Consolidated timeline made various comparative analysis more illustrative. Following figure. 14 exhibits the behavior of composite line in terms of power flows when incidents happened as per Table-II. It show that from time 0 to 0.5second, transmission line is conventional HVAC 380kV transmission line with 230kV AC applied. PQ flows are 171MW and 77.02MVAR. After the injection of 125kV, 4kA, 500MW DC current at 0.5second, active power has increased to 722MW and reactive power has decreased to 17MVAR. Decrease in reactive power is due to the VAR compensation of lagging power of rectifiers and inverters. At 1second, SLG was applied of duration 0.3seconds which reduced active power flow but still considerable power of around 369MW was flowing through healthy phases. At 1.3seconds, circuit breakers isolated the faulty phase with single pole switching and power flows increases to 630MW but a lot of oscillations are observed which shows that improvement is required in harmonic filters sizing during fault and SPS operation. However, it clearly indicates that more active power is transferred not only in normal operation but also in contingency/emergency condition. Check has been made so that current flows shall not violate thermal ampacity of individual sub-conductor which is around 800A for 1080kcmil conductor.

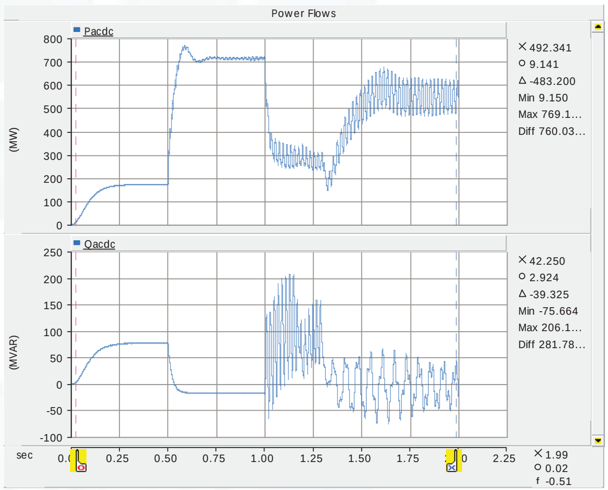

Fig. 14

Corresponding current plots for above figure.14 are exhibited in following figure.15 with addition of un-composite typical AC circuit on other arm of tower termed as "Iac". It shows that line currents are balanced in all the incident of event with exception of SLG and SPS for composite AC-DC line. It is quite evident that due to magnetic coupling of typical AC circuit on one arm of tower with other composite AC-DC circuit, variations are observed for various incidents but stability criterion remained under control. Exceptional phenomenon was observed when DC was injected on one of the two circuits. Other circuit experienced negative offset in current but it was damped as per timeconstant governed by mutual capacitance which made the DC component blocked after certain period of time.

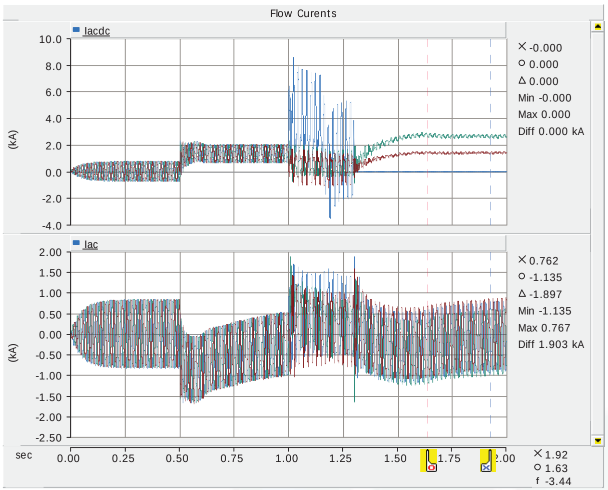

Fig. 15

Figure.16 shows behavior of DC source in terms of voltage & current for all the aforementioned events as per Table-II. While Figure 17 and Figure.18 describes characteristics of modelled rectifier and inverter during various events of table-II. From the plots, it shows that although there's margin of improvement in terms of removal of ripples during abnormal conditions in rectifier & inverter but all the respective values are tolerable and within the permissible limits.

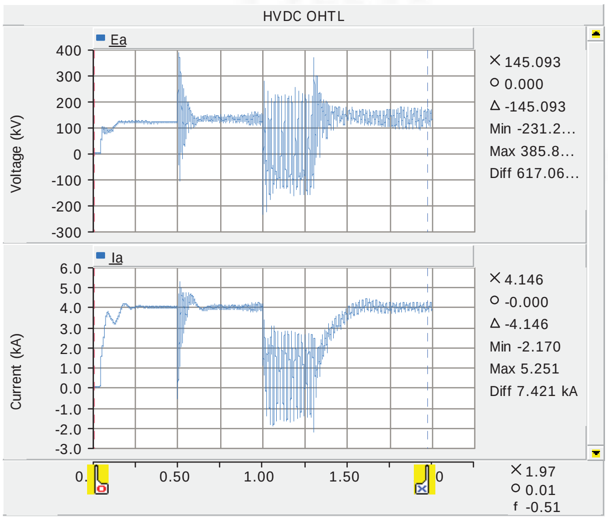

Fig. 16

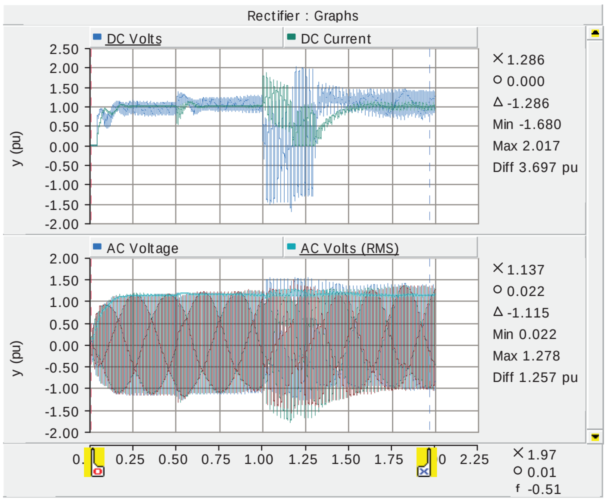

Fig. 17

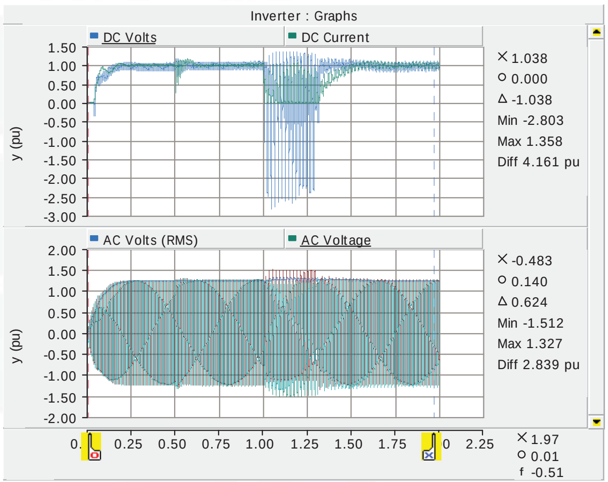

Fig. 18

One of the bottle-necks in such composite OHTL lies in the energization. After detailed studies, following sequence of switching operation as exhibited in table-III was finalized to get the best results:

Table-III

Sr#	Event	Time
1	Both ends of OHTL are open and line is de-energized	t=0 to 0.5s
2	Hail end is closed with jouf end open	t=0.5 to 2s
3	Line reactors are closed at 0.5s and opened at 0.9s	t=0.5 to 0.9s
4	DC is injected at 0.8s	t=0.8 to 2s

Voltages were observed at remote end, near end and midpoint at various events occurred as per above Table-III as shown in following Figure.19:

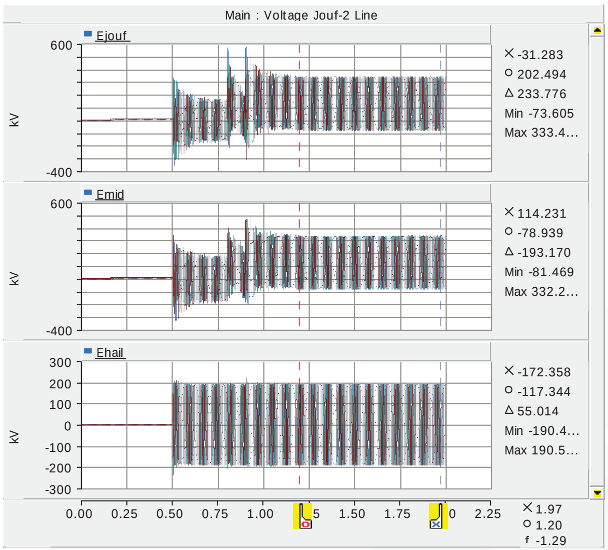

Fig. 19

Line reactors & neutral grounding reactors were specially sized and modelled for these simulations. As per table-III, sequence of switching is selected so that comparison can be made between typical AC and composite AC-DC line on same time line. If line reactors are not switched off on onset of DC, system is subjected to resonance so an overlap region of 0.1second is kept between reactors switching off and DC injection. Detailed analysis shows that temporary over-voltages existed but within allowable limits and are for very short duration. Peak phase-ground voltages are show in the Figure.19. Maximum Normal over-voltages pf composite AC-DC line appearing is 1.07pu. So conventional 380kV OHTL in KSA have sufficient safety margins for these over-voltages.

V. CONCLUSION

Composite EHV AC-DC power transmission through the existing conventional transmission system network and existing voltage levels was studied and analyzed through various configurations and worst scenarios. The conventional EHV AC lines, because of intrinsic transient stability problem cannot be burdened to their maximum thermal limit. In addition, during contingency/emergency situation rejection of power transfer is also significant. However, in proposed scheme, the practiced typical existing 380kV AC Transmission Line conductors are carrying both DC current along with AC current. The superimposed DC power flow has not only enhanced power transfer capability during normal/emergency scenario but has enhanced the stability as well. Furthermore, it has not caused violations to grid codes limits of stability. The research shows the prospect of converting a dual circuit AC line into simultaneous AC-DC power transmission line.

It has huge prospect in terms of existing infrastructure upgradability especially in GCC region since without any physical alteration in insulator strings, towers and conductors of the original line we can increase power capability, stability, durability, redundancy, short circuit localization. In addition, commercial constraints like right of the way issues, corridor allocations, construction time, health hazards, development authorities' objections and surely material costs make this proposal a lucrative field to be implemented.

Bottle necks have also been observed where further research is required. Behavior of protection devices, instrumentation, harmonic filters, ferro-resonance phenomenon of zig-zag grounding transformers etc are the vast fields where further research and study is foreseen.

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