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Improvement in Power Capacity by Simultaneous HVAC-HVDC Transmission System

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***Abstract* – A Simulink model has been proposed to test power upgradation by converting a double circuited hvac transmission system into a simultaneous hvac-hvdc transmission system. Sending end power and receiving end power have been calculated for a conventional hvac line at eight different line lengths. The same parameters along with dc link current and inverter voltage have been calculated for a simultaneous hvac-hvdc system at eight different line lengths. Difference between two successive line lengths was 25km. Ac and dc losses have been computed by employing the above mentioned parameters. Power upgradation has been calculated at all the eight lines by comparing the receiving end powers in simultaneous hvac-hvdc system with the respective conventional hvac system. Simulation results have been calculated.**

***Index Terms*–AC and DC power transmission, HVDC, HVAC, Simulation, Power Up gradation.**

I. INTRODUCTION

If not for Electric Power, our country's economy today would have been in jeopardy and future a conundrum. Ever since the advent of Electricity, mankind has been benefited in leaps and bounds. The development henceforth has been multidimensional in various countries across the 24 time zones, be it social, economic or cultural. The crux of urbanization lies in the growth of agricultural as well as industrial sector. The Planning commission hereby prioritizes research and development in Electric Power Generation, Transmission and Distribution. Contradictory to the obvious the demand for electricity has increased gradually but leaving behind footprints of erratic geographical growth. Power Generation is centered in remote areas due to economic and environmental factors while the load centers are close by cities and towns.

It has been observed that one could transmit power through the installed high capacity AC voltage lines only up to a certain upper limit beyond which the system runs into transient instability. Consequently, the lines are never loaded upto their maximum thermal limit rather much less than that [1]. This is a roadblock as one is forced to wonder for ways and means to elevate the capacity of the existing EHVAC transmission line prototype. Recent developments have exhibited the fact that 765/800KV lines are being constructed between Anapara-Unnao and Tehri-Meerut in Uttar Pradesh along with Moga-Krishanpura in Punjab and Vindyachal in MP. HVDC i.e. High Voltage Direct Current Transmission has seen the light of day in India operating at 500KV transmission voltage. Environmental constraints have long since limited the very realization of brand new power corridors. Thereby the onus has passed onto enhancing power transfer without any significant structural changes [2]. Development in Power Electronics has led to the ultimate saving solution – FACTS. Control mechanism of SCR devices in FACTS devices is extremely quick and efficient. There are promptly many options to choose from be it the Static VAR System (SVS), Static Phase Shifter (SPS) or the Controlled Series Capacitor (CSC) [3]. Rectifier control could be made possible by using a Proportional Integral Controller which required adjusting the firing angle [4]. Enhanced stability and improved damped out oscillations are few of the perks offered by these systems. Not only it is possible to successfully increase the transmission capacity by converting an EHVAC circuit into HVDC circuit, one could even determine the increase in magnitude [5].

It is also noteworthy that conversion into DC considerably decreased the per unit losses, improved lightning performance and accentuated reliability of the line [6]. Upon comparing and contrasting the performances of HVDC and HVAC transmission systems it has been found out that despite greater cost of HVDC equipment; qualities such as cost efficiency, zero stability problem, environmental friendly and human safety weighed strongly in favour of HVDC transmission system [7]. Added perks of such an arrangement happen to be enhanced transient stability, dynamic stability as well as damp out oscillations [8]. In terms of structure, self-supporting towers have been found to be more reliable as compared to guyed towers. In terms of reliability double circuit lines stood out [9]. In ac-dc transmission the overall performance has been compensated by capacitive VAR against the lagging VAR of conductors [10].

Modified semiconductor coated insulators have appreciatively altered the behavior of corona inception and flash over voltage of suspension dc and ac insulators [11]. In spite of superimposing dc current onto ac in combined transmission, it has been observed that there was no need to alter conductor size, insulator strings and towers [12]. The superimposed dc current made it possible for the line to be loaded to its thermal limit [13][14]. Reliability is a crucial factor. A four state component model simplified with the method of combining components and dividing subzone for DC substation as given in [15] has been studied to evaluate reliability to evaluate reliability.

System stability could be maintained with high values of pre fault power and fault clearance time [16]. It has also been demonstrated that a combined transmission lowered the fault current and improved the performance

[17]. An analytical approach has also been adopted by researchers to study the combined operation. A mathematical model is formulated to analyze the behavior of a composite system with an ac system [18][19]. Researchers have investigated that energy could be transferred with minimum losses after converting an existing HVAC line into HVDC [20].

However, the HVDC System fails to make any positive contribution to the system synchronizing torque and ultimately raise the margin of instability. This paved the path for researchers and engineers to think beyond the obvious and establish a scheme that would allow HVDC power transfer across an already fully functioning HVAC line hence germinating the seeds of Combined HVAC & HVDC Transmission System. Such a scheme would majorly help in ousting problems of transient instability. Control strategies could be established and operated on HVDC system in order to magnify the synchronizing and damping torques. This would stabilize the AC system by leaps and bounds and cut out any requirement for extra reactive power in converter controllers. In this paper the impact on power transfer capability is investigated with respect to the length of the transmission line.

II. METHODOLOGY

A. SIMULTANEOUS AC-DC TRANSMISSION

Figure 1 shows a basic scheme for power transfer in case of combined AC & DC power transfer. Such an arrangement could be achieved by careful and accurate conversion of a double circuit AC line into an integrated AC-DC line. It hereby becomes possible to achieve a suitable line carrying both three phase AC as well DC power. Consequently the total DC current gets evenly distributed across the three lines. This results in a homogenous set-up whereby each line now carries AC current along with one third of DC component. As given in the circuit, the DC power is acquired through the line commutated 12-Pulse Rectifier Bridge. The output from here is further connected to the neutral point at the secondary side of a zigzag transformer. The DC power is later converted into AC with the help of yet another line commutated 12-phase bridge Inverter at the receiving end side [2]. The output of the bridge is connected to the neutral winding at the secondary of another zigzag transformer placed at the receiving side. It is noteworthy that since DC current is equally divided across all the three phases, the resistance would remain constant and consequently in the three conductors of the transmission line as well. Due to an increase in voltage upon superimposing dc onto ac there occurs a need to add more discs in each of the string insulator in order to bear the increased dc voltage. Best part being that there is no alteration required among the spacing of the conductors. This is possible due to constant line to line voltage. There is also no need for any modification whatsoever in the tower structure [8].

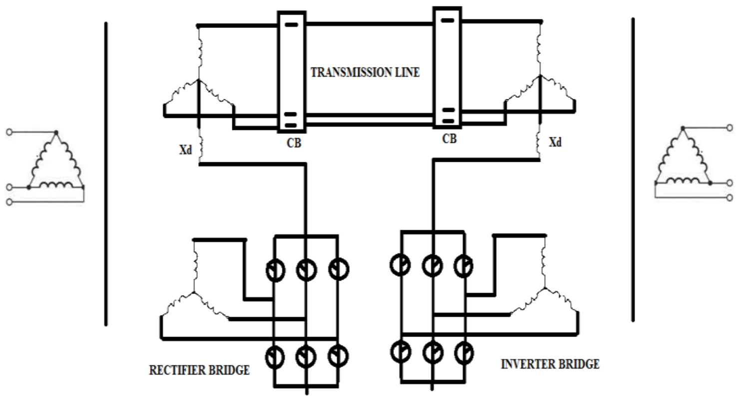

Fig.1. Basic Scheme for Simultaneous AC-DC Transmission [8]

Many other aspects have to be taken into consideration like the saturation of the transformer due to the dc component. The saturation of the transformer may be avoided by employing Zigzag transformers. Not to forget the three conductors in the second line behave as a much needed return path for the dc current. Yet another aspect that comes to attention is the presence of harmonics in dc current. These can be appreciatively reduced by inserting a reactor having a high value of reactance. Equal fluxes emanate from the dc current i.e. $I_d/3$ which practically flows in the limbs of the core of zigzag transformer [1]. Although the magnitude is same but the direction is opposite. Hence, overall net flux value dips to zero across the limbs of the core of the transformer at any given point in time. This is how saturation of the dc component is avoided in the limbs of the core of the transformer.

The winding on the primary side is Y while the other two secondary windings are connected such that there is a 30 degree difference across its phases thereby resulting in a total of six pulses in one alternation and twelve pulses in a single cycle. To implement the controllers one requires assessing and implementing component modules from the Sim-Power System section of the Simulink library. One may reflect that thyristors are fired using a suitable 12-Pulse Generator. Within the filter block two tuned filters have been attached which effectively filter out the unwanted 11 order and 13 order harmonics. Also higher order harmonics are filtered out using a high pass filter. There is also present a capacitor bank. The current flowing through the setup is could be found out from the voltage difference in the sending end and receiving end station. The firing angle α in a rectifier ensures a positive voltage in the circuit by being set at a minimum of 5 degrees. This is made possible by employing a Proportional Integral Controller [4]. Below this value the rectifier tends to effect voltage negatively. On the inverter side the minimum value of α is set to 92 degrees and maximum is set to 166 degrees. As one may view Master Control System is specific to the system, hence it is designed individually for every setup. Both the converter systems have the identical control systems in transmission. Master control controls the current

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command. Greater emphasis must be laid upon synchronizing the two converters so that they could operate with same current command [21].

B. MODELS

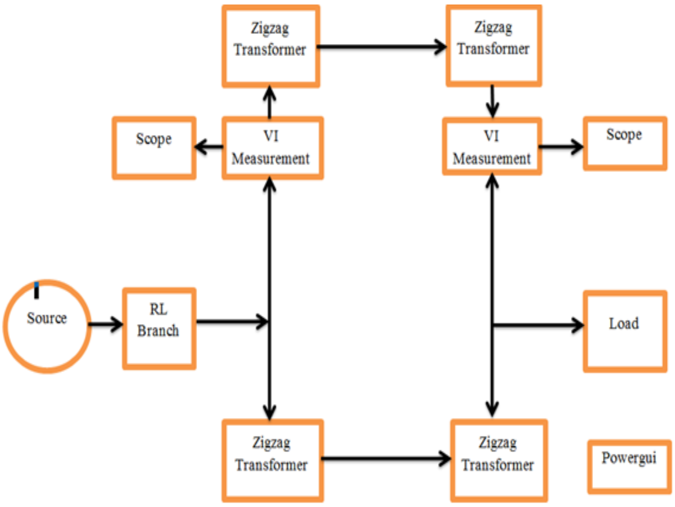

Fig.2. Block Diagram for a pure HVAC Transmission System

Figure 2 depicts an HVAC transmission system. This system contains three phase source connected to a three phase RL branch. A total of four zigzag transformers have been installed. The three phase shifting transformer used here has been implemented by using three single phase, three-winding transformers. Primary consists of winding 1 and 2 connected in zigzag. Secondary winding is in delta. It is a double circuit line therefore each circuit consists of two transformers. A three phase, 50 Hz distributed line transfers power from the sending end side to the receiving end side. A total of 8 line lengths have been considered namely: 425km, 450km, 475km, 500km, 525km, 550km, 575km and 600km. Two 50Hz, 600Mvar AC Filters have been incorporated into the system to prevent the odd harmonic currents from spreading out on the ac system. Filters provide the necessary reactive power compensation. The firing angle is set at 30 degrees. The converters' reactive power requirement is 60% of the power transmitted at the full load. Filters have been tuned to the quality factor of 100 to eliminate 11^{th} and 13^{th} order harmonics. The system is thus simulated at all the line lengths and observations are recorded.

Figure 3 depicts simultaneous HVAC & HVDC transmission system. This system consists of various parts other than the abovementioned. Rectifier and inverter have been used as 12 pulse converters using two universal bridge blocks connected in series. Nominal power for both of these has been set to 1200MVA and frequency to 50Hz. Converters are interconnected through a distributed line. The converter transformers are modeled with three phase transformer.

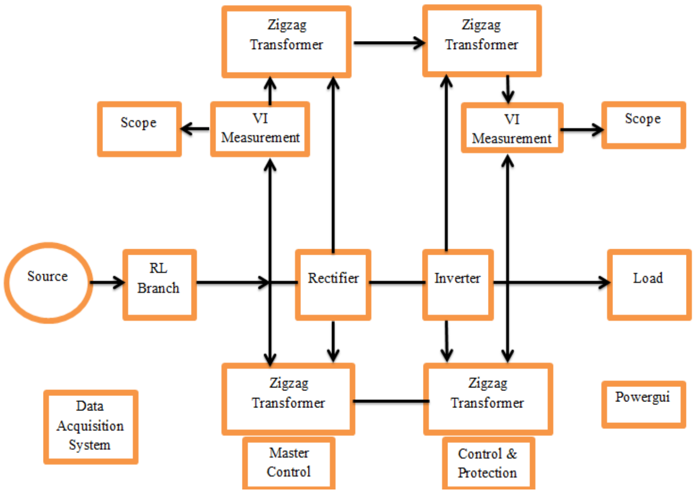

Fig.3. Block Diagram for a combined HVAC & HVDC Transmission System

The tap position is rather at a fixed position determined by a multiplication factor applied to the primary voltage of converter transformers. The values are 0.90 on rectifier side and 0.96 on inverter side. A Master Current Controller (MCC) has been used to control the current order for converters. This would eventually help to measure the conductor ac current, the dc current and send it to the converters.

C. SYNCHRONISATION AND FIRING SYSTEM

The 12 Pulse Firing Centre is the control center wherein pulse have been synchronised and generated. Primary voltages have been used synchronise and generate the pulses according to the alpha firing angle computed by the converter controller itself. A phase locked loop (PLL) has been used. The firing angle has been synchronised to the three voltages generated by the PLL. At zero crossing of the commutation voltages a ramp signal is reset. It has been seen that a firing pulse is generated whenever the ramp value became equal to the desired delay angle provided by the controller.

D. DC TRANSMISSION CONTROL

The current flowing through the dc link has been obtained by calculating the voltage difference between station A and station B. In rectifier operation the firing angle should not be below a certain minimum value i.e. 3-5 degrees. This has helped in ensuring that there would be a positive voltage across the valve at the firing instant. Likewise in Inverter operation the extinction angle should never be decreased below a certain minimum value i.e. 17-19 degrees. Else the system becomes susceptible to higher risks of commutation failure [21]. In order to keep the nominal rating of the equipment to a minimum it is imperative to keep both alpha and gamma as low as possible. This has been instrumental in reduction of harmonic distortion and sparing consumption of reactive power. The dc voltage level is controlled by the transformer tap changer in inverter station at sending end

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side whereas current is altered by changing the dc voltage in rectifier station at receiving end side. Hence voltage difference is achieved between the two stations. Hence the current is regulated through the link.

E. MATHEMATICAL EQUATIONS

Following equations have been incorporated for calculating the results. Each of the below mentioned equations is necessary to calculate the value of receiving end power in both the cases i.e. HVAC System and Simultaneous HVAC-HVDC System. All the parameters are carefully measured after simulating the model stated above and later the values are substituted in the following equations to make quantitative assessment of the systems [26].

$$P_{ac\_Rec\_End} = 2 \times P_R \quad \text{------ (1)}$$

$$P_{ac\_Sen\_End} = 2 \times P_S \quad \text{------ (2)}$$

$$P_{dc\_Sen\_End} = 2 \times V_{Rect} \times I_{dc} \quad \text{------ (3)}$$

$$P_{dc\_Rec\_End} = 2 \times V_{Inv} \times I_{dc} \quad \text{------ (4)}$$

$$P_{total\_HVAC} = P_{ac\_Rec\_End} \quad \text{----- (5)}$$

$$P_{total\_HVAC\_HVDC} = P_{ac\_Rec\_End} + P_{dc\_Rec\_End} \quad \text{--- -(6)}$$

$$P_{loss\_ac} = P_{ac\_Rec\_End} - P_{dc\_sen\_End} \quad \text{----- (7)}$$

$$P_{loss\_dc} = P_{dc\_Rec\_End} - P_{dc\_Sen\_End} \quad \text{----- (8)}$$

$$P_{upgradation} = \frac{P_{total\_HVDC} - P_{total\_HVAC}}{P_{total\_HVAC}} \times 100 \quad \text{- (9)}$$

Where,

P_R = Receiving End Active Power,
P_S = Sending End Active Power,
$P_{ac\_Rec\_End}$ = Total Receiving End AC Power,
$P_{ac\_Sen\_End}$ = Total Sending End AC Power,
$P_{dc\_Rec\_End}$ = Total Receiving End DC Power,
$P_{dc\_Sen\_End}$ = Total Sending End DC Power,
V_{Rect} = Rectifier Voltage,
V_{Inv} = Inverter Voltage,
I_{dc} = DC link Current,
V_S= Sending End Voltage,
V_R= Receiving End Voltage,
I_S = Sending End Voltage,
I_R = Receiving End Voltage,
P_{total_HVAC} = Total Receiving End Power in HVAC System,
-$P_{total\_HVAC\_HVDC}$= Total Receiving End Power in combined HVAC & HVDC System,
P_{loss_ac} = Total ac losses,
P_{loss_dc} = Total dc losses,
$P_{upgradation}$ = Power Upgradation,

III. SIMULATION RESULTS

The loadabiltiy of a Moose, ACSR Bundled conductor, 400 kV, 50Hz, double circuit line has been computed at eight transmission line lengths in Simulink. Line Parameters:-

Resistance per unit line length = 0.01273 Ω/km,
Inductance per unit length =0.9337 mH/km,
Capacitance per unit length =12.74 nF/km.

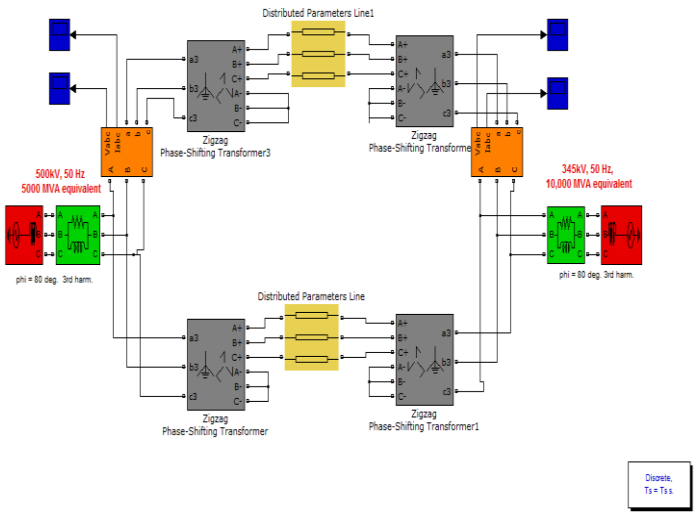

Fig.4. Simulink Model for a conventional HVAC Transmission System

Table I depicts the simulation results for a conventional HVAC Transmission System (**Fig.4**). To begin with various parameters have been calculated after simulating the respective model. Later the values were substituted in Equations 1 and 2 to calculate the total ac power at receiving end and sending end sides. All values have been calculated in megawatt. The penultimate column in this table exhibits the total sending end power and the last column shows the total receiving end power. The last column is later used to calculate the total power upgradation in the combined ac-dc system as compared to ac alone. Readings have been calculated for eight line lengths namely: 425km, 450km, 475km, 500km, 525km, 550km, 575km and 600km.

TABLE I-Power Analysis in a conventional HVAC System

S. No	Length (km)	P_S (MW)	P_R (MW)	$P_{ac\_Sen\_End}$ (MW)	$P_{ac\_Rec\_End}$ (MW)
1	425	304.4	169.2	608.8	338.4
2	450	293.7	158.6	587.4	317.2
3	475	283.9	149.2	567.8	298.4
4	500	275.1	140.6	550.2	281.2
5	525	267.2	132.9	534.4	265.8
6	550	260	125.8	520	251.6
7	575	253.4	119.4	506.8	238.8
8	600	247.4	113.5	494.8	227

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Volume 5, Issue 2, August 2015

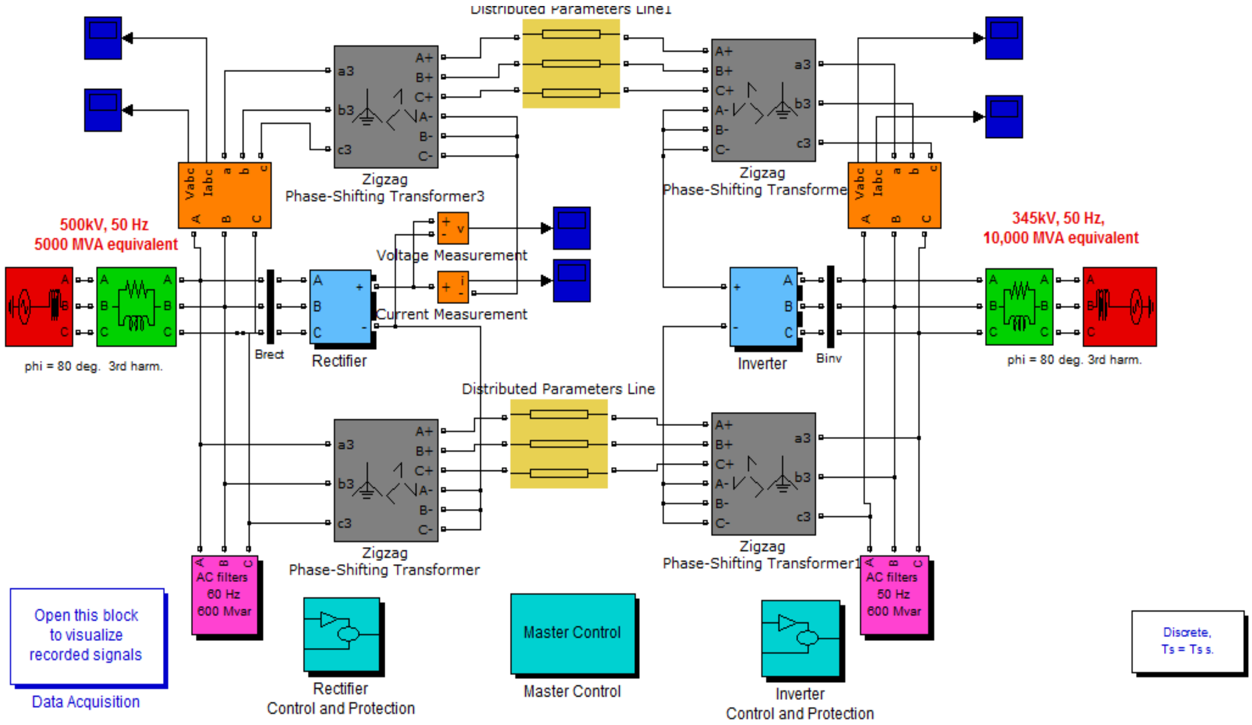

Fig.5. Simulink Model for a Simultaneous HVAC-HVDC Transmission System

Table II depicts the simulation results for a Simultaneous HVAC and HVDC Transmission System (**Fig.5**). To begin with various parameters have been calculated after simulating the respective model. Later the values were substituted in Equations 1-4 to calculate the total ac power at receiving end side, ac power at sending end side, dc power at sending end side and dc power at receiving end side. All values have been calculated in megawatt. All these values have been used to calculate the total power at receiving end inclusive of ac as well as dc component. This eventually has led to the calculation of power upgradation in the combined ac-dc system as compared to ac alone. Readings have been calculated for eight line lengths namely: 425km, 450km, 475km, 500km, 525km, 550km, 575km and 600km.

S.No	**Length (km)**	**P_S (MW)**	**P_R (MW)**	**$P_{ac\_Sen\_End}$ (MW)**	**$P_{ac\_Rec\_End}$ (MW)**	**$P_{dc\_Sen\_End}$ (MW)**	**$P_{dc\_Rec\_End}$ (MW)**
1	425	227.7	130.4	455.4	260.8	233.67	119.86
2	450	220.3	123.1	440.6	246.2	234.2	120.3
3	475	213.7	116.5	427.4	233	235.2	120.33
4	500	207.7	110.6	415.4	221.2	235.9	120.5
5	525	202.4	105.2	404.8	210.4	236.8	120.82
6	550	197.4	100.4	394.8	200.8	237.28	120.93
7	575	193	95.91	386	191.82	237.47	120.98
8	600	188.9	91.83	377.8	183.66	238.38	121.11

TABLE II-Power Analysis in Combined HVAC & HVDC System

Table III depicts the results for ac losses, dc losses in combined HVAC & HVDC Transmission System. Losses have been calculated with the help of Equations 1-4 and 7-8. The losses have been measured in 'kilowatt'. Losses have shown reasonable decrease as the line length increased. The difference between ac losses and dc losses showed a downward trend with every increase in line length. These losses have been computed at eight line lengths namely: 425km, 450km, 475km, 500km, 525km, 550km, 575km and 600km.

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ISO 9001:2008 Certified
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TABLE III-AC & DC Power Losses in Combined HVAC & HVDC System

S.No	Length (km)	P_{loss_ac} (kW)	P_{loss_dc} (kW)
1	425	457.88	267.7
2	450	432	253.11
3	475	409.26	241.83
4	500	388.4	230.8
5	525	370.28	220.9
6	550	352.72	211.54
7	575	337.7	202.59
8	600	323.56	195.45

Table IV depicts+ power upgradation in combined HVAC & HVDC Transmission System w.r.t HVAC Transmission System. It was interesting to note that Power transfer capacity enhanced for a combined system in comparison to a conventional HVAC System. As one may note by glancing at the Table IV, there has been a steady rise in power transfer capacity, about 3-4% for every increase in line length. While the power upgradation was merely 12.48% at 425km, it skyrocketed to 34.25% at 600km. Such a large increase indicated an upward trend in power upgradation with increase in line length.

TABLE IV-Power Upgradation in Combined HVDC & HVAC System w.r.t HVAC System

S.No	Length (km)	P_{total_HVAC} (MW)	$P_{total\_HVAC\_HVDC}$ (MW)	$P_{upgradation}$ (%)
1	425	338.4	380.66	12.48
2	450	317.2	366.5	15.54
3	475	298.4	353.33	18.48
4	500	281.2	341.7	21.51
5	525	265.8	331.22	23.48
6	550	251.6	321.73	27.87
7	575	238.8	312.8	30.98
8	600	227	304.77	34.25

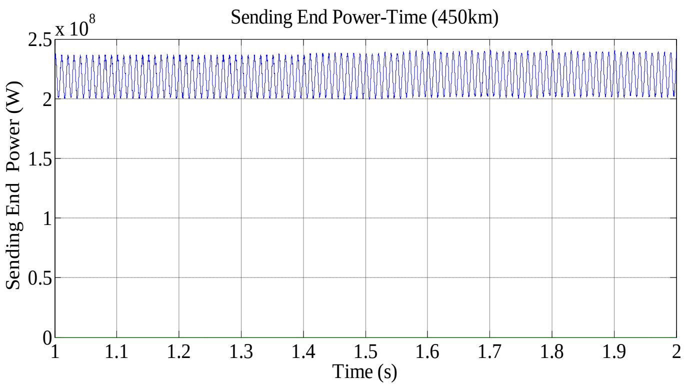

Fig.6.1. Sending End Power in HVAC Transmission System (450km)

Figure 6.1 depicted the Sending End Power of an HVAC Transmission System at 450km. The figure showed a three phase sinusoidal waveform amounting to 293.7 MW. Since this was a double circuit system the above computed value was multiplied by two to determine Total Sending End Power in HVAC System which was 587.4 MW. Likewise plots were studied at other line lengths as well.

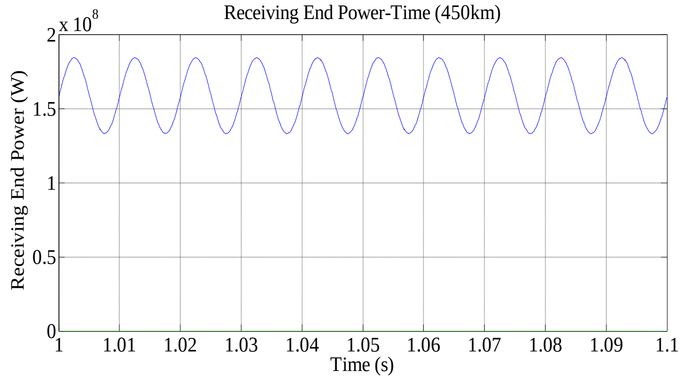

Fig.6.2.Receiving End Voltage in HVAC Transmission System (450km)

Figure 6.2 depicted the Receiving End Power of an HVAC Transmission System at 450km. The figure showed a three phase sinusoidal waveform amounting to 158.6 MW. Since this was a double circuit system the above computed value was multiplied by two to determine Total Receiving End Power in HVAC System which was 317.2 MW. Likewise plots were studied at other line lengths as well.

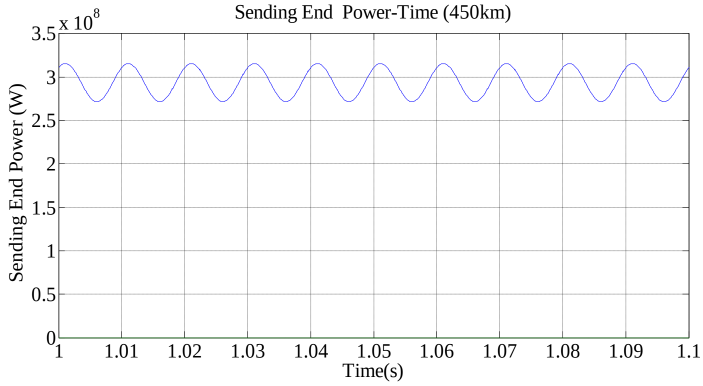

Fig.6.3.Sending End Power in Simultaneous HVAC-HVDC Transmission System (450km)

Figure 6.3 depicted the Sending End Power of a Simultaneous HVAC-HVDC Transmission System at 450km. The figure showed a three phase sinusoidal waveform amounting to 220.3 MW. Since this was a double circuit system the above computed value was multiplied by two and dc power component of 234.2 MW was added in order to determine Total Sending End Power in HVAC-HVDC System which was 674.8 MW. Likewise plots were studied at other line lengths as well.

Figure 6.4 depicted the Receiving End Power of a Simultaneous HVAC-HVDC Transmission System at 450km. The figure showed a three phase sinusoidal waveform amounting to 123.1 MW. Since this was a double circuit system the above computed value was multiplied by two and dc power component of 120.3 MW was added in order to determine Total Receiving End

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Volume 5, Issue 2, August 2015

Power in HVAC-HVDC System which was 366.5 MW. Likewise plots were studied at other line lengths as well.

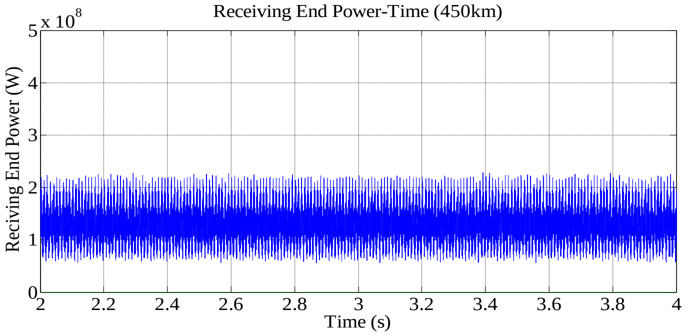

Fig.6.4.Receiving End Power in Simultaneous HVAC-HVDC Transmission System (450km)

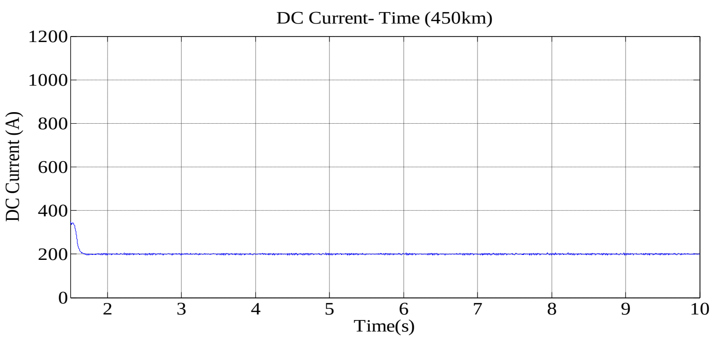

Fig.6.5. DC Current in Simultaneous HVAC-HVDC Transmission System (450km)

Figure 6.5.depicted the DC Current component of a Simultaneous HVAC-HVDC Transmission System at 450km. The figure showed a steady output amounting to 208.8 A. Since this was a double circuit system the above computed value was multiplied by two to determine total dc current component of 417.6 A. Likewise plots were studied at other line lengths as well. The results were consistent with each other with only negligible difference among them. The readings tended towards a pattern of constancy.

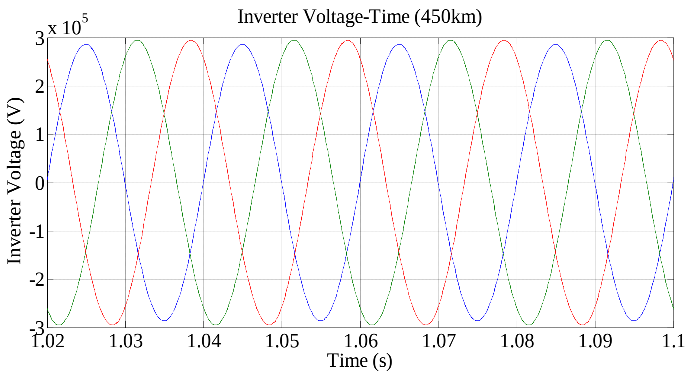

Fig.6.6. Inverter Voltage in Simultaneous HVAC-HVDC Transmission System (450km)

Figure 6.6.depicted the Inverter Voltage of a Simultaneous HVAC-HVDC Transmission System at 450km. The figure showed a three phase sinusoidal waveform amounting to 288.2 kV. Since this was a double circuit system the above computed value was multiplied by two to determine total receiving end dc voltage of 576.4 kV. Likewise plots were studied at other line lengths as well. The results were consistent with each other with a small difference among them. The readings tended towards a pattern of consistency.

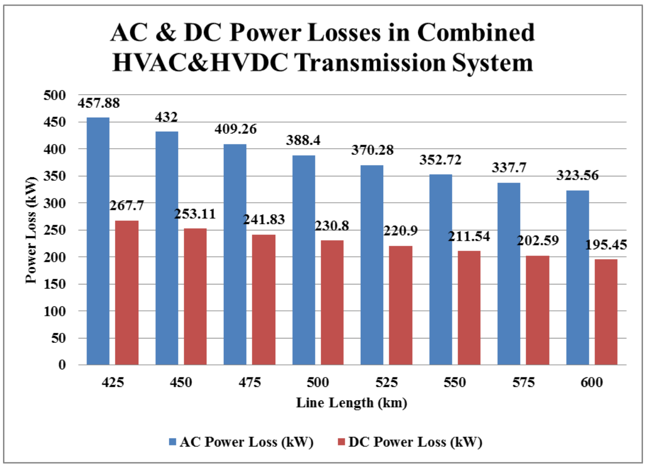

Fig.6.7. AC & DC Losses in Combined HVAC & HVDC System

Figure 6.7.depicted the AC and DC Losses in a Simultaneous HVAC-HVDC Transmission System at 425km, 450km, 475km, 500km, 525km, 550km, 575km and 600km. Both the losses showed a downward trend with each increase in line length. The value of ac losses reached a maximum of 457.88MW at 425km and a minimum of 323.56MW at 600km. Likewise dc losses also showed a downward trend with each increase in line length. The value of dc losses reached a maximum of 267.7MW at 425km and a minimum of 195.45MW at 600km.

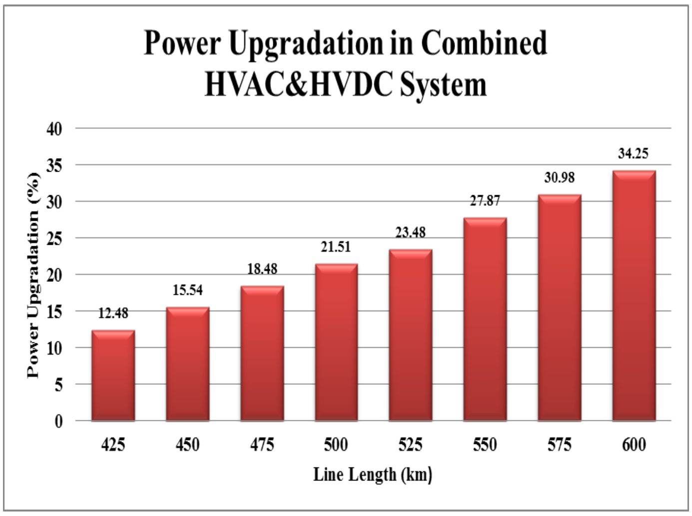

Fig.6.8. Power Upgradation in a Simultaneous HVAC-HVDC Transmission System

Figure 6.8 depicted the Power Upgradation in a Simultaneous HVAC-HVDC Transmission System w.r.t to an HVAC System at 425km, 450km, 475km, 500km, 525km, 550km, 575km and 600km. Power Upgradation was 12.48% at 425km, 15.54% at 450km, 18.48% at 475km, 21.51% at 500km, 23.48% at 525km, 27.87% at 550km, 30.98% at 575km and 34.25% at 600km. the data showed an increasing pattern with power upgradation being minimum at 425km and maximum at 600km. this only went on to prove that power transfer capacity increased with each increase in length.

IV. CONCLUSION

The possibility to convert an HVAC Transmission System into a Simultaneous HVAC & HVDC Transmission System has been demonstrated at different line lengths. AC and DC losses showed a tremendous decrease as the length of the line increased. Maximum losses have been recorded at 425km whereas minimum losses have been recorded at 600km. A 25km gap has been maintained between two successive lines. The gap between Receiving End Power in conventional HVAC system as compared to Receiving End Power in Simultaneous HVAC-HVDC Transmission System widened with increase in line length. Simultaneous HVAC-HVDC Transmission System registered heightened Power Upgradation as compared to their respective HVAC Systems. Power Upgradation enhanced as the length of the line increased. Power Transfer Capability was the least at 425km and the Power Upgradation Percentage almost tripled at 600km.

V. FUTURE SCOPE

This work has been performed for a double circuited set-up. However this could be extended to other types of systems as well. As is well known faults interrupt power flow in a line and it is mandatory to protect the system from its adverse effects. Therefore various protection equipment and protection schemes are incorporated. Considering this holdback one could employ suitable optimization technique to assess the effect of faults and relevant protection scheme to curb the same. Also the real challenge would be to practically adopt this scheme as it is yet to be implemented.

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