Improvement of Power System Stability by Simultaneous AC-DC Power Transmission

T.Vijay Muni, T.Vinoditha, D.Kumar Swamy

Abstract— This paper presents the concept of simultaneous ac-dc power transmission.Long extra high voltage (EHV) ac lines cannot be loaded to their thermal limits due to this instability occurs in the power system.With the scheme proposed in this paper,it is possible to load these lines very close to their thermal limits.The conductors are allowed to carry usual ac along dc superimposed on it.The advantage of parallel ac-dc transmission for improvement of transient stability and dynamic stability and dampout oscillations have been established.Simulation study is carried out in MATLAB software package.The results shows the stability of power system when compared with only ac transmission.

Index Terms— — Extra high voltage (EHV) transmission, flexiable ac transmission system (FACTS), HVDC, MATLab, simultaneous ac-dc transmission, Power System Stability, Transmission Efficeincy

1 INTRODUCTION

HVDC transmission lines in parallel with EHV ac lines are recommended to improve transient and dynamic stability as well as to damp out oscillations in power system. Long EHV ac lines can not be loaded to its thermal limit to keep sufficient margin against transient instability. But for optimum use of transmission lines here is a need to load EHV ac lines close to their thermal limits by using flexible ac transmission system (FACTS) components .Very fast control of SCRs in FACTS devices like state VAR system (SVS), controlled series capacitor (CSC), static phase shiftier (SPS) and controlled braking resistors oscillations as well as to control the voltage profile of the line by controlling the total reactive power flow. Only the basic idea is proposed along with the feasibility study using elementary laboratory model. The main object is to emphasize the possibility of simultaneous ac-dc transmission with its inherent advantage of power flow control improves stability and damps out oscillations in power system.

EHV ac line may be loaded to a very high value if the conductors are allowed to carry superimposed dc current along with ac current. The added dc power flow does not cause any transient instability.

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This paper presents a simple scheme of simultaneous EHV ac-dc power flow through the same transmission line with an object to achieve the advantages of parallel ac-dc transmission. Simultaneous ac-dc transmission may also claim advantages in some specific applications LV (low voltage) and MV (Medium voltage) system.

The flexible ac transmission system (FACTS) concepts, based on applying state-of-the-art power electronic technology to existing ac transmission system, improve stability to achieve power transmission close to its thermal limit. Another way to achieve the same goal is simultaneous ac–dc power transmission in which the conductors are allowed to carry superimposed dc current along with ac current. Ac and dc power flow independently, and the added dc power flow does not cause any transient instability.

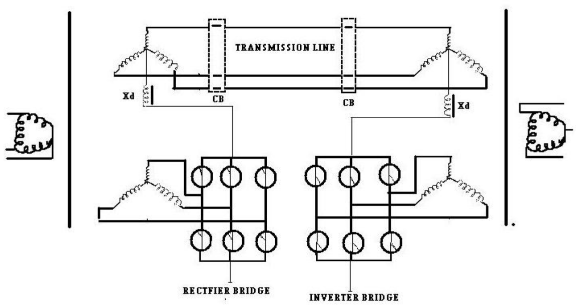

fig1 BASIC SCHEME FOR SIMULTANEOUS AC-DC TRANSMISSION

2 COCEPT OF SIMULTANEOUS AC-DC TRANSMISSION

The circuit diagram in Figure1 shows the basic scheme for simultaneous ac-dc transmission. The dc power is obtained through the rectifier bridge and injected to the neutral point of the zigzag connected secondary of sending end transformer, and again it is reconverted to ac by the inverter bridge at the receiving end. The inverter bridge is again connected to the neutral of zigzag connected winding of the receiving end transformer. Star connected primary windings in place of delta-connected windings for the transformers may also be used for higher supply voltage. The single circuit transmission line carriers both 3 –phase ac and dc power. It is to be noted that a part of the total ac power at the sending end is converted into dc by the tertiary winding of the transformer connected to rectified bridge. The same dc power is reconverted to ac at the received end by the tertiary winding of the receiving end transformer connected to the inverter bridge. Each conductor of the line carries one third of the total dc current along with ac current I_a .The return path of the dc current is through the ground. Zigzag connected winding is used at both ends to avoid saturation of transformer due to dc current flow. A high value of reactor, X_d is used to reduce harmonics in dc current.

In the absence of zero sequence and third harmonics or its multiple harmonic voltages, under normal operating conditions, the ac current flow will be restricted between the zigzag connected windings and the three conductors of the transmission line. Even the presence of these components of voltages may only be able to produce negligible current through the ground due to high of X_d.

Assuming the usual constant current control of rectifier and constant extinction angle control of inverter, the equivalent circuit of the scheme under normal steady state operating condition is shown in Fig.2.

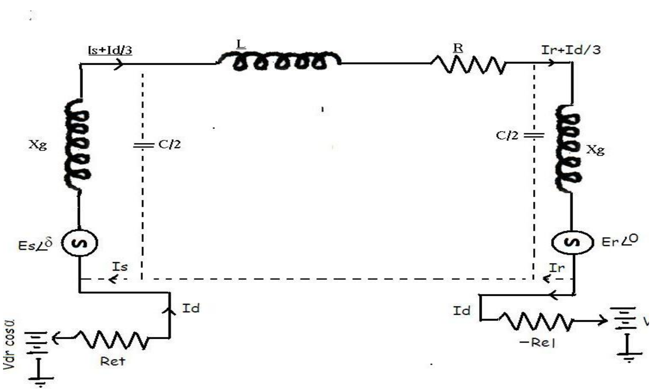

figure 2 Equivalent circuit

The dotted line in the figure shows the path of ac return current only. The ground carries the full dc current I_d only and each conductor of the line carries $I_d/3$ along with the ac current per phase

The expressions for ac voltage and current and the power equations in terms of A,B,C and D parameters of each line when the resistive drop in transformer winding and in the line conductors due to dc current are neglected can be written as

Sending end voltage:

$V_s = AV_R + BI_R$ (1)

Sending end current:

$I_s = CV_R + DI_R$ (2)

Sending end power:

$P_{s+jQS} = (-V_S V^*_R)/B^* + (D^*/B^*)Vs^2$ (3)

Receiving end power:

$P_{R+jQR} = (V_S^* V_R)/B^* - (A^*/B^*)V_R^2$ (4)

The expressions for dc current and the dc power, when the ac resistive drop in the line and transformer are neglected,

Dc current:

$I_d = (V_{dr}\cos\alpha - V_{di}\cos\gamma)/(R_{er}+(R/3) - R_{ci})$ (5)

Power in inverter:

$P_{di} = V_{di} \times I_d$ (6)

Power in rectifier:

$P_{dr} = V_{dr} \times I_d$ (7)

Where R is the line resistance per conductor, R_{cr} and R_{ci} commutating resistances, α and γ, firing and extinction angles of rectifier and inverter respectively and V_{dr} and V_{di} are the maximum dc voltages of rectifier and inverter side respectively. Values of V_{dr} and V_{di} are 1.35 times line to line tertiary winding ac voltages of respective sides.

Reactive powers required by the converters are:

$Q_{di} = P_{di}\tan\theta_I$ (8)

$Q_{dr} = P_{dr}\tan\theta_r$ (9)

$\cos\theta_I = (\cos\gamma + \cos(\gamma + \mu_i))/2$ (10)

$\cos\theta_r = (\cos\alpha + \cos(\alpha + \mu_r))/2$ (11)

Where μ_I and μ_r are commutation angles of inverter and rectifier respectively and total active and reactive powers at the two ends are

$P_{st} = P_s + P_{dr}$ and $P_{rt} = P_R + P_{di}$ (12)

$Q_{st} = Q_s + Q_{dr}$ and $Q_{rt} = Q_R + Q_{di}$ (13)

Total transmission line loss is:

$P_L = (P_s + P_{dr}) - (P_R + P_{di})$ (14)

I_a being the rms ac current per conductor at any point of the line, the total rms current per conductor becomes:

$I = \mathrm{sqrt}(I_a^2 + (I_d/3)^2)$ and $P_L \cong 3I^2R$ (15)

If the rated conductor current corresponding to its allowable temperature rise is I_{th} and

$I_a = X * I_{th;}$ X being less than unity, the dc current becomes:

$I_d = 3 \times (\mathrm{sqrt}(1-x^2))\, I_{th}$ (16)

The total current I in any conductor is asymmetrical but two natural zero-crossings in each cycle in

current wave are obtained for $(I_d/3I_a)$ <1.414.
The instantaneous value of each conductor voltage with respect to ground becomes the dc voltage V_d with a superimposed sinusoidally varying ac voltages having rms value E_{ph} and the peak value being:

$E_{max} = V + 1.414\, E_{ph}$

Electric field produced by any conductor voltage possesses a dc component superimposed with sinusoidally varying ac component. But the instantaneous electric field polarity changes its sign twice in cycle if $(V_d/E_{ph}) < 1.414$.Therefore, higher creepage distance requirement for insulator discs used for HVDC lines are not required.

Each conductor is to be insulated for E_{max} but the line to line voltage has no dc component and $E_{LL(max)} = 2.45$ Eph.Therefore, conductor to conductor separation distance is determined only by rated ac voltage of the line.

Assuming $V_d/E_{ph} = k$

$$P_{dc}/'P_{ac} \cong (V_d * I_d)/(3 * E_{ph} * I_a * \cos\theta) = (k * \mathrm{sqrt}(1-x^2))/(x * \cos\theta) \quad (17)$$

Total power

$$P_t = P_{dc} + P_{ac} = (1 + [k * \mathrm{sqrt}(1-x^2)]/(x * \cos\theta)) * P_{ac} \quad (18)$$

Detailed analysis of short current ac design of protective scheme, filter and instrumentation network required for the proposed scheme is beyond the scope of present work, but preliminary qualitative analysis presented below suggests that commonly used techniques in HVDC/ac system may be adopted for this purposes.

In case of fault in the transmission system, gate signals to all the SCRs are blocked that to the bypass SCR s are released to protect rectifier and inverter bridges. CBs are then tripped at both ends to isolate the complete system. As mentioned earlier, if (I_d3I_a) <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. Else CB's connected to the delta side of transformers (not shown in figure1) may be used to isolate the fault. Saturation of transformer core, if any, due to asymmetric fault current reduces line side current but increases primary current of transformer. Delta side CBs, designed to clear transformers terminal faults and winding faults, clear these faults easily.

Proper values of ac and dc filters as used in HVDC system may be connected to the delta side and zigzag neutral respectively to filter out higher harmonics from dc and ac supplies. However, filters may be omitted for low values of V_d and I_d.

At neutral terminals of zigzag winding dc current and voltages may be measured by adopting common methods used in HVDC system. Conventional cvts as used in EHV ac lines are used to measure ac component of transmission line voltage. Superimposed dc voltage in the transmission line does not affect the working of cvts. Linear couplers with high air-gap core may be employed for measurement of ac component of line current as dc component of line current is not able to saturate high air-gap cores.

Electric signal processing circuits may be used to generate composite line voltage and current waveforms from the signals obtained for dc and ac components of voltage and current. Those signals are used for protection and control purposes.

3 Selection of Transmission Voltage

The instantaneous value of each conductor voltage with respect to ground becomes more in case of simultaneous ac-dc transmission system by the amount of the dc voltage superimposed on ac and more discs are to be added in each string insulator to withstand this increased dc voltage. However, there is no change required in the conductor separation distance, as the line-to-line voltage remains unaltered. Therefore, tower structure does not need any modification if same conductor is used.Another possibility could be that the original ac voltage of the transmission be reduced as dc voltage is added such that peak voltage with respect to ground remain unchanged. Therefore, there would be no need to modify the towers and insulator strings.

4 Proposed Applications

1.Long EHV ac lines can not be loaded to their thermal limit to keep sufficient margin against transient instability and to keep voltage regulation within allowable limit, the simultaneous power flow does not imposed any extra burden on stability of the system, rather it improves the stability. The resistive drop due to dc current being very small in comparison to impedance drop due to ac current, there is also no appreciable change in voltage regulation due to superimposed dc current.

2. Therefore one possible application of simultaneous ac-dc transmission is to load the line close to its thermal limit by transmitting additional dc power. Figure3 shows the variation of Pt/Pac for changing values of k and x at unity power factor. However, it is to be noted that additional conductor insulation is to be provided due to insertion of dc.

3. Necessity of additional dc power transmission will be experienced maximum during peak load period which is characterized with lower than rate voltage. If dc power is injected during the peak loading period only with V_d being in the range of 5% to 10% of E_{ph}, the same transmission line without having any enhanced insulation level may be allowed to be used For

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a value of x=0.7 and V_d =0.05 E_{ph} or 0.10 E_{ph}, 5.1% or 10.2% more power may be transmitted.

4.By adding a few more discs in insulator strings of each phase conductor with appropriate modifications in cross-arms of towers insulation level between phase to ground may be increased to a high value, which permits proportional increase in E_{max}, Therefore higher value of V_d may be used to increase dc and total power flow through the line. This modification in the exiting ac lines is justified due to high cost of a separate HVDC line.

5. With the very fast electronic control of firing angle (α) and extinction angle (γ) of the converters, the fast control of dc power may also be used to improve dynamic stability and damping out oscillations in the system similar to that of the ac-dc parallel transmission lines.

6. Control of α and γ also controls the rectifier and inverter VAR requirement and therefore, may be used to control the voltage profile of the transmission line during low load condition and works as inductive shunt compensation. It may also be considered that the capacitive VAR of the transmission line is supplying the whole or part of the inductive VAR requirement of the converter system. In pure HVDC system capacitance of transmission line cannot be utilized to compensate inductive VAR.

7. The independent and fast control of active and reactive power associated with dc, superimposed with the normal ac active and reactive power may be considered to be working as another component of FACTS.

8. Simultaneous ac-dc power transmission may find its application in some special cases of LV and MV distribution system.

When 3-phase power in addition to dc power is supplied to a location very near to a furnace or to a work place having very high ambient temperature, rectification of 3-phase supply is not possible at that location using semiconductor rectifier. In such place simultaneous ac-dc transmission is advantageous.

In air craft 3-phase loads are generally fed with higher frequency supply of about 400Hz and separate line is used for dc loads. Skin effect restricts the optimum use of distribution wires at high frequency. Simultaneous ac-dc power transmission reduces both volume and weight of distributors.

9. Another possible application is the transmission of dc power generated by PV solar cells directly to remote dc loads through 3-phase ac line. In all cases of separate dc supply filter networks are not required.

5 Experimental Verification

The feasibility of the basic scheme of simultaneous ac-dc transmission was verified in the laboratory. Transformer having a rating of 2 kVA, 400/230/110V are used at each end. A supply of 3-phase, 400V, 50Hz are given at the sending end and a 3-phase, 400 V, 50 Hz,1 HP induction motor in addition to a 3-phase, 400V, 0.7 KW resistive load was connected at the receiving end. A 10 A, 110 Vdc reactor (Xd) was used at each end with the 230V zigzag connected neutral. Two identical SCR bridges were used for rectifier and inverter. The dc voltages of rectifier and inverter bridges were adjusted between 145 V to135 V to vary dc current between 0 to 3A.

The same experiment was repeated by replacing the rectifier at the sending and and the inverter at receiving end by 24V battery and a 5A, 25 rheostat respectively, between Xd and ground.

The power transmission with and without dc component was found to be satisfactory in all the cases. To check the saturation of zigzag connected transformer for high value of I_d, ac loads were disconnected and dc current was increased to 1.2 times the rated current for a short time with the input transformer kept energized from 400V ac. But no changes in exciting current and terminal voltage of transformer were noticed verifying no saturation even with high value of I_d.

6 Simulation Results

The loadability of Moose (commercial name), ACSR, twinbundle conductor, 400-kV, 50-Hz, 450-km double circuit line has been computed.

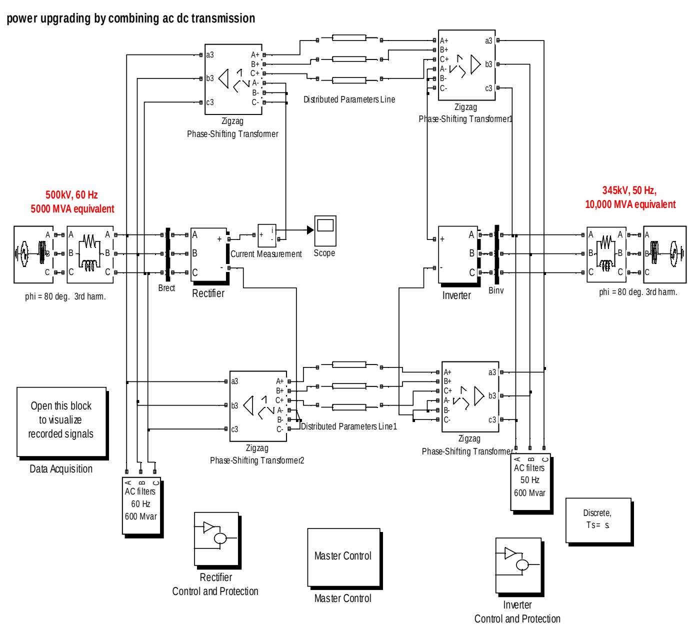

Fig 3: Simulink Model of Simultaneous AC-DC Transmission

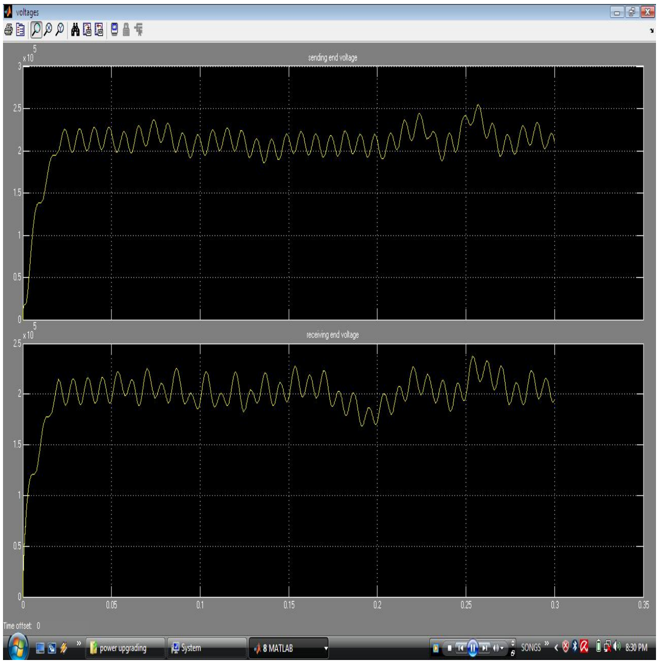

Fig 4 Sending end and receiving end voltages

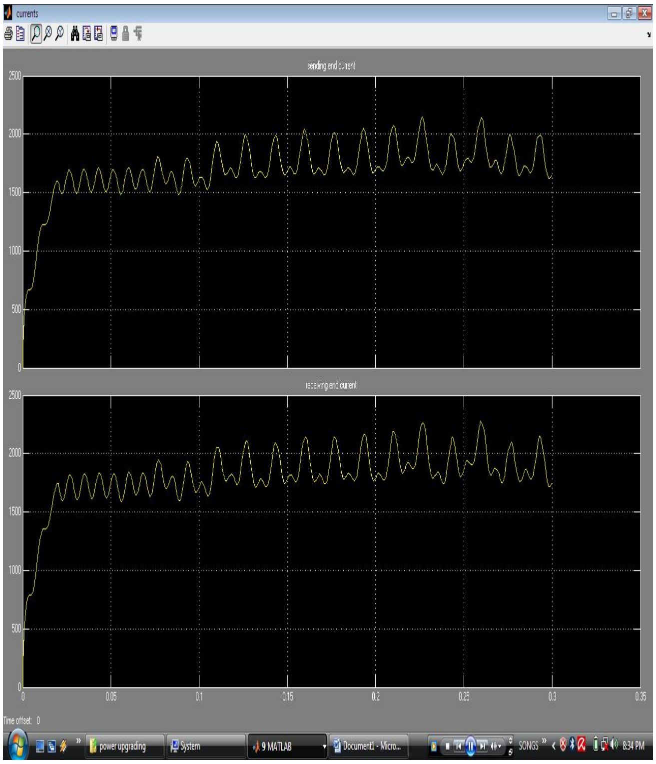

Fig 5: Sending and receiving currents

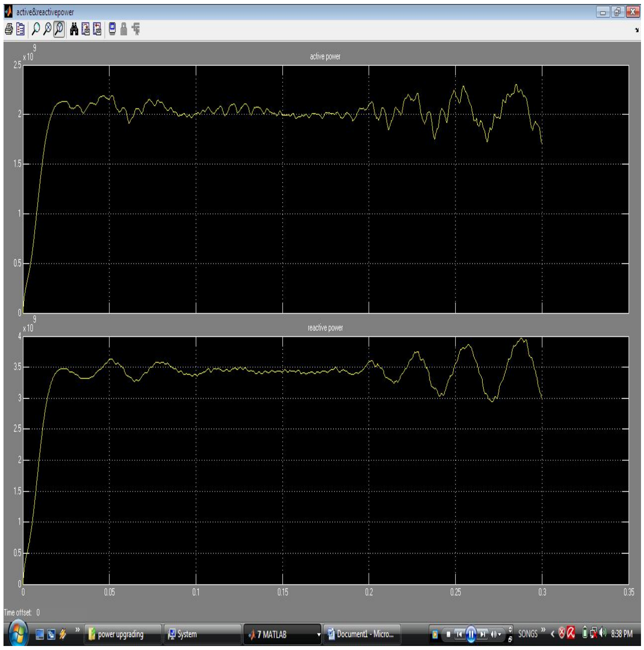

Fig 6: Combined AC-DC currents

TABLE I
COMPUTED RESULTS

Power Angle	30	45	60	75
AC Current(kA)	0.416	0.612	0.80	0.98
DC Current(kA)	5.25	5.07	4.80	4.50
AC Power(MW)	290	410	502	560
DC Power(MW)	1685	1625	1545	1150
Total Power(MW)	1970	2035	2047	1710

TABLE II
SIMULATION RESULTS

Power Angle	30	45	60	75
P_S (MW)	2306	2370	2380	2342
P_{ac} (MW)	295	410	495	540
P_{dc} (MW)	1715	1657	1585	1498
P_{ac} loss (MW)	12	30	54	82
P_{dc} loss (MW)	280	265	241	217
P_R (MW)	1988	2050	2060	1995

7 Conclusion

A simple scheme of simultaneous EHV ac-dc power transmission through the same transmission line has been presented. Expressions of active and reactive powers associated with ac and dc, conductor voltage level and total power have been obtained for

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steady state normal operating condition. The possible applications of the proposed scheme may be listed as: loading a line close to its thermal limit, improvement of transient and dynamic stability and damping of oscillations. In LV and MV distribution system the proposed scheme may be applied in a workplace having high ambient temperature or fed with high frequency supply or with PV solar cells. Only the basic scheme has been presented with qualitative assessment for its implementation. Details of practical adaptation are beyond the scope of the present work.

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