Analysis of Power Flow in Ac-Dc Transmission System with Communication Link Between Remote Terminals

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Abstract— The transient instability of a transmission line imposes severe limits on the amount of power being transferred in EHV ac systems at any given power angle. As the power transfer increases the line tends to become unstable. A combined ac-dc transmission line increases the power transfer capability of the line by considerable margin without causing any transient instability. The transmission line is allowed to carry a superimposed dc along with the ac current without any major changes in the existing line. The additional advantage is that the capacitive VAR of the line can be used to compensate for the leading VAR consumed by the converters. This paper presents the analysis of a combined ac-dc system with respect to the power flow in a converted and an unconverted line. The advantages of parallel ac-dc transmission is achieved with damping of the oscillations and independent control of ac and dc power transmissions. Substantial gain in the loadability of the line is obtained. The master current controller senses the ac current and regulates the dc current orders for the converters on line such that conductor current never exceeds its thermal limit.

Key words: Transient instability, HVDC transmission, Flexible ac transmission systems, SIMULINK

I. INTRODUCTION

MATLAB/SUMULINK is a high-performance, multifunctional software that uses functions for numerical computations, system simulation and application development[1]. Power System Blockset (PSB) is one of its design tools for modeling and simulating electric power systems within the SIMULINK environment. It contains a block library with components and devices found in electrical power networks that are based on electromagnetic and electromechanical equations[2]. PSB/SIMULINK can be used for modeling and simulation of both power and control systems. PSB solves the system equations through state-variable analysis using either fixed or variable integration time-step. The linear dynamics of the system are expressed through continuous or discrete time-domain state-space equations. It also offers the flexibility of choosing from a variety of integration algorithms[3].

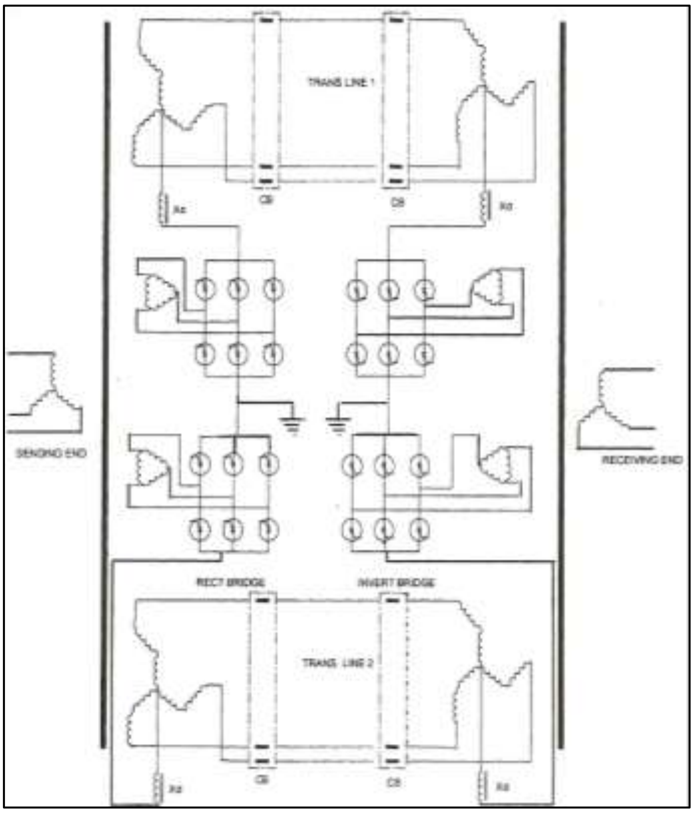

Fig. 1: Basic scheme for simultaneous AC-DC Transmission

Fig.1.shows the basic scheme for simultaneous ac-dc power flow through a double circuit transmission line [4]. The dc power is obtained through the rectifier bridge and injected into the neutral point of the zig-zag connected secondary of sending end transformer and is converted to ac again by the inverter bridge at the receiving end. The inverter bridge is again connected to the neutral of zig-zag connected winding of the receiving and transformer. The transmission line carries both three phase ac and dc power. A part of the total ac power at the sending end is converted into dc by the rectifier. The same dc power is reconverted into ac at the receiving end by the inverter.

Each conductor of each line carries one third of the total dc current along with the ac current I_a[5]. The return path of the dc current is through the three conductors of the second transmission line. Zig-zag connected winding is used at both the 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 the zero sequence and third harmonics or its multiple harmonic voltages, under normal operating conditions, the ac current flow is restricted between zig-zag connected windings and the three conductors of each transmission line[6]. Even the presence of these components of voltages may only be able to produce negligible current through the ground due to high value of X_d.

Assuming the usual constant current control of the rectifier and constant extinction angle control of the inverter, the equivalent circuit of the scheme under steady–state condition is shown in fig 2[4]. The dotted line shows the path of ac return current only. The second transmission line carries the return dc current I_d and each conductor of the line carries $I_d/3$ along with the ac current per phase.

Neglecting the resistive drops in the line conductors and transformer windings due to dc current, expressions for ac voltage and current and for active and reactive powers may be written in terms of A, B, C, and D parameters of each line as:

$$E_s = AE_R + BI_R \quad (1)$$

$$I_S = CE_R + DI_R \quad (2)$$

$$P_S + jQ_S = -E_S E_R^* / B^* + D^* E_S^2 / B^* \quad (3)$$

$$P_R + jQ_R = E_S^* E_R / B^* - A^* E_R^2 / B^* \quad (4)$$

Neglecting ac resistive drop in the line and transformer, the dc power P_{dr} and P_{di} of rectifier and inverter may be expressed as:

$$P_{dr} = V_{dr} I_d \quad (5)$$

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

Reactive powers required by the converters are

$$Q_{dr} = P_{dr} \tan \theta_r \quad (7)$$

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

Where

$$\cos \theta_r = [\cos \alpha + \cos(\alpha + \mu_r)] / 2 \quad (9)$$

$$\cos \theta_i = [\cos \gamma + \cos(\gamma + \mu_i)] / 2 \quad (10)$$

μ_i and μ_r are overlap angles of the inverter and rectifier respectively.

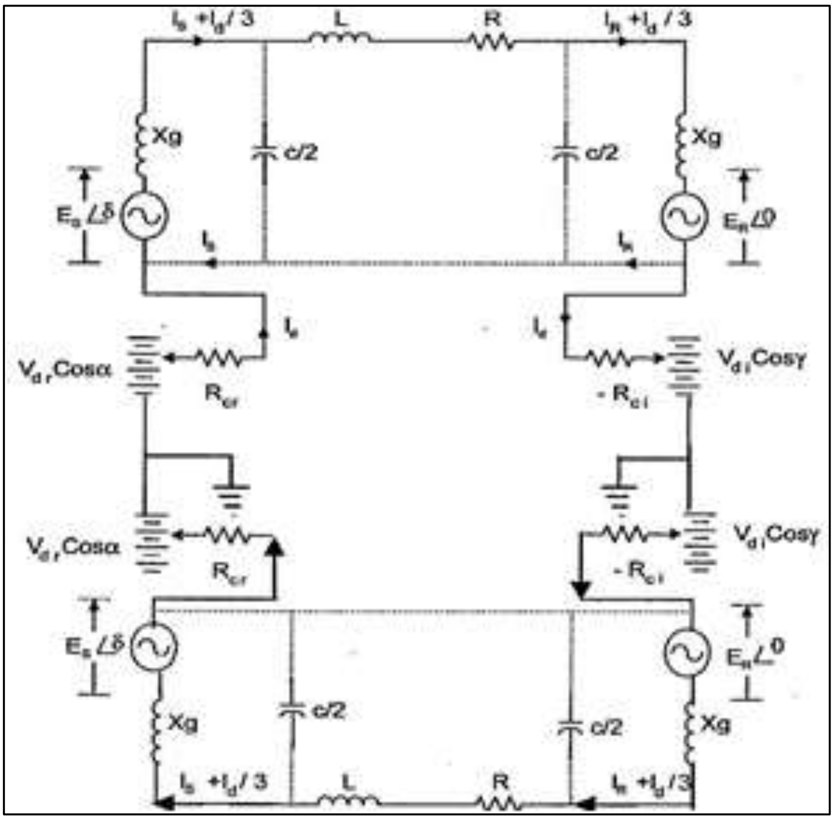

Fig. 2: Equivalent Circuit[1]

The total active and reactive powers at the two ends are:

$$P_{st} = P_s + P_{dr} \text{ and } P_{rt} = P_r + P_{di} \quad (11)$$

$$Q_{st}=Q_s+Q_{dr} \text{ and } Q_{rt} = Q_R + Q_{di} \quad (12)$$

Transmission losses for each line is

$$P_L = (P_s + P_{dr}) – (P_r + P_{di}) \quad (13)$$

Ia being the rms ac current per conductor at any point in the line, the total rms current per conductor becomes:

$$I = [\, I_a^2 + (I_d/3)^2]^{1/2} \quad (14)$$

Power loss for each conductor = I^2R

Power loss for each line $=P_L \approx 3I^2R$

The total current I in any conductor is asymmetrical but two natural zero–crossings in each cycle of the current wave are obtained if $I_d/I_a<3\sqrt{2}$ and the CBs at the two ends of the line interrupt current at natural zero and no special dc CBs are required. Allowing the maximum value of current in each conductor of the converted line to be equal to I^{th}, the thermal limit,

$$I_{th} = [\, I_a^2 + (I_d/3)^2]^{1/2} \quad (15)$$

Let V_{ph} and V_a be the rms ac voltages per phase of the line before and after conversion, respectively. The instantaneous value of each conductor voltage with respect to ground becomes the dc voltage vd with a superimposed sinusoidally varying ac voltage having rms value Va and the peak value being

$$V_{max} = \sqrt{2}\, V_{ph} = V_d + \sqrt{2}\, V_a \quad (16)$$

Each conductor is to be insulated for V_{max} but the line to line voltage of each line has no dc component and therefore.

$$V_{LL\ max} = \sqrt{6}\ Va$$

Allowing the asymmetrical voltage wave of each conductor with respect to ground to be zero at least once in each cycle;

$$V_d = V_{ph}/\sqrt{2} \text{ and } V_a = V_{ph}/2 \quad (17)$$

The approximate total power transfer through the double circuit line before conversion is

$$P'_{total} \approx 3V_{ph}^{\ 2} Sin\,\delta_1 / X \quad (18)$$

X is the transfer reactance per phase of the double circuit line δ_1 is the power angle between the voltages at the two ends.

The approximate total power transfer through the converted line is

$$P_{total}=P_{ac} + P_{dc} = 3V_a^2 \text{ Sin } \delta_2/X + 2V_dI_d \quad (19)$$

The power angle δ_2 between the ac voltages at the two ends of the converted line may be increased to a high value because of the fast controllability of P_{dc}. For a constant value of total power, P_{dc} may be modulated by fast control of the current controllers of the dc power converters.

Approximate value of ac current per phase per circuit of the double circuit line is

$$I_{ph}/Ckt =V_a(\text{Sin } \delta/2)/X \quad (20)$$

Preliminary qualitative analysis suggests that commonly used techniques in HVDC/AC system may be adopted for the purpose of the design of protective scheme, filter and instrumentation network to be used with the converted line for simultaneous ac-dc power flow[7]. In case of a fault in the transmission system, gate signals to all the SCRS are blocked and that to the by-pass SCRS are released to protect the rectifier and inverter bridges[8]. Circuit Breakers are then tripped at both the ends to isolate the complete system. A surge diverter connected between the zig-zag neutral and ground protects the converter bridge against any over voltage. Saturation of the transformer in case if any, due to asymmetrical fault current, reduces line side current but increases the primary current of transformer. Star side CBS, designed to clear transformer terminal voltage and winding faults, clear these faults easily.

Proper values of ac and dc filters as used in HVDC system may be connected to the star side and zig-zag neutral respectively to filter out higher harmonics from dc and ac supplies.

DC current and voltages may be measured at zig-zag winding neutral terminals by adopting common methods used in HVDC system. AC component of the transmission line voltage is measured with conventional CVTS used in EHV ac lines. 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. DC component of line current is not able to saturate high air-gap cores[9].

Electrical 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.

II. RESEARCH METHOD

A. CIGRE HVDC Benchmark System

The single line diagram of the first CIGRE HVDC benchmark system is shown in fig 3[10]. The system is a monopolar 500 kV, 1000MW HVDC link with 12-pulse converters on both rectifier and inverter sides, connected to weak ac systems (short circuit ratio of 2.5 at a rated frequency of 50HZ) that provide a considerable degree of difficulty for dc controls. Damped filters and capacitive reactive compensation are also provided on both sides. The power circuit of the converter consists of the following sub-circuits:

1) HVDC System

a) AC side

The AC sides of the HVDC system consist of supply network, filters and transformers on both sides of the converter. The ac supply network is represented by a Thevenin equivalent voltage source with equivalent source impedance. AC filters are added to absorb the harmonics generated by the converter as well as to supply reactive power to the converter.

b) DC Side

The dc side of the converter consists of smoothing reactors for both rectifier and the inverter side. The dc transmission line is represented by an equivalent T- network, which can be tuned to fundamental frequency to provide a difficult resonant condition for the modeled system.

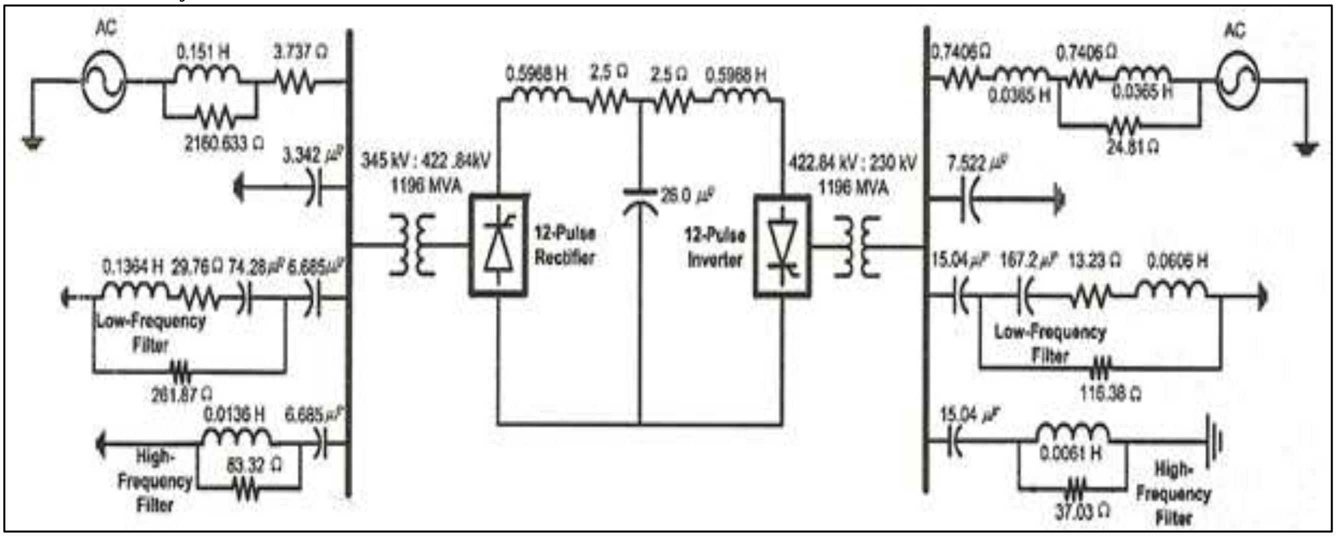

Fig. 3: Single line diagram of CIGRE benchmark HVDC system

2) Converter

The converter stations are represented by 12-pluse configuration with two six-pulse valves in series. In the actual converter, each valve is constructed with many thyristors in series. Each valve has a (di/dt) limiting inductor, and each thyristor has parallel RC snubbers.

B. Cigre Hvdc System Model in Psb/Simulink

1) Power Circuit Modeling[11]

a) Converter Model

The converters (rectifier and inverter) are modeled using six-pulse Graetz bridge block, which includes an internal Phase Locked Oscillator (PLO), firing and valve blocking controls, and firing angle (α)/extinction angle (γ) measurements. It also includes built-in RC snubber circuits for each thyristor. Thyristor valves are modeled as ideal devices, and therefore, negative turn-off and firing due to large (dv/dt) or (di/dt) are not considered.

b) Converter Transformer Model

Two transformers on the rectifier side are modeled by three-phase two winding transformer, one with grounded wye-wye connection and the other with grounded wye-delta connection. The model uses saturation characteristic and tap setting arrangement. The inverter side transformers use a similar model.

c) DC Line Model

The dc line is modeled using an equivalent-T network with smoothing reactors inserted on both sides.

d) Supply Voltage Source

The supply voltage on both rectifier and inverter sides have been represented through three phase ac voltage sources.

e) Filters and Reactive Support

Tuned filters and reactive support are provided at both the rectifier and the inverter ac sides, as shown in Fig.3.

2) Control System Model

The control model mainly consists of α/γ measurements and generation of firing signals for both the rectifier and inverter. The PLO is used to build the firing signals. The output signal of the PLO is a ramp, synchronized to the phase- A commutating bus line-to-ground voltage, which is used to generate the firing signal for Valve1. The ramps for other valves are generated by adding 60˚ to the valve 1 ramp. As a result, an equidistant pulse is realized. The actual firing time is calculated by comparing the α order to the value of the ramp and using interpolation technique. At the same time, if the valve is pulsed but its voltage is still less than the forward voltage drop, this model has a logic to delay firing until the voltage is exactly equal to the forward voltage drop. The firing pulse is maintained across each valve for 120˚.

The α and γ measurement circuits use zero-crossing information from commutating bus voltages and valve switching times and then convert this time difference to an angle (using measured PLO frequency). Firing angle α (in seconds) is the time when valve i turns on minus the zero crossing time for valve i. Extinction angle γ (in seconds) for valve i is the time at which the commutation bus voltage for valve i crosses zero (negative to positive) minus the time valve i turns off. Following are the controllers uses in the control schemes:

1) Extinction Angle (γ) Controller;
2) DC Current Controller;
3) Voltage Dependent Current Limiter (VDCOL).

a) Rectifier Control

The rectifier control system uses Constant Current Control (CCC) technique. The reference for current limit is obtained from the inverter side. This is done to ensure the protection of the converter in situations when inverter side does not have sufficient dc voltage support (due to fault) or does not have sufficient load requirement (load rejection). The reference current used in rectifier control depends on the dc voltage available at the inverter side. DC current on the rectifier side is measured using proper transducers and passed through necessary filters before they are compared to produce the error signal. The error signal is then passed through a PI controller, which produces the necessary firing angle order α. The firing circuit uses this information to generate the equidistant pulses for the valves using the technique described earlier.

b) Inverter control

The extinction angle Control or γ control and current control have been implemented on the inverter side. The CCC with Voltage Dependent Current Order Limiter (VDCOL) has been used here through PI controllers. The reference limit for the current control is obtained through a comparison of the external reference (selected by the operator or load requirement) and VDCOL (implemented through lookup table) output. The measured current is then subtracted from the reference limit to produce an error signal that is sent to the PI controller to produce the required angle order. The γ control uses another PI controller to produce gamma angle order for the inverter. The two angle orders are compared, and the minimum of the two is used to calculated the firing instant.

III. RESULTS AND ANALYSIS

Assuming the following values for V_a and V_d the theoretically computed values for various quantities are shown in table I.

V_a = per phase rms value of the ac component of the composite ac-dc line with superimposed dc

V_d = superimposed dc voltage

X= transfer reactance per phase of the double circuit transmission line

$V_d = V_{ph}/\sqrt{2}$ $\quad$ $Va = V_{ph}/2$

Where V_{ph}=ac voltage /ph/circuit

Assuming the line voltage to be 400kV

V_{ph} = 231kV

V_a =115.47kV

V_d =163.36Kv

To have a zero crossing in the line voltage wave V_a has been increased from 115.47kV to 120kV and V_d has been decreased from 163.36 to 160kV that is

V_a=120kV

V_d=160kV

A. Calculated Results

Power Angle(δ) Degrees	30°	45°	60°	75°	80°
Ac power(MW) Pac = $3V_a^2 Sin(\delta)/X$	290	410	502.61	560.6	571.55
Ac current Ia(KA)=Va Sin(δ/2)X	0.4166	0.612	0.805	0.98	1.035
Dc current(KA)= $3\sqrt{I_{th}^2 - I_a^2}$	5.253	5.07	4.829	4.529	4.418
Dc power Pdc(MW)= $2V_d * I_d$	1684.8	1624.9	1545.5	1149.44	1413.76
$P_{total} = P_{ac} + P_{dc}$ (MW)	1971	2034	2048	2010	1985

Table 1: Computed Results

B. Simulated Results

Assuming X=74.4435/ph and the surge impedance loading of 1124.2MW, the simulated results are shown in table II

Power Angle(δ)	**30°**	**45°**	**60°**	**75°**	**80°**
Ps(MW)	2246	2546	3181	2272	4626
Pac(MW) transfer	690	1111	1224	67880	599.9
Pdc(MW) transfer	1574	1585	2108	3951	5526
Pac-loss(MW)	150	993.3	-467.8	-2370	-3961
Pdc-loss(MW)	1401	196.9	763.6	2670	4267
Ploss-total(MW)	290	296.2	295.8	299.6	306
Pr(MW) total transfer	2114	2597	3332	71830	6125
Dc current Id (KA)	5.242	5.085	4.608	11.57	3.595
Percentage increase of power transfer	76.94	82.49	83.51	79.66	77.5

Table 2: Simulated Results

IV. CONCLUSION

In this paper it was attempted to simulate a combined ac-dc system in the SIMULINK environment. Various quantities of combined ac-dc system are computed and the simulated values are found to be in close conformity with the computed results. At various powers transmission angles the dc power flow, ac power flow, the total transfer, dc current, and conductor current are computed. The most important things to be verified for successful simulation is the power transfer in the combined ac-dc system. In the combined ac-dc power transfer is considerably more at all the power angles.

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