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Choice of best transmission line conductor and percentage line compensation required in order to achieve best power evacuation scheme for IPP's

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Abstract: *Private participation in generating power is being encouraged in the country in order to meet high power requirement. As a result, many independent power producers (IPP) are establishing pit head thermal power stations. Many a times, the IPPs have to execute a contract with the state electricity board, under whose jurisdiction the location of the generating plant comes up lies, that a certain percentage of the installed capacity of the plant shall be supplied to the state grid and the balance power can be supplied to others. In such cases, there is a requirement for precisely controlled power flow over a transmission line between the IPP's generating station and the state grid substation at which the contracted power is to be delivered and provision for evacuating the balance power to nearby state grid substation. In a case where the installed capacity of the IPP is 500 MW, 300MW of power shall be supplied to the state grid whenever the generation is more than 300MW and full generated power if the generation is less than 300 MW. To achieve this control of power flow is essential. Hence it is required to select best conductor is required in order to reduce transmission losses and selection of percentage of compensation required to achieve control over the power flow in an AC transmission line. In this paper performance analysis is carried out in order to select best transmission line conductor amongst various conductors available and also percentage line compensation required to reduce reactive power flow and to control voltage and current in an AC transmission line.*

Keywords: *ACSR, Bersimis, conductor, twin, triple, quad moose conductor, line compensation etc..*

I INTRODUCTION

All transmission lines in a power system exhibit the electrical properties of resistance, inductance, capacitance and conductance. The inductance and capacitance are due to effects of magnetic and electric fields around the conductor. These parameters are essential for the development of the transmission line models used in power system analysis. The shunt conductance accounts for leakage currents flowing across insulators and ionized pathways in the air. The leakage currents are negligible compared to the current flowing in the transmission line and may be neglected. On long transmission lines, light loads are appreciably less than SIL results in a rise of voltage at the receiving end and heavy loads appreciably greater than SIL will produce dip in voltage. Shunt reactors are widely used to reduce high voltages under light load or open line conditions. Series compensation is used to improve voltage, increase power transfer, and the system stability. In this paper analysis is carried out in order to select best conductor amongst various conductors and also compensation required to reduce reactive power flow and to control voltage and current in AC transmission line.

II LINE PARAMETERS

2.1. Line resistance: The DC resistance [2] of a solid round conductor at a specified temperature is given by

$$R_{dc} = \boldsymbol{\sigma} \mathbf{l}/\mathbf{A} \tag{2.1}$$

Where R_{dc}= DC resistance.
$\boldsymbol{\sigma}$= conductor resistivity.
$\boldsymbol{l}$ = conductor length.
A= conductor cross sectional area.

The conductor resistance is affected by three factors: frequency, spiraling, and temperature. When AC flows in a conductor, the current distribution is not uniform over the conductor cross sectional area and the current density is greatest at the surface of the conductor. This causes the ac resistance to be somewhat higher than the DC resistance. This behavior is known as skin effect. At 50 Hz, the ac resistance is about 2 percent higher than the DC resistance. The conductor resistance increases as temperature increases. This change can be considered linear over the temperature normally encountered and may be calculated from

$$R_t = R_o(1 + \alpha t) \tag{2.2}$$

Where R_t= resistance at t degree Celsius
$R_{0=}$ resistance at 0^o Celsius.
t= Temperature rise above 0^o Celsius
α= Temperature coefficient of resistivity $1/^o$C.

In practice the resistivity and temperature coefficient are measured and specified for t=20°C. Practical equations with reference to t=20°C

$$\mathrm{Rdc} = \mathrm{R}_{20}[1 + \alpha_{20}(\mathrm{t})] \tag{2.3}$$

Where R_{dc}= DC resistance in ohm/km
R_{20}= DC resistance at 10°C.
t= temperature of conductor.
α= Temperature coefficient of resistance at 20°C, in $1/^o$C.

For copper conductor α_{20}= 0.00393, for aluminum conductor α_{20}= 0.00403, for lead sheath of cables α_{20}= 0.00393, and for galvanized steel α_{20}= 0.0032 to 0.0039. Due to spirallity, R_{dc} of a stranded conductor is more than simple un-stranded conductor. Multiplying factor for spirallity K_{sp}= 1.02 to 1.05.AC resistance of conductors is higher than DC resistance due to following

Skin effect factor Ks: Multiplying factor depends upon frequency and cross sectional area of conductor
Ks= 1.007 for 50Hz and A=1.6cm^2, Ks= 1.02 for 50Hz and A= 3.2cm^2, Ks= 1.1 for 50Hz and A=6.5cm^2

Proximity effect factor Kp: This is neglected for overhead lines. This is to be taken into account for cables. Effective AC resistance is expressed in terms of multiplying factors into DC resistance

$$R_{ac} = K\, R_{dc} \tag{2 .4}$$

Where

$$K = Ksp\ Ks\ Kp \tag{2.5}$$

2.2 Inductance of Three Phase Double Circuit Lines: A three phase double circuit line consists of two identical three phase circuits. The circuits are operated with a1-a2, b1-b2 & c1-c2 in parallel. Because of geometrical differences between conductors, voltage drop due to line inductance will be unbalanced. To achieve balance, each phase conductor must be transposed within its group and with respect to the parallel three phase line. Consider a three phase double circuit line with relative positions a1 b1 c1-c2 b2 a2, as shown in fig 1.1 [3].The GMD (Geometric Mean Distance) between each phase group

$$\mathrm{Dab} = (\mathrm{Da1b1\ Da1b2\ Da2b1\ Da2b2})^{1/4} \tag{2.6}$$
$$\mathrm{Dbc} = (\mathrm{Db1c1\ Db1c2\ Db2c1\ Db2c2})^{1/4} \tag{2.7}$$
$$\mathrm{Dac} = (\mathrm{Da1c1\ Da1c2\ Da2c1\ Da2c2})^{1/4} \tag{2.8}$$

The equivalent GMD per phase is then

$$\mathrm{GMD} = (\mathrm{Dab\ Dbc\ Dac})^{1/3} \tag{2.9}$$

Similarly the GMR(Geometric Mean radius) of each phase group is

$$\mathrm{Dsa} = (\mathrm{Ds\ Da1a2})^{1/4} \tag{2.10}$$
$$\mathrm{Dsb} = (\mathrm{Ds\ Db1b2})^{1/4} \tag{2.11}$$
$$\mathrm{Dsc} = (\mathrm{Ds\ Dc1c2})^{1/4} \tag{2.12}$$

Where Ds is the geometric mean radius of the bundled conductors.
The equivalent geometric mean radius for calculating the per phase inductance to neutral is

$$\mathrm{GMR} = (\mathrm{Dsa\ Dsb\ Dsc})^{1/3} \tag{2.13}$$

The inductance per phase in henries per kilometer is

$$\mathrm{L} = 0.2\ln\left(\frac{\mathrm{GMD}}{\mathrm{GMR}}\right) \tag{2.14}$$

Where L is inductance per phase in henries per kilometer.

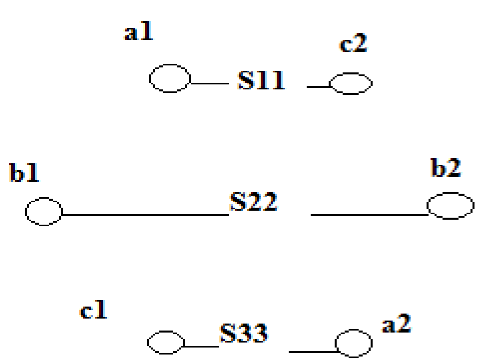

Fig 2.1Transposed double circuit line

2.3 Capacitance of A Three Phase Double Circuit Lines: Transmission line conductors exhibits capacitance with respect to each other due to the potential difference between them. The amount of capacitance between conductors is a function of conductor size, spacing, and height above ground. Consider a three phase double circuit line with relative phase positions a1b1c1-a2b2c2, as shown in fig1. Each phase conductor is transposed within its group and with respect to the parallel three phase line. The effect of shield wires and the ground are considered to be negligible for this condition. Per phase equivalent capacitance to neutral is obtained to be [3]

$$C = (2\pi\epsilon o)/\ln(\frac{GMD}{GMR}) \qquad (2.15)$$

Where C is capacitance to neutral in farad per kilometer.
Capacitance to neutral in Farad per kilometer is.

$$C = 0.0556/\ln(\frac{GMD}{GMR}) \qquad (2.16)$$

2.4 Corona: When the surface potential gradient of a conductor exceeds the dielectric strength of the surrounding air, ionization occurs in the area close to the conductor surface. This partial ionization is known as corona. Corona produces power loss, audible hissing sound in the vicinity of the line, ozone and radio and telephone interference. Corona is a function of conductor diameter, line configuration, type of conductor, and condition of its surface. Atmospheric conditions such as air density, humidity and wind influence the generation of corona. Corona can be reduced by increasing the conductor size and the use of conductor bundling. The power loss associated with corona can be represented by shunt conductance g. However, under normal operating conditions g, which represents the resistive leakage between phase and ground, has negligible effect on performance and is customarily neglected. (i.e... g=0) [3]

2.5 Surge Impedance Loading: When the line is loaded by being terminated with impedance equal to its characteristic impedance, the receiving end current is given [3]

$$Ir = Vr/Zc \qquad (2.17)$$

For a lossless line Z_c is purely resistive. The load corresponding to the surge impedance at rated voltage is known as the Surge Impedance Loading (SIL).

$$SIL = 3V_rI_r = 3 * V_r * \frac{Vr}{Zc} \qquad (2.18)$$

$$V_r = V_{rated}/\sqrt{3} \qquad (2.19)$$

SIL is a useful measure of transmission line capacity as it indicates a loading where the line's reactive requirements are small. For loads significantly above SIL, shunt capacitors may be needed to minimize voltage drop along the line, while for light loads significantly below SIL, shunt inductors may be needed. Generally the transmission line full load is much higher than SIL.

2.6 Thermal Loading: The power handling ability of a line is limited by the thermal loading limit and stability limit. The increase in the conductor temperature, due to the real power loss, stretches the conductor. This will increase the sag between transmission towers. At higher temperatures this may result in irreversible stretching. The thermal limit is specified by the current carrying capacity of the conductor and is available in the manufacturer's data. If the current carrying capacity is denoted by $I_{thermal}$, the thermal loading limit of a line is

$$S_{thermal} = 3 * V_{rated} * I_{thermal} \qquad (2.20)$$

Where, V_{rated} is the rated voltage of the transmission line.

2.7 Power Transmission Capability: According to the power transfer equation, the theoretical max power transfer is obtained when $\delta = 90$. The practical load angle for the line alone is limited to no more than 30 to 45. This is because of the generator and transformer reactance, which, when added to the line, will result in larger δ for a given load. For planning and other purposes, it is very useful to express the power transfer formula in terms of SIL. For a loss less line 3Φ power is given by

$$\mathbf{P3\Phi} = \left(\frac{\mathbf{Vs(L-L)}}{\mathbf{Vrated}}\right) * \left(\frac{\mathbf{Vr(L-L)}}{\mathbf{Vrated}}\right) * \left(\frac{\mathbf{Vrated^2}}{\mathbf{Zc}}\right) * \left(\frac{\mathbf{sin\partial}}{\mathbf{sin\beta_L}}\right) \qquad (2.21)$$

Where, β= line phase constant= $2 * \pi * f * \sqrt{L * C}$.
$\boldsymbol{\partial}$= load angle.
V_s (L-L) = sending end line to line voltage.
V_r(L-L)= receiving end line to line voltage.
Z_c= surge impedance= $\sqrt{L/C}$.
L= Line inductance.
C= line Capacitance.

2.8 Line Compensation:

2.8.1 Shunt Reactors: Shunt reactors are applied to compensate for the undesirable voltage effects associated with line capacitance. The amount of reactor compensation required on a transmission line to maintain the receiving end voltage at a specified value can be obtained as follows

$$\mathbf{X_{lsh}} = \left(\frac{\mathbf{\sin\beta l}}{\mathbf{1-\cos\beta l}}\right) * \mathbf{Z_c} \qquad (2.22)$$

The three phase shunt reactor rating is

$$Q = (kV)rated^2/X_{lsh} \quad Mvar \qquad (2.23)$$

Where, V_{rated} = rated transmission voltage in kV.

2.8.2 Series Capacitor Compensation: Series compensation is proposed at the receiving end of the line as it helps in boosting up the receiving end bus voltage to small extent and causes corresponding increases in the power transmitted. Series capacitors are connected in series with the line and are used to reduce the series reactance between the load and the supply point. This results in improved transient and steady state stability, more economical loading and min voltage dip on load buses. Series capacitors have the good characteristics that their reactive power production varies concurrently with the line loading. With the series capacitor the power transfer over the line for a lossless line is given by

$$\mathbf{P3\emptyset} = \frac{\mathbf{abs(Vs(L-L)) * abs(Vr(L-L) * \sin\partial}}{\mathbf{X - X_{cser}}} \qquad (2.24)$$

Where, X= line reactance.

X_{cser}= series capacitor reactance.

The ratio Xcser/X expressed as percentage is usually referred to as the percentage compensation. The percentage compensation is in the range of 25 to 70 percent. One major drawback with series capacitor compensation is that special protective devices are required to protect the capacitors and bypass the high current produced when a short circuit occurs [3].

III LINE PARAMETERS CALCULATION

3.1 Line parameters:

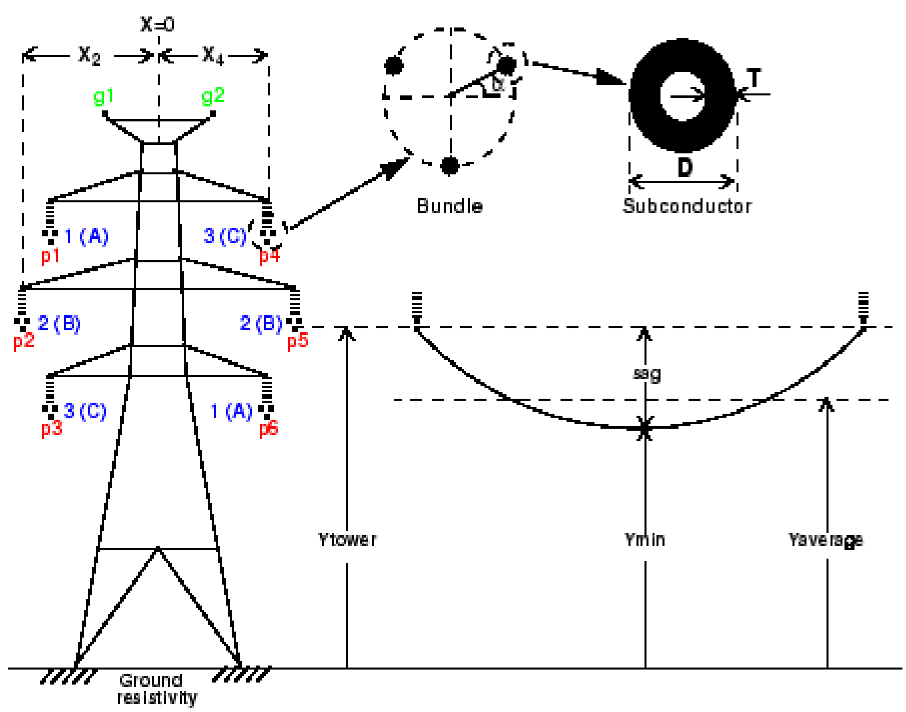

Fig 3.1 Configuration of a Three-Phase Double-Circuit Line

The line considered is a double circuit with standard vertical configuration, both circuits on the same tower. The same line configuration is used irrespective of the type of conductor for line loading performance comparison purpose. Table 3.1 shows the line resistance, inductive reactance per km of the line length.

Table 3.1 Line parameter for different conductors

SI NO	Conductor configuration	Resistance (Ω/km)	Inductive reactance (Ω/km)	Susceptance (micro-mho/km)
1	Twin moose ACSR	0.028713	0.31337	3.698
2	Twin moose AAAC	0.029490	0.31319	3.7
3	Quad moose ACSR	0.014655	0.25107	4.625
4	Quad moose AAAC	0.015048	0.25090	4.627
5	Triple moose ACSR	0.01934	0.2753	4.211
6	Quad Bersimis ACSR	0.011415	0.24960	4.6546

3.2 Line Loading For Chosen Conductor Configuration: The power transfer capability of the line with different conductors and their bundle configuration is investigated. The different conductors and their bundle configuration considered are Twin moose ACSR & AAAC, Quad moose ACSR & AAAC, Triple moose ACSR and Quad Bersimis ACSR. Line lengths considered were 315 km representing X sending end and Y receiving end. The series compensation is proposed at the receiving end of the line as it helps in boosting up the receiving end bus voltage to a small extent and causes corresponding increase in power transmitted. The line is provided with minimum shunt compensation of 50 x 2 MVAr per circuit to control the line voltage during light load and line charging conditions and absorb excessive reactive power generated during total load throw off at Y receiving end.

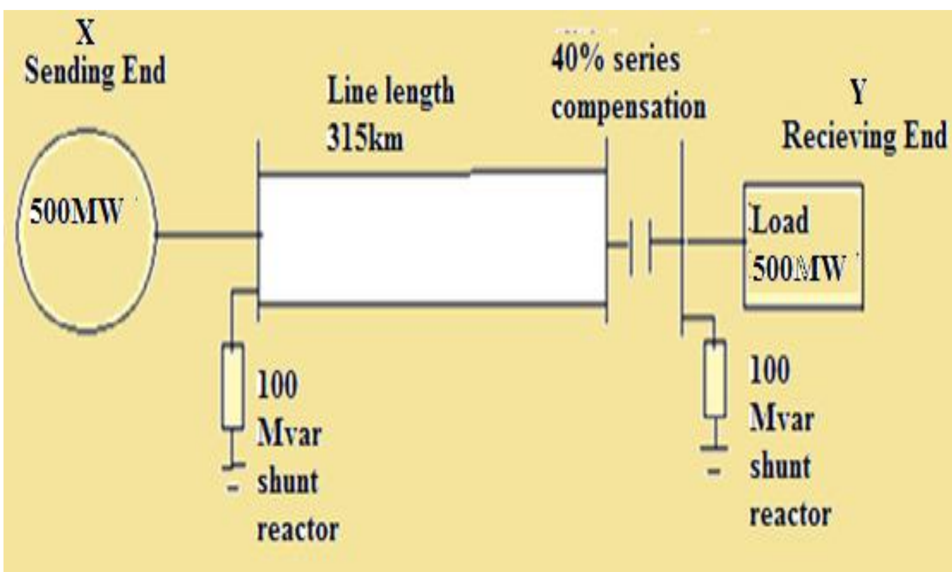

Fig 3.2 Line configuration

The line configuration is as shown in fig 3.2. The results of the computation of Thermal Loading, Surge impedance loading line real power flows, various bus voltages, and generator power factor and line real power losses with 30% and 40% series compensation at Receiving end using MATLAB Program are shown in table 3.2, 3.3 and 3.4. It could be observed from the result that even with the quad bundle configuration of Bersimis conductor for the 315km, 400kv double circuit line, it is not possible to receive 500MW at Y receiving end. It shall be noted that under normal circumstances, the power available at the sending end of the line is about 8% less of the rated generation capacity due to consumption by the auxiliary loads in the generating station itself. This makes the maximum power it could be received at Y receiving end to be 453MW.

Table3.2 Line Loading for Line configuration shown in fig 3.2

SI NO	Conductor	Thermal rating		Thermal loading	SIL Per circuit	Loading Limit Of 315km Line Per circuit	Loading Limit with 50% shunt compensation per circuit	Loading Limit with 50% shunt compensation and 40% series compensation per circuit
	Name	amp	temp	MW	MW	MW	MW	MW
1	Twin Moose ACSR	450	75	675	548	713	504	840
2	Twin Moose AAAC	450	85	962	548	713	504	840
3	Quad Moose ACSR	457	75	1350	686	892	630	1050
4	Quad Moose AAAC	457	85	1924	686	892	630	1050

Table 3.3 Line Loading for Line configuration shown in fig 3.2

SI No	Conductor	Line length	% Series Compensation At receiving end	Vs	Vr	Pr	Qr
	Name			(KV)	(KV)	(MW)	(MVAr)
1	Twin Moose ACSR	315	40	411.377	400	500	242
			30	411.383	400	500	242
2	Twin Moose AAAC	315	40	411.685	400	500	242
			30	411.691	400	500	242
3	Quad Moose ACSR	315	40	405.808	400	500	242
			30	405.813	400	500	242
4	Quad Moose AAAC	315	40	405.964	400	500	242
			30	405.968	400	500	242
5	Triple Moose ACSR	315	40	407.663	400	500	242
			30	407.668	400	500	242
6	Quad Bersimis ACSR	315	**40**	**404.529**	**400**	**500**	**242**
			30	404.533	400	500	242

Table 3.4 Line Loading for Line configuration shown in fig 3.2

Ps	Qs	PL	QL	PFs	PFr
(MW)	(MVAr)	(MW)	(MW)		
517.443	242.114	17.443	0.114	0.905753	0.9
517.443	242.133	17.443	0.133	0.90574	0.9
517.915	242.114	17.915	0.114	0.905901	0.9
517.915	242.133	17.915	0.133	0.905888	0.9
508.903	242.091	8.903	0.091	0.903028	0.9
508.903	242.107	8.903	0.107	0.903018	0.9
509.141	242.091	9.141	0.091	0.903106	0.9
509.141	242.106	9.141	0.106	0.903096	0.9
511.749	242.100	11.749	0.100	0.903948	0.9
511.749	242.117	11.749	0.117	0.903936	0.9
506.934	**242.091**	**6.934**	**0.091**	**0.902381**	**0.9**
506.934	242.106	6.934	0.106	0.90237	0.9

Hence a line with quad bundle Bersimis conductor and 40% compensation would be more than adequate between X end and Y end than other conductors.

3.3 Case Studies: Estimation of power loss at different line loadings for various line configurations is carry out in forthcoming sections.

3.3.1 Case study 1: Estimation of power loss for the given line configuration shown in fig 3.3.

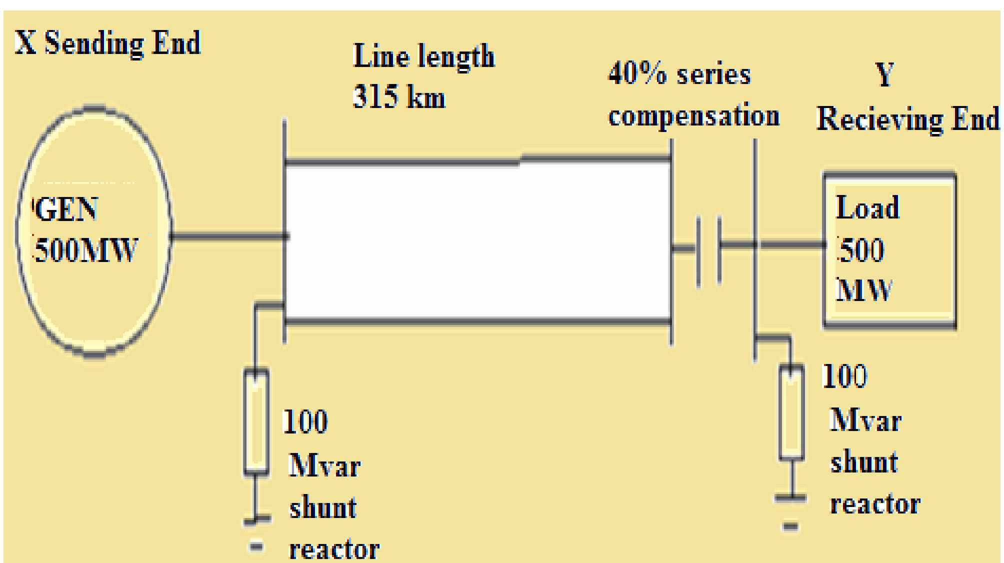

Fig 3.3 Line configuration for case study1

Table 3.5 Results of line configuration shown in fig 3.3

SI NO	Conductor	Vs	Vr	Ps	Pr	Qs	Qr	PL	QL
		(KV)	(KV)	(MW)	(MW)	(MVAr)	(MVAr)	(MW)	(MVAr)
1	Quad Bersimis ACSR	**404.529**	400	**506.934**	500	242.091	242	**6.934**	0.091

It shall be noted that under normal circumstances, the power available at the sending end of the line is about 8% less of the rated generation capacity due to consumption by the auxiliary loads in the generating station itself. It could be observed from result that the maximum power could be received at receiving end Y is 453MW [500MW-PL-8%(500MW)].

3.3.2 Case study 2: Estimation of power loss for the given line configuration shown in fig 3.4.

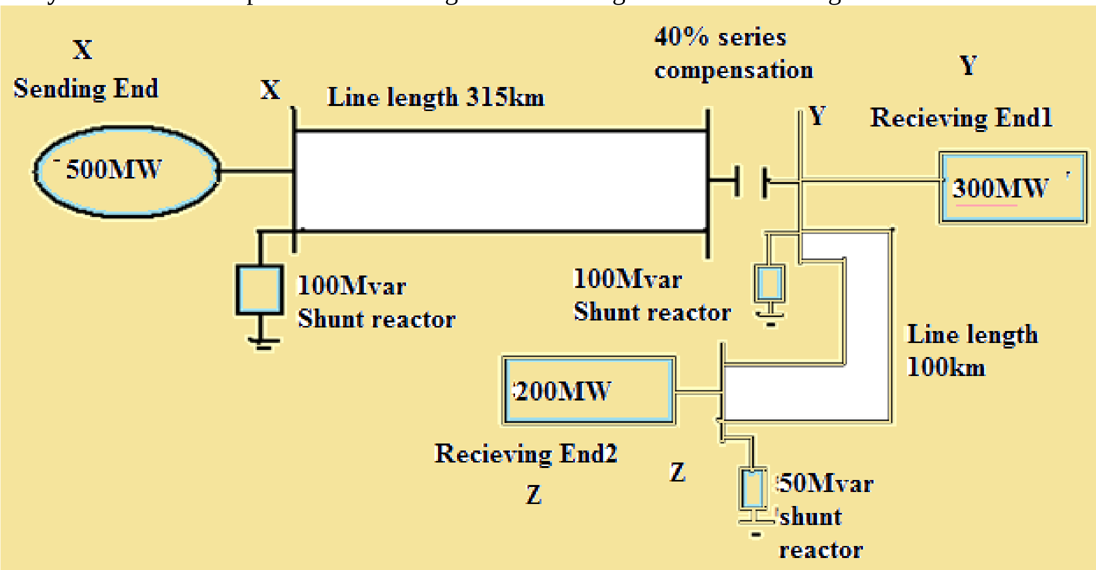

Fig 3.4 line configuration for case study 2

It shall be noted that under normal circumstances, the power available at the sending end of the line is about 8% less of the rated generation capacity due to consumption by the auxiliary loads in the generating station itself. It could be observed from the result that maximum power that could be received at Y receiving end is 453MW [500MW-PL-8 %(500MW)]. Out of this 453MW, 300MW is loaded to Y end and remaining power to Z end. Maximum power that could be received at Z end is 152.66MW [153MW - PL(Y-Z)].

Table 3.6 Results of line configuration shown in fig 3.4

SI NO	Sending End(X) voltage	Receiving End1(Y) voltage	Receiving End2(Z) voltage	MW load at receiving End1(Y)	MW load at Receiving End2(Z)	PL(X-Y) 315km	PL(Y-Z) 100km	Total loss
						(MW)	(MW)	(MW)
	(PU)	(PU)	(PU)					
1	1.00	1.012	1.00	300	200	**6.934**	0.339	7.27

3.3.3 Case study 3: Estimation of power loss for the given line configuration shown in fig 5.3. It shall be noted that under normal circumstances, the power available at the sending end of the line is about 8% less of the rated generation capacity due to consumption by the auxiliary loads in the generating station itself. It could be observed from the result that maximum power that could be received at X receiving end is 456 [500- P_L(Sending End-X)-8%(500MW)]. Out of this 456MW, 300MW is transmitted to Y end and remaining power to Z receiving end. Maximum power that could be received at Y end is 298.95MW [300MW- PL(X-Y)]. And Maximum power that could be received at Z end is 155.9MW [156- PL(X-Z)].

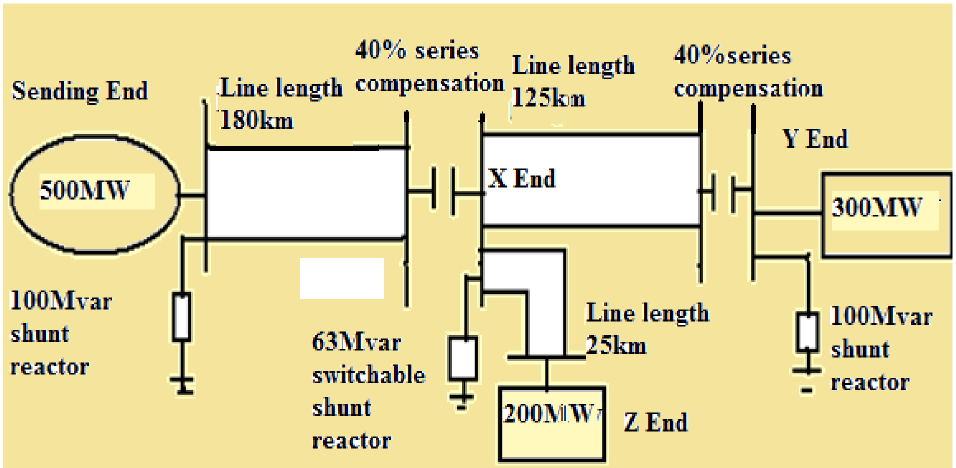

Fig 5.5 Line configuration for case study 3

Table 5.7 Results of line configuration shown in fig 5.5

Vs	Vx	Vy	Vz	Load at Z	Load at Y	PL(Sending End-X) 180km	PL(X-Z) 25km	PL(X-Y) 135km	Total Loss
(PU)	(PU)	(PU)	(PU)	(MW)	(MW)	(MW)	(MW)	(MW)	(MW)
1.00	1.01	1.00	1.00	200	300	3.963	0.086	1.042	5.091

3.3.4 Case study 4:

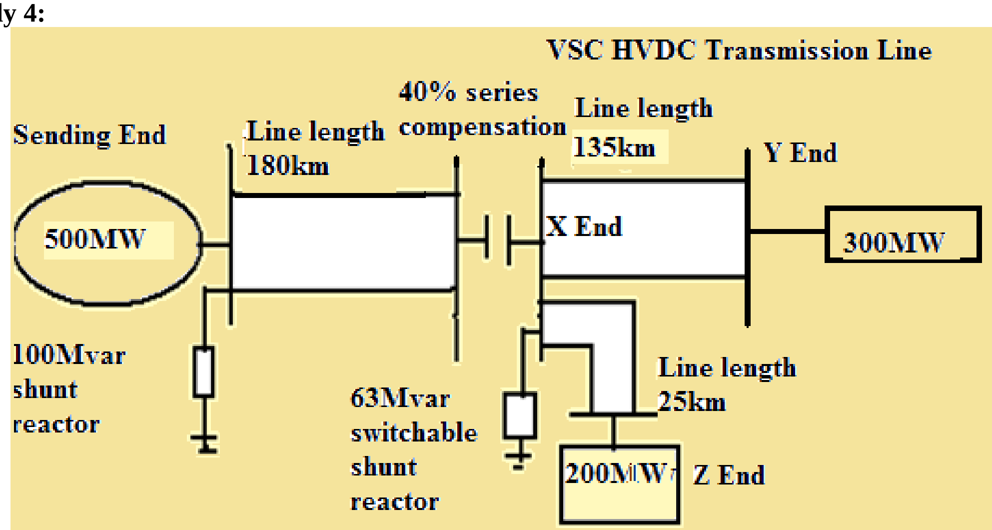

Fig 5.6 Line configuration for case study 4

In this case X-Y transmission line is replaced by VSC HVDC transmission. The performance analysis of a VSC HVDC transmission line needs to carry out to compare with AC transmission in order to elect best power evacuation scheme for IPP's.

IV CONCLUSION

In this paper analysis is carried out to select best conductor which yields low loss and percentage compensation required to achieve control over the power flow in AC transmission line is carried out using MATLAB. From the analysis it can be observed that a transmission line with quad bundle Bersimis conductor and 40% line compensation would be more adequate to achieve precise control over the power flow in AC transmission line.

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