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The Utility of Series Compensation in "High Phase Order Transmission System (HPOTS)": A Paradigm to Enhance Power System Capability

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ABSTRACT: *This paper discusses the comparative study of the existing GETCO'S (Gujarat Energy Transmission Co.) 400 KV 3-phase double circuit line, up-rated with Six-phase with different loading conditions, and voltage ratings with respect to transmission line efficiency, regulation and SIL with a discussion on the salient points of Six-phase system with respect to 3-phase double circuit line and HVDC transmission system. By using HPOTS the transmission capability of 3-phase double circuit can be enhanced by 1.71 to 1.74 times or for the same amount of power transfer we require compact tower design, reveals in saving in tower and foundation cost at the same time it will mitigate the problem of right of way. While studying the effectiveness of series compensation to improve voltage regulation and power transfer capability of HPOTS it's observed that the net transfer reactance depends on "Degree Compensation", "location" of the compensation bank, line length and the number of banks over which series compensation is distributed. The series compensation was found to be most effective at midpoint of the line but if we count the line resistance then the said position will shift slightly towards receiving end. The result obtained is graphically plotted for readers' ease.*

Keyword: *GETCO, High Phase order Transmission System, HPOTS, Series Compensation, Transmission System*

I. INTRODUCTION

The HVDC transmission and Multiphase power transmission are the emerging two options for addressing the problems with the bulk power transmission over the long distance, out of them the HVDC system is having many advantages like non-synchronous tie, less numbers of conductors required, less losses etc but has substantially higher cost for the terminal equipments, it's inability to transfer reactive power between the two ends, and to change the voltage level is difficult be the major drawbacks which has shadowed its' said advantages and has compelled the research engineers to tailor new policy for the electrical power transmission and to switch over to the another option that is Multiphase Power Transmission or High Phase Order Transmission.

II. METHODOLOGY

The use higher phase order system, as the phase voltage increases with the increase in phase order, with same phase to line voltage to that of the 3-phase double circuit, Six-phase system can transfer more power (As in Six phase V_{line} will be equal to V_{phase}) conversely, maintaining same phase to neutral voltage will decrease phase to phase voltage for the HPO lines means lines can be built with less spacing between the phases, this, reduces the amount of right of way and the tower size to build the HPO line.

We know that the stability requirement, limits the permissible power on EHV lines, which decreases with the increase in line length. The use of Series Capacitors in long distance transmission lines offers an effective and economical means of improving the stability limits and permits line to carry more power. The amount of series capacitance used in the line is referred by the Degree of Series Compensation (S), which is defined as a ratio of capacitive reactance of the series capacitor to the inductive reactance of whole line. The net transfer reactance is not just the arithmetic difference between the total inductive reactance and capacitive reactance of series capacitor but it depends on "Degree of Series Compensation", "location" of the compensation bank along the line, the line length and the number of series capacitor banks over which series compensation is distributed.

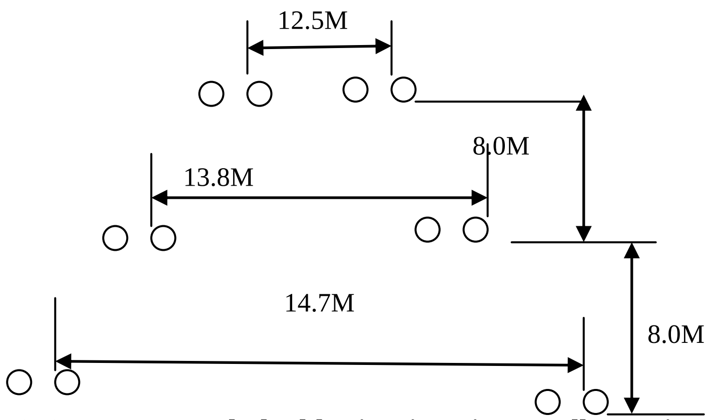

Fig. 1 GETCO's existing, 400kv 3-ph double circuit 10 in. Bundle spacing, twin mouse conductor used, dia. 31.77 mm, 900a c.c./conductor height of lowest conductor from ground: 21.9 m

Line Constants and Assumptions:

Line length : 400 to 1000 Kms   Operating Voltage : 400 KV
Type of conductor : Twin mouse   Bundle spacing : 25 Cms
Phase spacing : As shown in figure just below
Height of the lowest conductor from ground : 21.9 M
Computed line parameters per Km. for 3-ph Double Circuit:
L= 0.0005014 C= 2.43 E -8
Computed line parameters per Km. for 6-ph conversion of the same configuration:
L= 0.001268 C= 9.01 E -9

- Terminal equipments and machine variants are not considered.
- Shunt compensation specified as susceptance

Following table: 1 of the comparative design output shows the hike in power transfer capability of the existing GETCO'S 400 KV line if converted in to the Six-phase. But it can be inferred that the regulation is poorer, compared to the 3-phase double circuit line. Further we can see that for the same power to be transferred, the voltage level for six-phase power transmission can be reduced, which reduces the overall tower size and hence, the cost and at the same time mitigate the problems of right of way. The table given below is prepared from the GETCO (Gujarat Energy Transmission Co.)) 400 KV three phase double circuit line data and this configuration when converted in to six phase, it is assumed that the line is cyclically transposed and the line length of 200 Kms is considered.

Table 1: 3-phase Double Circuit with various configurations

3-PH DOUBLE CIRCUIT WITH VARIOUS CONFIGURATIONS										
SR	TYPE	VOLT	IL	REG	EFFI	L	C	SIL	PF	PS IN MW
1	400 KV GEB'S CONFIG DOUBLE CKT	400	1800	7.38	95.88	0.0005014	2.43E-08	1112.71	0.9992	2601.16
		400	900	2.98	97.81	0.0005014	2.43E-08	1112.71	0.9673	1274.89
6-PH CIRCUIT WITH VARIOUS CONFIGURATIONS										
5	6-PH GEB'S CONFIG	400	1800	8.8347	97.596	0.001268	9.01E-09	2558.74	0.9771	4426.39
		400	900	2.9046	98.7628	0.001268	9.01E-09	2558.74	0.9974	2187.06
	6-PH GEB'S CONFIG	231	1800	22.005	95.92	0.001268	9.01E-09	853.36	0.8917	2600.15
		231	900	6.9729	97.907	0.001268	9.01E-09	853.36	0.9883	1273.73

Salient Points derived from the above table:-
From the table 1, we can derive following important points of the High Phase Order Transmission:

- If symmetrical configuration inherently balanced is used , less effect of transposition
- HPOs have higher inductance and lower capacitance i.e. greater SIL capability.
- As for six-phase Vphase = Vline as it forms equilateral triangle (Angle = 60).
- For 3-ph double circuit power = 2x3 Vph Iph cosθ   Where Vphase = Vline / √3
- For 6-ph up rated line power = 6 Vph Iph cosθ   Where Vphase = Vline
- This fact gives 1.7 to 1.74 times more power than the existing three phase double circuit line depending upon the line configuration.
- For the same power transfer we keep Vphase same this will reduce Vline so it will reduce the overall dimension of the tower, hence the foundation cost and right of way problem.
- For the same power transfer 6-ph conversion gives better regulation has higher SIL
- For more power transfer if 6-ph conversion is made then it gives poor regulation, but this problem can be well addressed with the available FACTs devices.

III. EXPERIMENT & RESULTS

Effect of the Location of Series Capacitors:-

For the long transmission line, where the line charging plays a vital role, the position, of series capacitor, along the transmission line is of utmost importance. The location affects the fault currents, voltage seen by the protective devices, stability limit and also the maximum power frequency over voltages. Three important positions normally considered are,

A) Sending end
B) Receiving end
C) Mid-point of the line

For the loss less line, the best location for the series capacitor from stability point of view can be mathematically proved to be at the centre of the line. The effect of the line resistance is to shift optimum location slightly towards the receiving end. The various effects of series compensation and its location can best be studied by the general line constants.

Figure 2 shows the variation of the constant B_0, the transfer impedance which determines the power capability of the line. The transfer impedance is a minimum when the series capacitor is located at the centre of the line. As seen from the figures for a normal compensation of 50%, the transfer impedance is about 20% less when the capacitor is placed at the centre that when placed at either ends.

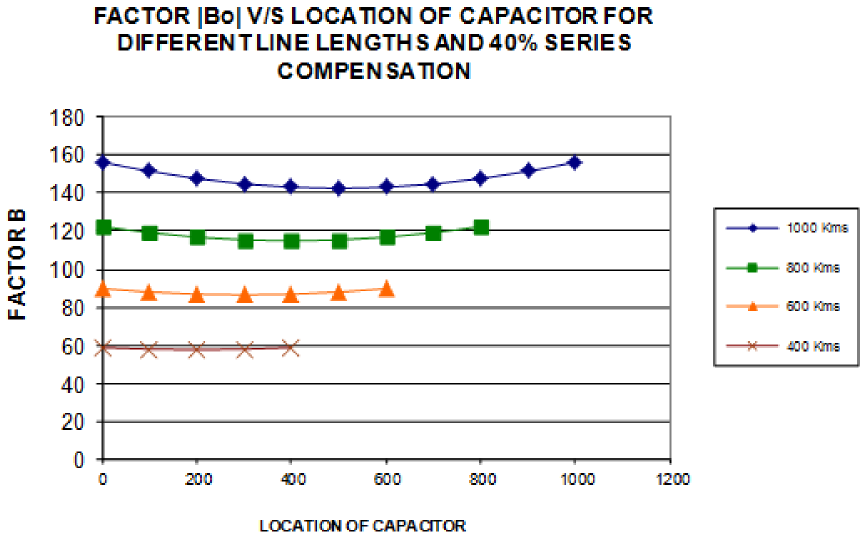

Fig 2: variation of the constant B_0 vs Location of capacitor chart

Compensation Efficiency:-

The stability limit of a series compensated line, neglecting the effect of line resistance and line charging can be written as:

$$P_{r\,max} = |E_s E_r| / (X_L - X_C) \_\_\_ (1)$$

Here, the net transfer impedance of the compensated line is taken as the algebraic difference of the inductive and capacitive reactances. This assumption is correct, in so far as short lines are concerned. But for the longer lines the resultant transfer reactance will be more than the above value, due to the line charging effect. In order to account for this discrepancy, the term "Compensation Efficiency" is introduced and this indicates the effectiveness of the series capacitor in reducing the transfer impedance.

The Compensation Efficiency (K) is defined as the ratio of the net reduction of transfer reactance to the reactance of the series capacitor used. Thus the effective series reactance X'c (as compared to the actual value X_C) is given by,

$$X'_C = K X_C \_\_ (2)$$

And the maximum power transfer over the line can be calculated as….

$$P_{rmax}=|E_sE_r|/(X_L-X'_C)=|E_sE_r|/X_L (1\text{-}SK) \_\_\_ (3)$$

Where, X_L is the transfer reactance of the line. The compensation efficiency is usually less than 100 %, but under certain conditions it can be more than this value. A high value for K is desirable for realizing high stability limit.

Expression for the Compensation Efficiency:

When a series capacitor is placed at distance X from the sending end of the transmission line, as shown in figure 2 the effective transfer impedance is given by,

$$B_0 = A_1B_2 + B_1D_2 - j\, A_1D_2X_C \_\_\_\_ (4)$$

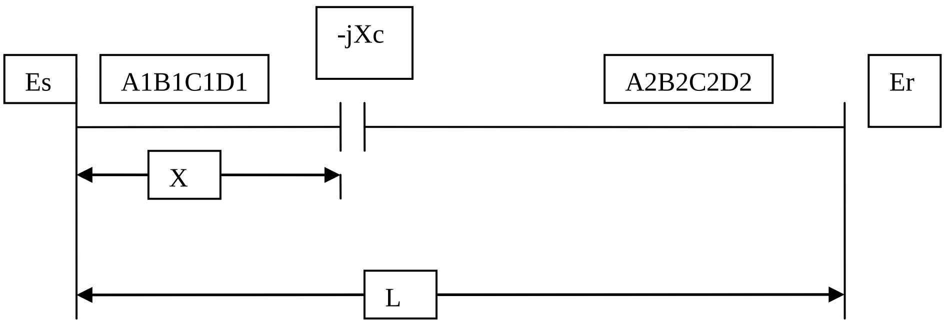

Fig 3: Schematic of Series capacitor and impedance

This expression shows that even though a series capacitor of reactance X_C is used the net reduction in transfer impedance is only $A_1D_2X_C$. Hence the coefficient of Xc in this expression for B_0 must represent the effectiveness of series compensation. Since the compensation efficiency is defined as the ratio of the reactances only, it is given by,

$$K = Re\,(A_1D_2) \_\_\_\_ (5)$$

The curve in figure 4 shows the variation in compensation efficiency for the single capacitor bank for different line lengths. The capacitor will be most effective when placed at the mid-point of the line irrespective of the line length. The compensation efficiency is dependent on line length and the location of the capacitor, but it is independent of the degree of series compensation. In addition the effectiveness of the series compensation decreases with the increasing line length, which means that the given degree of series compensation results in lesser improvement in stability limit for longer lines.

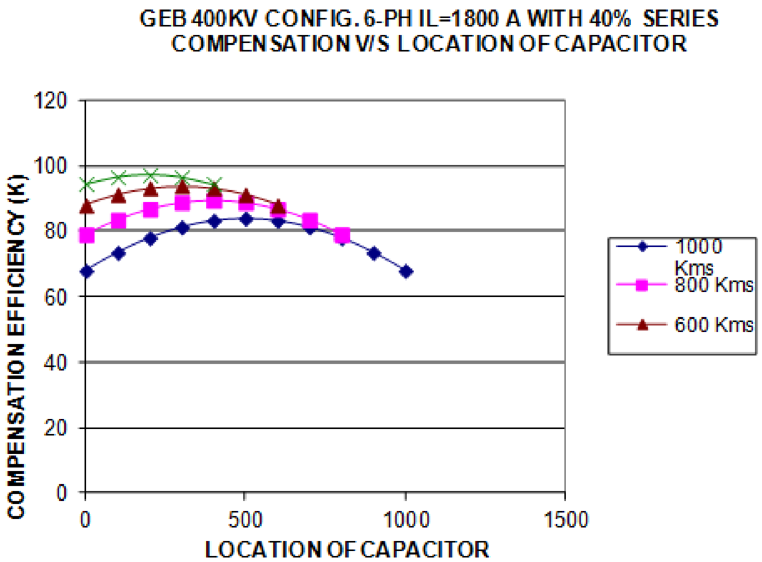

Fig 4: Compensation efficiency vs Location of Capacitor

The constraint of maximum permissible voltage across the capacitor during the fault condition and over-loads, necessitates the provision of splitting the compensation and providing banks at a number of places along the line. When two equal capacitor banks are placed at one third points along the line, the compensation efficiency is given by equation (8), and in such cases, the compensation efficiency will be a function of the degree of series compensation also, in addition to the line length and the location.

$$K=Re(A^3+ABC-jA^2CX_C/4) \_\_\_\_ (6)$$

Where A, B and C are general line constants for the one-third length. Similarly equation (9) gives the compensation efficiency when three capacitor banks are quarter points along the line.

$$K=Re \{(A^2+BC-jACX_C/3)(3A^2+BC-jACX_C/3) + 4A^2BC\}/3\_\_\_\_ (7)$$

Where A, B and C are general line constants for the one-fourth length. The above equation shows that the compensation efficiency varies with the degree of series compensation also. However it has been found that at low degrees of series compensation the compensating efficiency with two capacitor banks is slightly less than that obtained with a single capacitor bank. This, in fact, is the reason for the requirement of higher MVAR rating for two capacitors at one-third points than for one capacitor at mid-point.

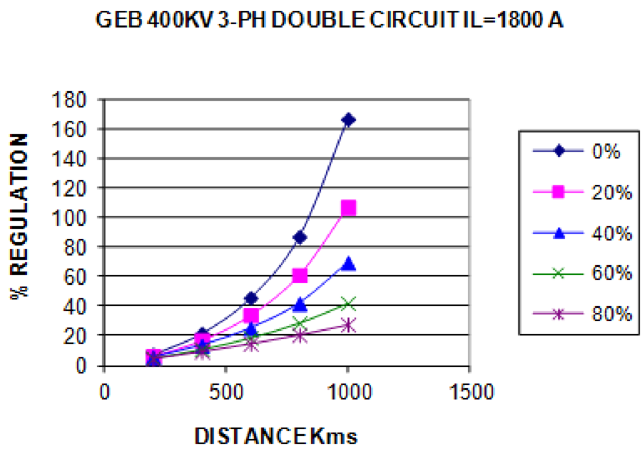

Fig 5: %regulation vs. Distance graph

Various graphs from figure 5 and 6 exhibit the effect of series compensation on the voltage regulation of the three phase double circuit line and the same line if converted into six-phase then the effect of series compensation on line regulation for the tabled lines are studied and from that it can be observed that though the six-phase line configuration has comparatively poorer regulation, the same, can be improved with the use of series compensation. Here also it can be emphasized that the best location for the series capacitance is at the mid-point of the line.

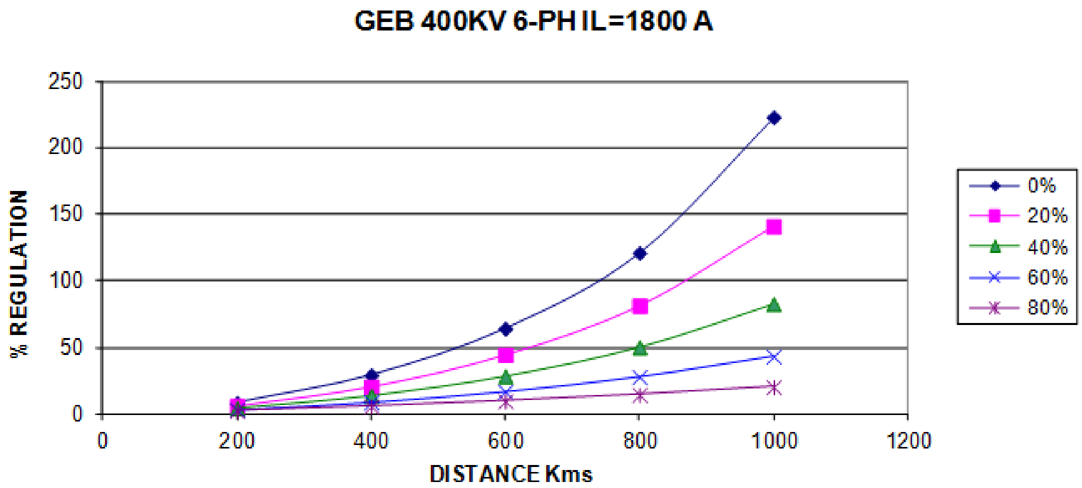

Fig 6: %regulation vs. Distance graph

IV. CONCLUSION

From the work stated above following points may be derived:

- If symmetrical configuration inherently balanced is used , less effect of transposition
- HPOs have higher inductance and lower capacitance i.e. greater SIL capability.
- As for six-phase $V_{phase} = V_{line}$ as it forms equilateral triangle (Angle = 60).
- For 3-ph double circuit power = 2x3 V_{ph} I_{ph} $\cos\theta$ Where $V_{phase} = V_{line} / \sqrt{3}$
- For 6-ph up rated line power = 6 V_{ph} I_{ph} $\cos\theta$ Where $V_{phase} = V_{line}$
- This fact gives 1.7 to 1.74 times more power than the existing three phase double circuit line depending upon the line configuration.
- For the same power transfer we keep V_{phase} same this will reduce V_{line} so it will reduce the overall dimension of the tower, hence the foundation cost and right of way problem.
- For the same power transfer 6-ph conversion gives better regulation has higher SIL
- For more power transfer if 6-ph conversion is made then it gives poor regulation, but this problem can be well addressed with the available FACTs devices.
- The net transfer reactance is not just the arithmetic difference between the total inductive reactance and capacitive reactance of series capacitor but it depends on "Degree of Series Compensation", "location" of the compensation bank along the line, the line length and the number of series capacitor banks over which series compensation is distributed.
- For the longer lines the resultant transfer reactance will be more than the above value, due to the line charging effect. In order to account for this discrepancy, the term "Compensation Efficiency" is introduced and this indicates the effectiveness of the series capacitor in reducing the transfer impedance.
- The Compensation Efficiency (K) is defined as the ratio of the net reduction of transfer reactance to the reactance of the series capacitor used.
- Transfer impedance is a minimum when the series capacitor is located at the centre of the line.
- The effect of the line resistance is to shift optimum location slightly towards the receiving end.
- The effectiveness of the series compensation decreases with the increasing line length means that the given degree of series compensation results in lesser improvement in stability limit for longer lines.

However it has been found that at low degrees of series compensation the compensating efficiency with two capacitor banks is slightly less than that obtained with a single capacitor bank. This, in fact, is the reason for the requirement of higher MVAR rating for two capacitors at one-third points than for one capacitor at mid-point.

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