Line Loadability in Indian Perspective

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Abstract: **The importance of line loadability limit is well understood in grid management for its reliable and efficient operation. Loading limit of any line depends on various parameters like its line length, fault level of connected substations, inductor/capacitor connected in series/shunt etc. In the year 1953 St. Clair has suggested Line loadability with respect to surge impedance loading and mathematical model was developed by R.D.Dunlop in 1979 for calculation of line loading limit. Central Electricity Authority of India (CEA) also came up with a modified method to calculate loadability limit in its "Transmission planning manual" published in year 1994. In this paper authors have discussed the limitations of earlier methods and proposed a new method for calculation of voltage regulation which intern can be utilized for calculation of line loading and supported by a case study.**

Keywords- Line Loadability, Thermal Loading of line, SIL, St. Clair curve

I. INTRODUCTION

WITH the enactment of Electricity act 2003, and introduction of non-discriminatory open access for the use of transmission system, Indian power sector has experienced paradigm shift in its governance. Apart from already existing long term exchange of power, the concept of short term exchange of power has helped for seamless transfer of power from surplus area to shortage area. This concept has further gained momentum with the introduction of power exchange(s). all such new product like advance short term open access (STOA), day ahead STOA, contingency STOA etc. made available for exchanging electricity has put a lot of pressure on existing transmission system to accommodate those transaction(s).

To operate system securely as well as to accommodate all such transaction to the extent possible, a term "Total Transfer Capability" (TTC) is introduced by system operators which determine the quantum of power which can be safely transferred from source to sink through the existing network(s). TTC is generally restricted by line loading limit which is minimum of thermal limit, voltage limit and stability limit. Where thermal and voltage limits are well define, steady state stability limit are subjective and depends upon various factors which are varying in nature. In past there are many authors/utilities who have come up with their suggestions to define modified SIL taking consideration of compensation and line length, the most famous authors are H.P. St. Clair and R.D. Dunlop. In year 1996 CEA also came up with "Transmission Planning Criteria" where they suggested same approach for modification of SIL.

In this paper authors have introduced a new method for calculation of voltage regulation where both bus reactor and line reactors are considered in the context of line loadability.

II. LITERATURE SURVEY

Line loadability is defined as degree of line loading expressed in terms of percentage of SIL, limited by thermal, voltage drop and stability limit. This concept was introduced by H.P. St. Clair in year 1953 [1]. St. Clair curve in Fig.1 shows the universal loadability curve for overhead uncompensated transmission line as a function of line length up to 400 miles, applicable to all voltage level. In 60Hz system for 300miles line length has a loadability of about 1.0 SIL. It could be concluded from St. Clair curve is that KW-Mile product is constant.

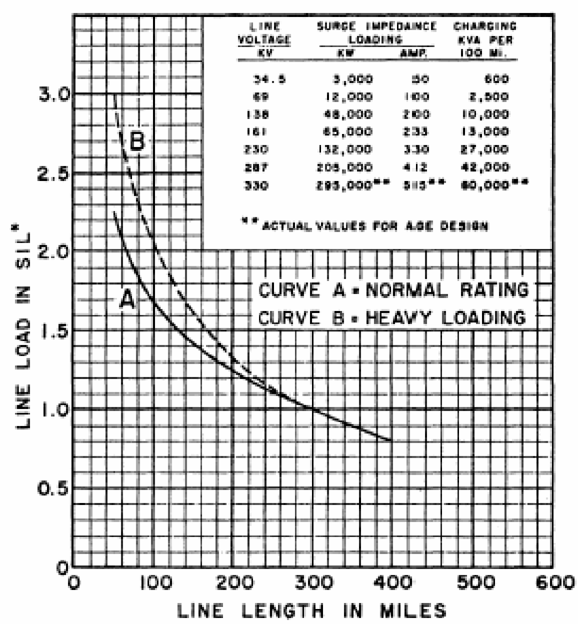

Figure 1 St.clair curve

In 1967, the Planning Department of the American Electric Power Service Corporation faced [2] with a growing need for similar curves applicable to the lines of voltage classes higher than 345-kV and longer than 400 miles, modified the St. Clair's curve as shown in Fig. 2. This Fig.2, just like the original curve, was arrived at through practical considerations.

Analytical analysis for loadability characteristics of EHV and UHV transmission lines was done in 1979, by R.D.Dunlop et.al [3] where author has developed the mathematical model for calculation of line loadability for voltage level up to 1500kV and length 600mile respectively. Author has also shown the effect of series and shunt compensation on line loading and considered the maximum allowable voltage regulation is 5% and steady state stability margin is 30% shown in Fig.3.

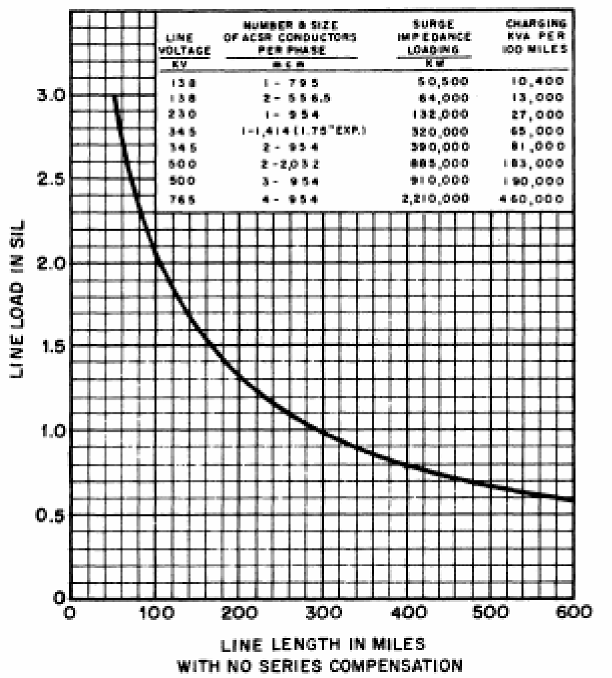

Figure 2 Modified St. Clair curve

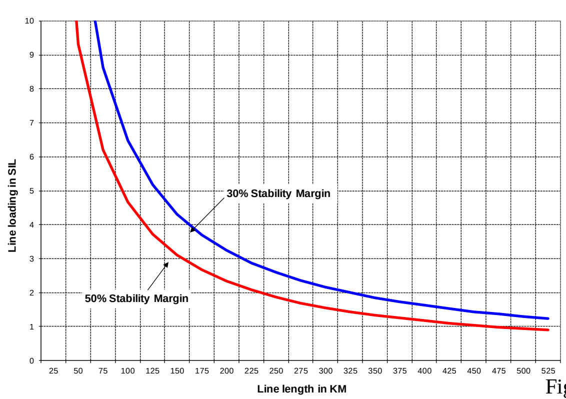

Figure 3 St.Clair curve for 30% and 50% Stability Margin

In 1994 Central Electricity Authority has developed the Transmission Planning Criteria [4] and suggested that voltage regulation of 5% and phase angular difference of 30° between two ends of the line to be consider for calculation of line loading. In case of shunt compensated lines, the SIL will get reduced by a factor K_1 where

K_1 = (1-degree of reactive compensation)$^{1/2}$

And in case of capacitive series compensation, the SIL get increased by K_2 where

K_2 = 1/ (1- degree of series compensation)$^{1/2}$

Permissible line loading = SIL x K_1 x K_2 x K_3,

K_3 = Multiplying factor from St. Clair's curve

III. POINTS FOR DISCUSSION

(i) In order to control over voltage in high voltage substation both line reactors or/and bus reactors are used. However for calculation of line loadability only line reactors are considered but bus reactors are not considered in CEA planning criteria 1994.

A typical 400KV sub-station single line diagram is shown in Fig.4 where bus reactor and line reactor are used to control the over voltage.

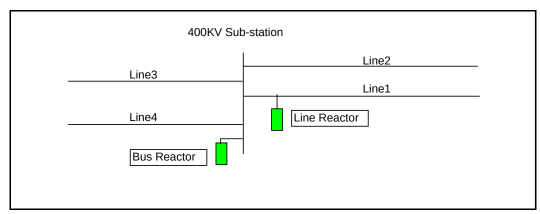

Figure 4 Typical EHV Sub-Station

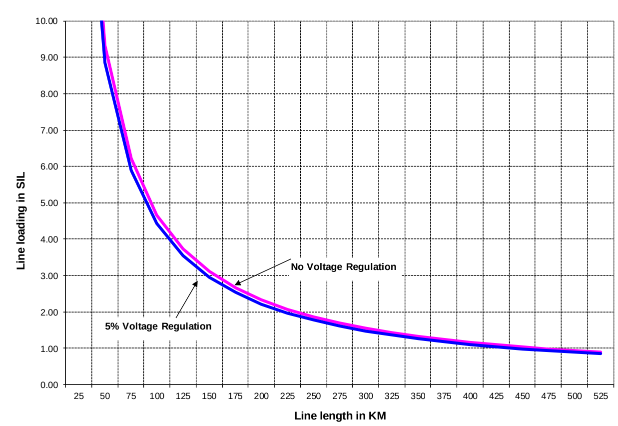

Figure.5 St.Clair with angle difference of 30° at both ends

(ii) Power transfer in a line V_1V_2 SIN δ / X_L where, X_L is line reactance depends upon line length and type of conductor where, V_1,V_2 are terminal voltage of sending end and receiving end. Receiving end voltage depends upon the voltage regulation of the line. **Author R.D. Dunlop et.al [3] considered maximum allowable voltage regulation along the line 5% shown in Fig. 5.** In well connected system voltage regulation take place not only due to line voltage drop but also due to the other lines connected at the same sub station. From above discussion voltage regulation needs to be recalculated due to presence of bus reactors and other lines connected at same sub station.

IV. VOLTAGE PROFILE ALONG WITH LINE

At surge impedance load reactive power generated by charging capacitance of line is equal to reactive power absorbed by the line. Hence, no reactive power exchange by the line as a result voltage profile remains flat. The simplified expression [6] of voltage profile (V) along with line is

$$\tilde{V} = \tilde{E}_S \frac{\cos\beta(l/2-x)}{\cos(\theta/2)}$$

For a lossless line, sending end voltage (E_S) and receiving end voltage (E_R) are same

Where l is line length

β phase constant

$\theta = \beta l$, x is distance from receiving end

Plot of voltage variation along the line for no load condition shown in Fig. 6. for a 400KM line with E_R=E_S=1.0 PU. The generators at the sending end and receiving end are capable of absorving the reactive power due to line charging. In the Fig.6 it is clear that mid point voltage is more than either end voltage. Under load, E_S leads E_R in phase and the power factor at midpoint will be unity.

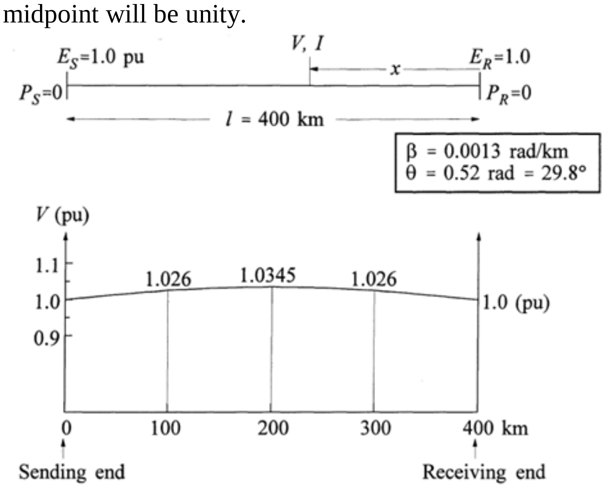

Figure.6 Voltage profile along the line [6]

V. PROPOSED METHOD FOR CALCULATION OF VOLTAGE REGULATION

Factors affecting voltage regulation:-

a) Reactive VAR absorbed by the line
b) All Bus and Line reactors connected at sub station
c) Number of line connected at sub station

Authors assumed that mid of the line considered as null point for VAR exchange.

From Fig.4 400KV Sub station Line 1 is 200KM long and others lines are 100KM and line parameters in PU/KM of Twin moose conductor at 100MVA base, R= 0.00001862, X= 0.0002075 and B= 0.00555.

Line reactor of rating 50MVAR and Bus reactor of rating 50MVAR are installed at 400KV.

MVAR absorbed by line1 is I^2X_{L1}

Reactive VAR at 400KV Sub station = ½ I^2X_{L1} + 50 + 50

Total Capacitive VAR at 400KV = ½ (V^2/X_{c1}+ V^2/X_{c2}+ V^2/X_{c3}+ V^2/X_{c4}), where X_{c1}, X_{c2}, X_{c3} and X_{c4} are the charging reactance of line1 to line4.

VAR mismatch at 400KV s/s

Capacitive VAR – Inductive VAR from mid point of the lines.

= ½ (V^2/X_{c1}+ V^2/X_{c2}+ V^2/X_{c3}+ V^2/X_{c4}) – (½ I^2X_{L1} + 50 + 50)

As Voltage and VAR are coupled

$\Delta V/V = \Delta Q$/fault level,

ΔQ VAR mismatch from above equation

ΔV Change in voltage due to change in ΔQ.

Fault level = $1/X_{L1}+1/X_{L2}+1/X_{L3}+1/X_{L4}$ (approximate calculation) in PU 3-Ø fault level

Where X_{L1}, X_{L2}, X_{L3}, X_{L4} are reactance of line1 to 4 respectively.

VI. LINE LOADING CALCULATION

Power transfer in a line-1 V_1V_2 SIN δ / X_{L1}, for 30° load angle of line1 from Fig.4.

P= (1*1 Sin 30)/ (0.0002075 * 200) = 12.04 PU.

Calculation of voltage regulation due to flow of 12.04PU

½ I^2X_{L1}=3.01 PU, Total reactor = 0.5+0.5 = 1 PU

½ (V^2/X_{c1}+ V^2/X_{c2}+ V^2/X_{c3}+ V^2/X_{c4}) = 1.3875 PU

ΔQ= 3.01+1-1.3875 = 2.6225

Fault level = 168.26 PU

ΔV= 2.6225/168.26= 0.015585 this is the voltage drop at one end from mid point of the line

Similarly to calculate for other end voltage drop from mid point of the line, for approximate calculation make it double for other half of the line.

So, Receiving end voltage 1-2XΔV = 0.96883 PU

Power transfer reduce due to voltage regulation = 12.04*0.9688 = 11.66PU

For a given 200KM line of twin moose conductor can be loaded up to 1167MW. Line loading of twin moose conductor for line length from 100KM to 400KM calculated as shown in Table 1. As per CEA calculation of 100KM line loading is less than the 200KM line loading that comes out due to the compensation of short transmission line. The line loading of short transmission line is limited by thermal loading limit [5] shown in Table 2. It is concluded from Table 1 and Table 2 that

200KM long transmission line could be loaded up to thermal loading limit for 35°C ambient temperature and 75°C conductor temperature.

TABLE 1 Line loading

Twin moose conductor	Line loading in MW			
R= 0.00001862 PU/KM X= 0.0002075 PU/KM B= 0.00555 PU/KM	As per Dunlop ΔV=5%, δ = 44°	δ = 30°	As per CEA ΔV=5%, δ =30°	Proposed Technique δ =30°
100KM line length	3180	2289	720	2261
200KM line length	1590	1144	848	1167
300KM line length	1060	763	638	789
400KM line length	795	572	503	598

TABLE 2 Thermal Capacity of line

ACSR Moose (54/3.53 mm AL + 7/3.53 mm Steel); Region-Northen; Max design temerature 60,65,67 and 70 Degree Celcious; conductor age :**one to ten years**				
Ambinet Temerature (°C)	Capacity (MW)	Capacity (MW)	Capacity (MW)	Capacity (MW)
	60 (°C)	65 (°C)	67 (°C)	75 (°C)
20	1289	1389	1426	1565
22.5	1191	1300	1340	1489
25	1101	1219	1263	1422
27.5	1012	1141	1189	1331
30	904	1048	1100	1284
32.5	797	960	1016	1247
35	788	952	1010	1210
37.5	571	785	855	1087
40	533	759	832	1068

VII. CASE STUDY

The Eastern Regional Grid comprises the states of West Bengal, Orissa, Bihar, Jharkhand and Sikkim. The installed capacity of Eastern region is 23119 MW (including Talcher STPS Stg-II) and peak demand met is of the order of 14000 MW. The energy consumption is around 270 MU per day and daily net export from Eastern region is around 40 MU. Eastern Regional Load Despatch Center [ERLDC] has been designated by Electricity Act 2003, as the apex body in grid operation to ensure secure and economic operation of the Eastern Regional power system. As such the EHV grid is operating under the supervision and control of ERLDC on round the clock basis. Tala Transmission system has been built primarily to evacuate power from Tala (Bhutan) HPS to Northern Region of India. The beneficiaries of Tala (1020MW) in the Northern Region are the states of UP, Delhi, Punjab, Haryana, Rajasthan and Jammu & Kashmir. During monsoon around 1700-2000 MW power needs to be evacuated from Hydro stations viz. Tala(Bhutan), Chukha(Bhutan), Teesta (510MW) and surplus of Hydro generation of NER. Essentially this entire hydro power is being pooled at Binaguri 400kV S/S. The huge quantum of hydro power gets evacuated through 400KV Purnea-Muzaffarpur D/C. These two circuits have quad moose conductor, 240KM long and 40% fixed series capacitive compensation and 15% Dynamic compensation from TCSC.

On 22 September 2009 line loading testing was done by ERLDC on 400KV Purnea-Muzaffarpur D/C line. Following actions were taken before commencing of the Test:-

(a) Islanding scheme at Chukha was checked and was kept in service to ensure islanding of one machine of CHPC along with Thimpu load in the event of any contingency.

(b) The CT ratios at Purnea and Muzaffarpur ends for Purnea – Muzaffarpur circuit were checked and confirmed as 2000/1. Necessary action was taken in order to display and monitor the Purnea – Muzaffarpur flow at ERLDC.

(c) It was expected that there could be voltage rise across the series capacitor installed at Purnea under such high power flow conditions and over-voltage protection setting for Purnea – Muzaffarpur line was ensured as 1.12 pu with 5 seconds delay.

Following actions were taken to carry out the testing:-

1. At 1138 Hrs. the power flow per circuit in Purnea – Muzaffarpur D/C was 700 MW. Instruction was issued to Tala, Teesta and NER to back down their respective generations and at 1154 Hrs. the power flow in each of the circuit could be brought down to 518 MW.
2. At 1156 Hrs. the FSC at Purnea – Muzaffarpur 400 kV Circuit I was opened. The power flow in Circuit – I also reduces to 373 MW whereas the power flow in Circuit – II rise to 670 MW (total flow 1043 MW).
3. Prior to opening of the Purnea – Muzaffarpur Circuit I the voltages at Muzaffarpur was 418 KV and that of Binaguri was 422 kV,. It was reported by Purnea that the voltage at Purnea was around 420 kV.
4. At 1210 Hrs, the Purnea – Muzaffarpur Circuit I was opened. Power flow at Purnea – Muzaffarpur Circuit II was 1049 MW. After opening of Circuit I, the voltage at Purnea and Muzaffarpur became 417 KV and 408 KV respectively.
5. From 12:16 Hrs., gradually the generation at Tala was increased by 400 MW when at 12:36 Hrs. the S/C Purnea – Muzaffarpur II flow became 1424 MW. At 12:36 Hrs. generation at NER was released and power flow at 12:49 Hrs. became around 1682 MW. Teesta was running with its two machines delivering 340 MW at 13:09 Hrs. 3rd machine of Teesta was synchronized and generation was raised. At 13:12 Hrs. the power flow in Purnea – Muzaffarpur II touched an all time maximum of 1814 MW. However, immediately Teesta generation and injection from NER were reduced at 13:19 Hrs. The power flow in Purnea – Muzaffarpur circuit II brought down to 1511 MW.
6. While angular difference between Malda and Purnea s/stns. was checked through Estimator it was decided to take an attempt to close the 220 kV

Malda – Dalkhola D/C .At 13:19 Hrs. 220 kV Malda – Dalkhola Circuit II and at 13:27 Hrs. Malda – Dalkhola Circuit I was closed. The 220 kV D/C carried around 100 MW of power from Dalkhola to Malda direction and corresponding relief was also observed in Purnea – Muzaffarpur Circuit II.

7. At 13:35 Hrs. Purnea – Muzaffarpur Circuit I was closed when the power flow in the Purnea – Muzaffarpur Circuit – II was 1455 MW and TCSC of Purnea – Muzaffarpur Circuit - I was taken into service at 13:38 Hrs.

Similar operation was attempted for loading for Purnea – Muzaffarpur Circuit – I. the detailed actions carried out during the operation is shown in Fig 7.

Although the line was not tested upto its thermal limit However 400KV Purnea-Muzaffarpur S/C loaded up to 1730MW for half an hour and the maximum loading of line was 1814 MW, shown in Fig.7. For the steady state line loading limit calculated based on available Power flow and both end voltages data that comes out 2186MW. Line loading calculated from proposed technique stability limit for 400KV Purnea-Muzaffarpur S/C workout to 2147MW and thermal loading limit is 2136MW [5] at 40°C ambient Temperature and 75°C conductor Temperature.

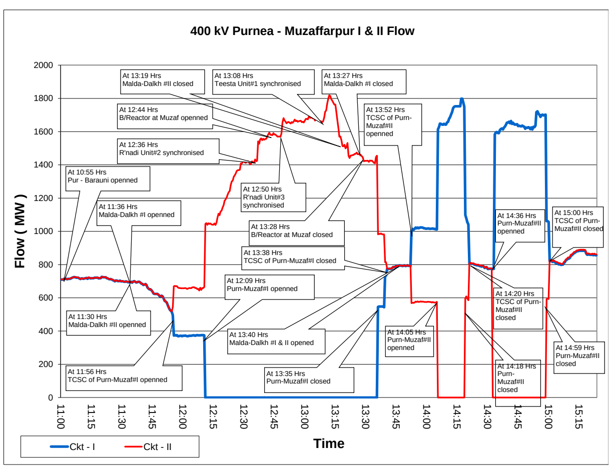

Figure 7 Line loading of 400Kv Purnea-Muzaffarpur ckt 1 & 2

VIII. CONCLUSION

In well connected system voltage regulation take place not only due to line voltage drop but also due to the Bus reactor and Line reactor and other lines connected at the same sub station. Author has calculated the voltage regulation which in turn utilised for calculation of accurate line loading. 180KM long transmission line could be loaded up to thermal loading limit for 35°C ambient temperature and 75°C conductor temperature.

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