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A Comparative Assessment of Ferranti Effect in Power Transmission Systems with PI Model and Distributed Line models

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Abstract The Cenozoic era of power system is with electrical energy network comprising of a huge transmission network equipped with EHV and UHV long transmission lines. These lines are subjected to continuous variations of the distributed loads all over the network. The subjective loads are varying with zero load to very heavy loads lead to insecurity of the power system with large variations in both voltage and frequency of the power system. When transmission lines subjected to no load or lightly loaded operations then the Ferranti effect will arise in the power network leading to very high over voltages. This article presents the simulation results of Ferranti effect and its illustration in transmission lines in four stages. The first stage the long transmission line is considered with a operating voltage of 360KV line-to-line voltage in KV and standard Indian frequency of 50Hz is considered for case study for all four stages of the case study. The stage one presents the case study results of Ferranti Effect Phenomenon with the use of MATLAB programming method. The Ferranti Effect of the said line is analysed with the line length variation from zero to 800KM line length, the MATLAB programme used the long line equations to obtain the receiving end voltage plot by keeping the sending end voltage at constant value of 208 KV per phase voltage. In the second stage the system with same parameters has been used to carry out by using a PI line model of Simulink blocks. The stage three with the distributed line model of Simulink blocks with same line and length variation. Finally in stage four presents the comparison results of both pi line model and distributed line models with the variation of line length up to 800KM and illustrated the severity of Ferranti effect.

Keywords: *Ferranti Effect, Thyristor Switched Reactor, Power Transmission, Transmission Lines, PI model line, Distributed Line*.

1. Introduction

The interconnected power network fortified with massive number of transmission lines and these lines subjected to the tempestuous load turbulences from no load to very substantial loads. When transmission lines subjected to no load or lightly loaded operations then the Ferranti effect will arise in the power network leading to very high over voltages [1] to [6].

The Ferranti effect of the transmission lines is most effective parameter of the power system performance, which effects the operation of many components of the network to which the influence of the effective line is in vicinity. The EHV and UHV lines are most affected by these load fluctuations, these lines can be categorised by medium transmission lines and long transmission lines [7] to [13].

The next part of the article focussed on the modelling aspects of these two lines, one is medium lines divided as nominal T and nominal PI networks and long lines can be modelled with its rigours solution or approximated as equivalent T and equivalent PI models. All these models have been discussed and analysed in the first part of the article [12] to [15].

2. Materials and Methods

2.1. Power Transmission Systems

The power transmission in the modern power systems playing a vital role and day by day the length of the lines increasing and enhancing the need of mitigation of Ferranti effect due to tremendous load variations. The application of medium and long transmission lines are in the power transmission is enormous and they lead to Ferranti effect.

The modelling of medium and long transmission lines are crucial in analysing the root cause of Ferranti effect. This part of the article focussed on the modelling aspects of the transmission lines. They are three categories, first one is Nominal T line, second is nominal PI model and lastly long distributed line with rigorous solutions [10] to [15].

The Ferranti effect has been observed in both medium and long transmission lines, the line is considered as medium transmission line if the line length is less than or equal to 200 km and these lines can be analysed using Nominal-T and Nominal-Π configurations [7] to [10]. The line with more than 200KM can be considered as a distributed long line which requires a rigorous solution or with equivalent T and equivalent PI models. The following sections devoted

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for the modelling of all these types.

2.2. Nominal-T Configuration

In Nominal-T configuration as illustrated in Fig.1, the total shunt capacitance of line is lumped at the midpoint of the transmission line and the line inductance is divided into two equal halves, each is concentrated at both sending and receiving ends [1] to [4]. Fig.2. illustrating the Phasor diagram of Nominal-T method, phasor OD1 is showing the receiving end voltage V_r and OD is illustrated the sending end voltage V_s . The equations from (1) to (14) illustrates the modelling of the nominal T line. The equation (12) showing the sending end current and equation (14) represents the sending end voltage V_s .

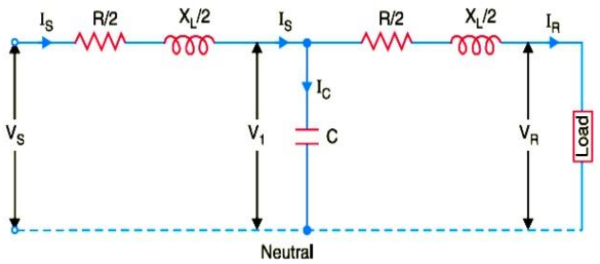

Fig.1. Equivalent circuit of Nominal-T method

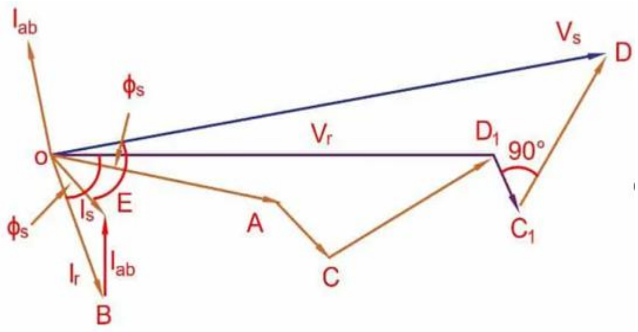

Fig.2. Phasor diagram of Nominal-T method

$V_S = AV_R + BI_R$ (1)

$I_S = CV_R + DI_R$ (2)

$Z/2 = R/2 + jX_L / 2$ (3)

$V_1 = V_R + I_R (Z/2)$ (4)

$I_S = I_R + I_C$ (5)

$I_S = I_R + YV_1$ (6)

$I_S = I_R + Y (V_R + I_R (Z/2))$ (7)

$I_S = I_R + YV_R + YI_R (Z/2)$ (8)

$I_S = YV_R + I_R + YI_R (Z/2)$ (9)

$I_S = YV_R + (1 + YZ/2) I_R$ (10)

$I_S = CV_R + DI_R$ (11)

$I_S = YV_R + (1 + YZ/2) I_R$ (12)

$V_S = V_1 + I_S (Z/2)$ (13)

$V_S = (1 + YZ/2)V_R + Z(1 + YZ/4) I_R$ (14)

2.3. Nominal- Π Configuration

In Nominal-Π configuration as illustrated in Fig.3, each total line capacitance is sub divided into two equal halves, concentrated at both the ends and the total impedance is placed at middle of the transmission line [1] to [5]. The total series impedance is concentrated at middle of the line and the current is I_1, which is the phasor sum of load current I_r and current through the load end admittance I_{c2}. Hence voltage drop is ZI_1 and sending end voltage V_s is obtained with phasor sum of V_r and ZI_1. The modelling of the line is described with the following equations (15) to (22). Equation (20) showing the sending end voltage and equation (22) illustrating the sending end current I_s.

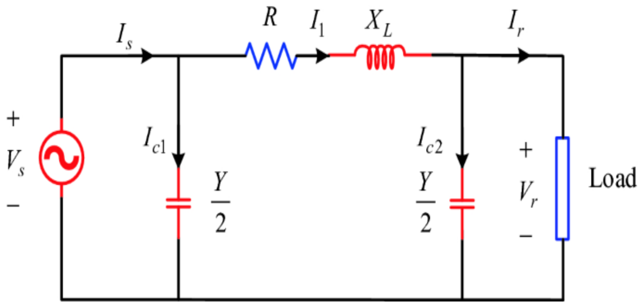

Fig. 3. Phasor diagram of Nominal- Π method

If the length of the line exceeds 200 km then that line is considered to be long transmission line where the line parameters are distributed over entire transmission line. Ferranti effect is predominant in long lines than in medium lines.

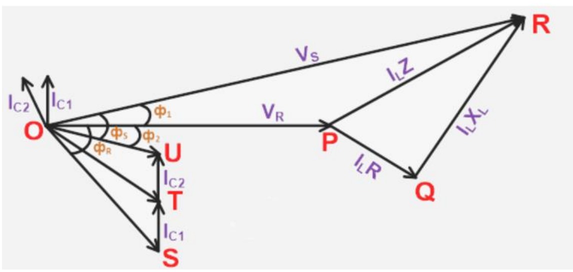

Fig. 4. Equivalent circuit of Nominal- Π method

$I_s = I_1 + I_{C2}$ (15)

$I_s = I_1 + (Y/2) V_s$ (16)

$I_s = I_R + (Y/2) V_R + (Y/2) V_s$ (17)

$V_S = (1 + ZY/2) V_R + Z I_R$ (18)

$V_S = AV_R + BI_R$ (19)

$V_S = (1 + ZY/2) V_R + Z I_R$ (20)

$I_S = CV_R + DI_R$ (21)

$I_s = Y (1 + YZ/4) V_R + (1 + (YZ / 2)) I_R$ (22)

2.4. Distributed parameters line

The transmission lines with more than 200km is categorised as a long line and Fig. 5. illustrating the distributed long transmission line model equivalent circuit with distributed line parameters of series impedance and shunt admittance sections as shown in Fig. (5). The modelling of the long transmission line has been illustrated by the following equations (23) to (31).

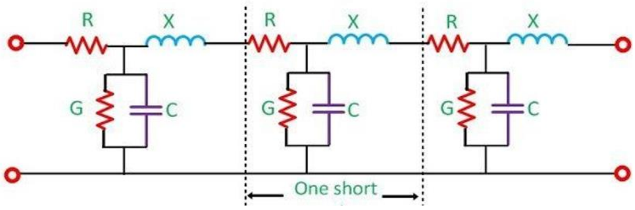

Fig. 5. Distributed long transmission line model equivalent circuit

$$\frac{d^2Vx}{dx^2} = \frac{dIx}{dx} z \quad (23)$$

$$\frac{d^2Vx}{dx^2} = yzVx \quad (24)$$

$$C1e^{rx} + C2e^{-rx} \quad (25)$$

$$r = \sqrt{yz} \quad (26)$$

$$\frac{dV}{dx} = c1re^{rx} - c2re^{-rx} = zIx \quad (27)$$

$$Ix = \frac{C1}{Zc} e^{rx} - \frac{C2}{Zc} e^{-rx} \quad (28)$$

$$Vx = V_R \left(\frac{e^{rx}+e^{-rx}}{2}\right) + I_R Zc \left(\frac{e^{rx}-e^{-rx}}{2}\right) \quad (29)$$

$$Ix = V_R \frac{1}{Zc} \left(\frac{e^{rx}-e^{-rx}}{2}\right) + I_R \left(\frac{e^{rx}+e^{-rx}}{2}\right) \quad (30)$$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \begin{bmatrix} V_S \\ I_S \end{bmatrix} \quad (31)$$

2.5. Ferranti Effect

The phasor diagram, which describing the phenomenon of Ferranti effect is shown in below Fig.6, it is clearly evident that the receiving end voltage is lower than the sending end voltage under no load and lightly loaded conditions. Fig.6 illustrates the phasor diagram illustrating Ferranti effect [7] to [10].

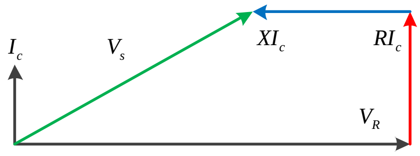

Fig.6. Phasor diagram illustrating Ferranti effect

3. Case Study and Simulation Results

3.1. Stage 1 MATLAB programme for illustrating Ferranti effect

The transmission line with the sending end voltage of 360KV line-to-line voltage in KV with power frequency of standard Indian value with 50Hz and the below Table1. encapsulates the Transmission line parameters for MATLAB Programme, PI line model and distributed parameters line models for simulation study. The zero sequence parameters have been taken as equal to three times the positive or negative sequence parameters for resistances, inductances and capacitances only. The subsequent part of the article has illustrated the MATLAB programme for the study of line with line length variation from zero to 800KM and

Fig.7 is illustrating the receiving end voltage for illustrating Ferranti effect of Long distributed parameters line of 800KM Line of 400KV with MATLAB Programme, which is increasing non uniformly with the line length variation and hence the phenomenon of Ferranti Effect is totally non linear in behavior and it may require non linear control systems or modern control methods are required to address the Ferranti Effect phenomenon in modern power system study.

Table1. Transmission line parameters for both pi model and distributed parameters line models

S. No	Specifications	Positive Sequence & Negative sequence Values	Zero Sequence values	Remarks
1	R in Ohm/km	0.045	0.14	Zero sequence value is app 3 times the positive sequence values
2	L in H/km	1.4mH	4.2mH	
3	C in F/km	10 pF	30pF	
4	Length in km	100 to 600 with step size of 100		Uniform variation of 100 km
5	Sending end voltage in KV (line-to-line)	360		Per phase voltage of 208KV

```
% Ferranti effect plot

clc;

clear all;

C = 10*10^-9;

% Length of the line (len) is taken as 800 km with an equal spacing of 25 km.

len = 0:25:800;

% Total capacitance of the 800 km long line,

C_tot = len*C;

% Series inductance, L = 1.044 mH per km of line length

L = 1.4*10^-3;

L_tot = len*L;

f = 50;

% For a sending end voltage of 380kV,

Vs = 360;

% phase shift,

beta = len.*(2*pi*f*sqrt(L*C));

% Characteristic Impedance is Zc,

Zc = sqrt(L/C);

% Sending end Voltage is Vr,

Vr = Vs./cos(beta);

plot(len, Vr)

axis([0 800 0 800]);

xlabel('line length in km');

ylabel('Receiving end Voltage in kV');
```

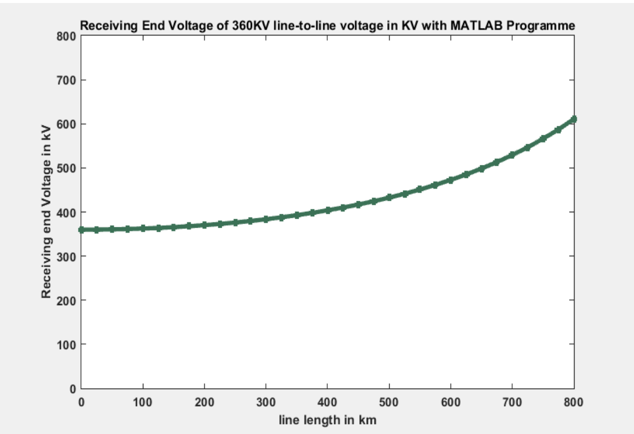

Fig.7 The receiving end voltage for illustrating Ferranti effect of Long distributed parameters line of 800KM Line of 400KV with MATLAB Programme.

3.2. Stage 2 the illustration of Ferranti effect with PI model

Stage two with the pi line model of Simulink blocks with same sending end voltage of 360kv and length variation of 100km to 800km of equal spacing of 100km, Case three with the distributed line model of Simulink blocks with same line and length variation.

The Simulink models of the designed system have been developed for the case study and simulated with various line Lenths of equal spacing of 100km and simulation results have been presented with graphs, tables and bar charts in the subsequent sections. Fig.8 shows the Simulink model for the system with pi model, and Table 2 shows the Ferranti Effect results for both pi model. The Fig.9 is illustrating the receiving end per phase voltage against the variation of line length from 100km to 800km with pi line model in which it is evident that for 800km length the receiving end voltage is abruptly increased to very huge value and hence pi model is not suitable for case study of very long transmission lines.

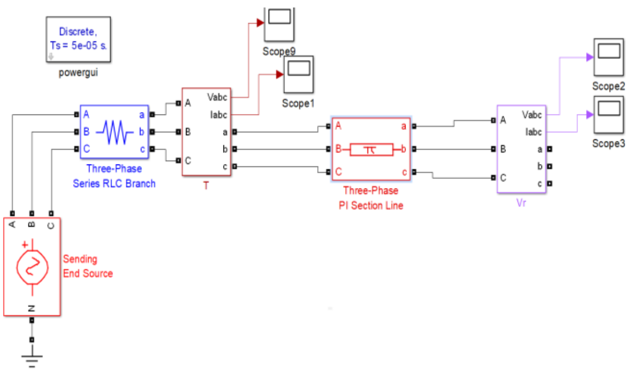

Fig.8 Simulink model for the system with PI model

Table2. Ferranti effect results for both pi model

S. No	line Length in km	Per Phase V_s in kV	V_r in kV under no load With Pi line model
1	100	208	207
2	200	208	207
3	300	208	207
4	400	208	207
5	500	208	207
6	600	208	207

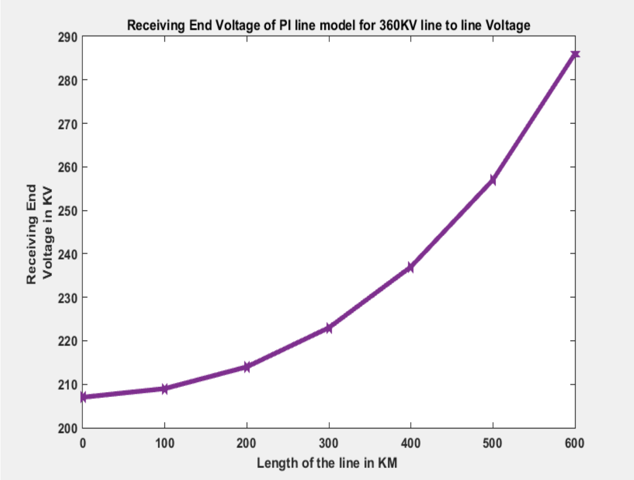

Fig.9 The receiving end per phase voltage for variation of line length from 100km to 600km with pi line model

3.3. Stage 3 the illustration of Ferranti effect with distributed parameters model

Stage three with the distributed parameters line model of Simulink blocks with same sending end voltage of 400kv and length variation of 100km to 800km of equal spacing of 100km. Fig.10 illustrates the Simulink model for the system with distributed line model, Table 3 encapsulates the Ferranti effect results for distributed parameters line model. Fig.11 shows the receiving end per phase voltage for variation of line length from 100km to 800km with distributed line model, hence it is a clear evident that the distributed parameters line results are uniform throughout the line length with equal incremental line length of 100km. Hence distributed parameters line is best suitable for the simulation study of long transmission lines also unlike pi line model.

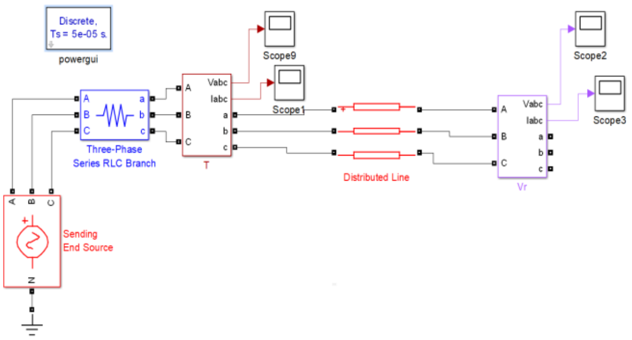

Fig.10 Simulink model for the system with distributed line model

Table 3. Ferranti effect results for distributed parameters line model

S. No	line Length in km	Per Phase V_s in kV	V_r in kV under no load With Distributed line model
1	100	208	209
2	200	208	214
3	300	208	223
4	400	208	237
5	500	208	257
6	600	208	286
7	700	208	328
8	800	208	392
9	900	208	495
10	1000	208	682
11	1100	208	1094
12	1200	208	2118

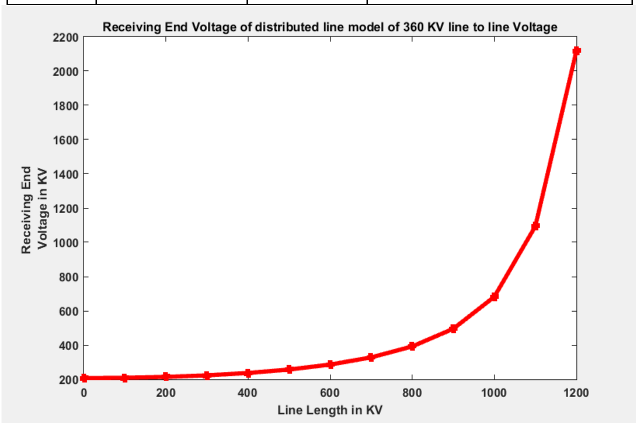

Fig.11 The receiving end per phase voltage for variation of line length from 100km to 1200km with distributed line model

3.4. Stage 4 comparative analysis of Ferranti effect with PI line and distributed parameters models

The comparative analysis of the PI model and distributed parameters line model of Simulink blocks have been presented in this section. Table 4 encapsulates the Ferranti effect results for both pi model and distributed parameters line models and Fig.12 illustrates the Ferranti effect bar chart for both pi model and distributed parameters line models. Hence it clear evident that the distributed parameters line gives the accurate results for long lines which are more than 600km line length. The variation of the receiving end voltage in both PI line model as well as distributed parameters lines are almost similar up to 600KM line length, after that point the PI line model is unsuitable for the study of the phenomenon of Ferranti Effect since it leads to abrupt results, which are impractical but the distributed parameters line is giving the most accurate results which are practicable.

Table 4. Ferranti effect results for both pi model and distributed parameters line models

S. No	line Length in km	Per Phase V_s in kV	V_r in kV under no load With Pi line model	V_r in kV under no load With Distributed line model
1	100	208	209	209
2	200	208	214	214
3	300	208	223	223
4	400	208	237	237
5	500	208	257	257
6	600	208	286	286
7	700	208	644	328
8	800	208	864	392

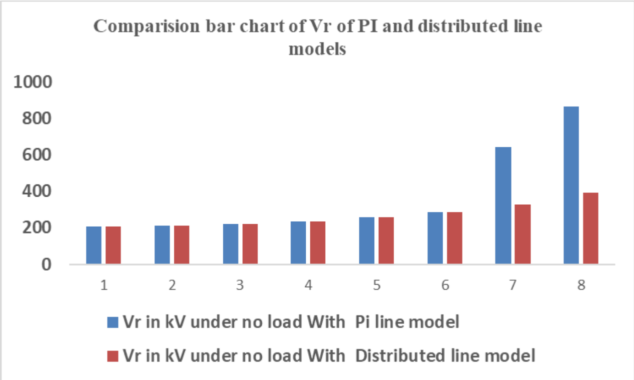

Fig.12 Ferranti effect bar chart for both pi model and distributed parameters line models

4. Conclusions

This article presents the simulation results of Ferranti effect and its illustration in transmission lines in four stages. The first stage the long transmission line is considered with a operating voltage of 360KV line-to-line voltage in KV and standard Indian frequency of 50Hz is considered for case study for all four stages of the case study. The stage one is evaluated the Ferranti Effect and presented the results with the MATLAB programme 360KV line with variation of line lengths with equal spacing of 25KM and severity of the Ferranti effect is plotted with a graph and is increasing with line length and is quite nonlinear in nature and these results are evident that it is suitable up to 600KM line length. In the second stage the system with same parameters has been used to carry out by using a PI line model of Simulink blocks. The stage three with the distributed line model of Simulink blocks with same line and length variation. Finally in stage four presents the comparison results of both pi line model and distributed line models with the variation of line length up to 800KM and illustrated the severity of Ferranti effect.

The transmission line with the sending end voltage of 360KV line-to-line voltage in KV with power frequency of standard Indian value with 50Hz and the below Table1. encapsulates the Transmission line parameters for MATLAB Programme, PI line model and distributed parameters line models for simulation study. The zero sequence parameters have been taken as equal to three times the positive or negative sequence parameters for resistances, inductances and capacitances only. The subsequent part of the article has illustrated the MATLAB programme for the study of line with line length variation from zero to 800KM and

Stage two with the pi line model with same sending end voltage of 360kv and length variation of 100km to 800km of equal spacing of 100km, The Simulink models of the designed system have been developed for the case study and simulated with various line Lenths of equal spacing of 100km and simulation results have been presented. The conclusion of this part is with pi line model in which it is evident that for 800km length the receiving end voltage is abruptly increased to very huge value and hence pi model is not suitable for case study of very long transmission lines.

Stage three with the distributed parameters line model of Simulink blocks with same sending end voltage of 400kv and length variation of 100km to 800km of equal spacing of 100km. Fig.13 illustrates the Simulink model for the system with distributed line model. Hence it is a clear evident that the distributed parameters line results are uniform throughout the line length with equal incremental line length of 100km but curve is nonlinear. Hence distributed parameters line is best suitable for the simulation study of long transmission lines also unlike pi line model.

The comparative analysis of the PI model and distributed parameters line model of Simulink blocks have been presented in this section. Hence it clear evident that the distributed parameters line gives the accurate results for long lines which are more than 600km line length. The variation of the receiving end voltage in both PI line model as well as distributed parameters lines are almost similar up to 600KM line length, after that point the PI line model is unsuitable for the study of the phenomenon of Ferranti Effect since it leads to abrupt results, which are impractical but the distributed parameters line is giving the most accurate results which are practicable.

References:

[1] Venu Yarlagadda, G. Lakshminarayana, G. Ambati, T. Nireekshana and G. A. Karthika, "Mitigation of Ferranti Effect and Voltage Control in Transmission Systems Using Fuzzy Logic Controlled SVC," *2022 International Conference on Smart Technologies and Systems for Next Generation Computing (ICSTSN)*, 2022, pp. 1-6, doi: 10.1109/ICSTSN53084.2022. 9761300.

[2] Venu Yarlagadda, Giri Prasad Ambati, E.Shiva prasad, KuntlaVeeresham, G.Radhika, "Synchronous and Voltage Stability Improvement using SVC and TCSC and its Coordination Control" Design Engineering, ISSN: 0011-9342, vol-2021, issue No: 6, pp: 3624-3635.

[3] G. Chavan, S. Acharya, S. Bhattacharya, D. Das and H. Inam, "Application of static synchronous series compensators in mitigating Ferranti effect," *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016, pp. 1-5, doi: 10.1109/PESGM. 2016.7741380.

[4] Venu Yarlagadda, D.Ravi Kumar, E.Shiva prasad , Giri Prasad Ambati , Lakshminarayana Gadupudi , "Prototype models of FACTS Controllers and its Optimal Sizing and Placements in Large Scale Power Systems using Voltage Stability Indices" Design Engineering , ISSN: 0011-9342, vol-2021,issue No:6,pp: 3636-3659.

[5] Y. Venu, Nireekshana, T., Phanisaikrishna, B. (2021). Mitigation of Ferranti Effect Using Thyristor Controlled Reactor. In: Komanapalli, V.L.N., Sivakumaran, N., Hampannavar, S. (eds) Advances in Automation, Signal Processing, Instrumentation, and Control. i-CASIC 2020. Lecture Notes in Electrical Engineering, vol 700. Springer, Singapore. https://doi.org/10.1007/978-981-15-8221-9_236

[6] Venu Yarlagadda, NireekshanaTuraka, Giri Prasad Ambati, S Poornima "Optimization of Voltage Stability based Shunt and Series Compensation using PSO" Design Engineering Vol2021, Issues 7, Pages 8679–8694.

[7] Tingyi He, Shengnan Li, Shuijun Wu, Ke Li, "Small-Signal Stability Analysis for Power System Frequency Regulation with Renewable Energy Participation", Mathematical Problems in Engineering, vol. 2021, Article ID 5556062, 13 pages, 2021. https://doi.org/10.1155/2021/5556062

[8] J. Liu, W. Yao, J. Wen et al., "Impact of power grid strength and PLL parameters on stability of grid-connected DFIG wind farm," IEEE Transactions on Sustainable Energy, vol. 11, no. 1, pp. 545–557, 2020.

[9] X. Yan, "A review of cyber security risks of power systems: from static to dynamic false data attacks," Protection and Control of Modern Power Systems, vol. 5, no. 3, pp. 8–19, 2020.

[10] G. Tu, Y. Li and J. Xiang, "Analysis and Control of Energy Storage Systems for Power System Stability Enhancement," 2019 Chinese Control Conference (CCC), 2019, pp. 560-565, doi: 10.23919/ChiCC.2019.8865814.

[11] S. R. Paital, P. K. Ray and A. Mohanty, "A review on stability enhancement in SMIB system using artificial intelligence based techniques," 2018 IEEMA Engineer Infinite Conference (eTechNxT), 2018, pp. 1-6, doi: 10.1109/ETECHNXT.2018.838 5324.

[12] B. Baadji, H. Bentarzi and A. Bouaoud, "SMIB power system model with PSS for transient stability studies," 2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B), 2017, pp. 1-5, doi: 10.1109/ICEE-B.2017.8191996.

[13] S.Kalyani, M.Prakash and g. A.Ezhilarasi, "Transient stability studies in SMIB system with detailed machine models," 2011 international conference on recent advancements in electrical, electronics and control engineering, 2011, pp. 459-464, doi:10.1109/iconraeece.2011.6129781.

[14] Yarlagadda V., Giri Prasad A., Rami Reddy Ch., Nireekshana T., Seshu Kumari B.V., Satyanarayana P.V.V. " Suppression of Ferranti Effect of Transmission System Using Closed Loop Control of FACTS Devices," Journal of Electrical Systems (JES) ISSN: 1112-5209, 18-4 (2022): 474-486.

[15] Venu Yarlagadda, Srinivasa Rao Jalluri, Giriprasad Ambati, Chava Sunil Kumar, B. Devulal " Power Quality Improvement of Thyristor Controlled Reactor using Harmonic Filters," Journal of Electrical Systems (JES) ISSN: 1112-5209, Electrical Systems 20-10s(2024):1542-1552