# TRANSMISSION LINE COMPENSATION FOR POWER SYSTEM STABILITY IMPROVEMENT

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*Abstract*—Modern power systems which are rapidly growing, required constant attention to monitor their performance. Attention is also required to ensure that the voltage stability margin of the power system is above the desired level .This paper described the transmission line compensation to improve the system stability. In order to achieve the objective, three methods of line compensation were implemented, series capacitor, shunt capacitor and shunt reactor to improve the system stability by looking at the voltage regulation. The system stability is then compared with the Voltage Stability Index (L).This is done for three different transmission lines. The proposed methods were applied to 30 bus IEEE systems to show its feasibility and capability. All simulations were done using MATLAB version 7.5.

*Keywords*—**Transmission line, Line Compensation, Series Capacitor, Shunt Capacitor, Shunt Reactor, Voltage Regulation, Voltage Stability Index (L).**

## 1.0 INTRODUCTION

Power systems involve generation, transmission and distribution. Voltage stability is a major concern in the planning and operation of electric power system. Voltage stability is closely associated with other aspects of power system steady state and dynamic performance. Voltage control, reactive power compensation and management, rotor angle (synchronous) stability, protective relaying and control center operations all influence voltage stability. The voltage stability phenomenon has been well recognized in distribution systems. Several analytical techniques have been proposed to assess the risk of voltage instability. Voltage stability is important for power system operation and planning because voltage instability may lead to voltage collapse and hence outage and monetary losses, and possibly total system black out [6, 8]. Furthermore, a stable system contributes to reliability and reduction in system losses [9].

Reactive power compensation is often the most effective way to improve both power transfer capability and voltage stability. Reactive power compensation can be divided into series and shunt compensation. Active compensation means a feedback control systems regulates voltage or other variables. Common forms of reactive compensation are series capacitor bank, shunt reactor and capacitor bank and static var compensators. Under load transformer tap changing also provides voltage or reactive power control [2]. The main objective of this project is to improve voltage and the system stability. Matlab program is used to determine voltage regulation and voltage stability (L). Three lines with highest power losses are considered for simulations.

## 2.0 THEORETICAL BACKGROUND

### 2.1 Power Flow Analysis

A power flow or load flow program computes the voltage magnitude and angle at each bus in a power system under balanced three phase steady state conditions. There are many techniques of solving a load flow in power system such as:

(i) The Gauss Method
(ii) The Gauss- Siedel Method
(iii)The Newton Raphson Method
(iv)The Fast Decouple Method

In this project Newton Raphson Method is used to calculate the power flow, because of its quadratic convergence. Newton's method is mathematically superior to the Gauss-Seidel method and is less prone to divergence with ill conditioned problems. For large power systems, the Newton-Raphson method is found to be more efficient and practical. The number of iterations required to obtain a solution is independent of the system size. [3]

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \text{...........(1)}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \text{.........(2)}$$

Equation (1) and (2) constitute a set of nonlinear algebraic equations in terms of the independent variables, voltage magnitude in per unit, and phase angle in radians.

### 2.2 Index Formulation

The voltage stability index (L) was developed by Abdul Rahman T.K [6] as given in equation (1)

$$L=\left(\frac{4\left[V_0V_L\cos(\theta_0-\theta_L)-V_L^2\cos(\theta_0-\theta_L)^2\right]}{V_0^2}\right)\text{.........(1)}$$

Where ;

$V_0$ = open circuit voltage

$V_L$ = load voltage

$\theta_0$ = open circuit angle

$\theta_L$ = base angle

L must be kept less than 1.0 to maintain voltage stability. If L exceeds 1.0, the voltage at the referred bus becomes imaginary which indicates that voltage collapse has occurred in the system [4].Since $(\theta_0-\theta_L)$ very small, $(\theta_0-\theta_L)\approx 1.0$ which can be simplified to

$$\text{L}=\frac{4(V_0V_L-V_L^2)}{V_0^2}\text{..................................(2)}$$

The Sensitivity Index (SI) is given by,

$$\text{SI} = \frac{\partial L_i}{\partial P_i}\text{..........................................(3)}$$

$$=\frac{\partial L_i}{\partial V_{L,i}}X\frac{\partial V_{L,i}}{\partial P_i}\text{.........................(4)}$$

Where;

$$\frac{\partial L}{\partial V_{L\,i}}=\left(\frac{[4V_0-8V_L}{V_0^2}\right)$$

$\frac{\partial V_{Li}}{\partial P_i}$ Comes from inverse jacobian matrix

### 2.3 Line Compensation Concept

Compensation consists of injecting reactive power to improve power system operation. More specifically keep voltages close to nominal values, reduce line currents and hence network losses. Reactive power compensation also contributes to voltage stability margin enhancement. Compensation is provided by either capacitors installed in series with transmission lines or shunt elements connected to a particular load bus. In this study shunt and series compensation technique is adopted to improve the voltage stability margin [1].

### 2.3.1 Series Capacitor Compensation

Series capacitor are connected in series with the line usually located at the midpoint, and are used to reduce the series reactance between the load and the supply point.

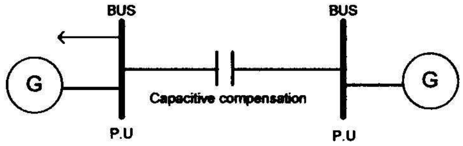

Figure 2.1: Series Capacitor Compensation

### 2.3.2 Shunt Capacitor Compensation

Shunt capacitor are used for lagging power factor circuits created by heavy loads. The effect is to supply the requisite reactive power to maintain the receiving end voltage at a satisfactory level. Capacitor are connected either directly to a bus bar or to the tertiary winding of a main transformer and are disposed along the route to minimize the losses and voltage drop.

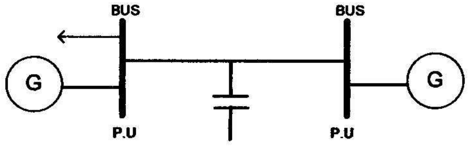

Figure 2.2: Shunt Capacitor Compensation

### 2.3.3 Shunt Reactor Compensation

Shunt reactor are applied to compensate for the undesirable voltage effect associated with line capacitance. Shunt reactor maybe either line connected or bus connected (often on the tertiary winding of autotransformer). The primary purposes of transmission system with shunt compensation near load area are voltage control and load stabilization [5]

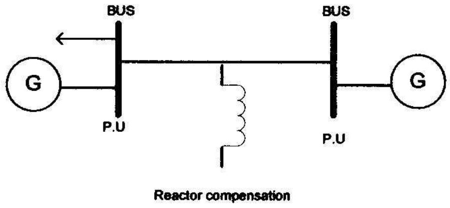

Figure 2.3: Shunt Reactor Compensation

## 3.0 METHODOLOGY

The 30-bus IEEE distribution system is used as a test in this study. The schematic diagram for 30-bus IEEE distribution system is show in Appendix A. The study was aimed to identify the stability of the system by using shunt or series compensation. The study started by simulation load flow program to compute the voltage at each busbar and the power loss in between each line. The lines with maximum losses are chosen for compensation. Three methods of compensation were applied to this lines and the voltage regulation are calculated. The results obtained were then compared with the voltage stability index (L).

The following step are implemented to improve the system stability:

i. Run load flow of an existing system and tabulate the data of power losses of 30 bus IEEE.
ii. The sensitivity index (SI) program is used to determine the sensitive bus. The highest SI value indicates the highest transmission line losses.
iii. Then, different sizes of series capacitor shunt capacitor and shunt reactor were injected respectively at the sensitive transmission line and the values are varied to improve the system stability.
iv. The values of compensation versus voltage regulation and voltage stability index were plotted.

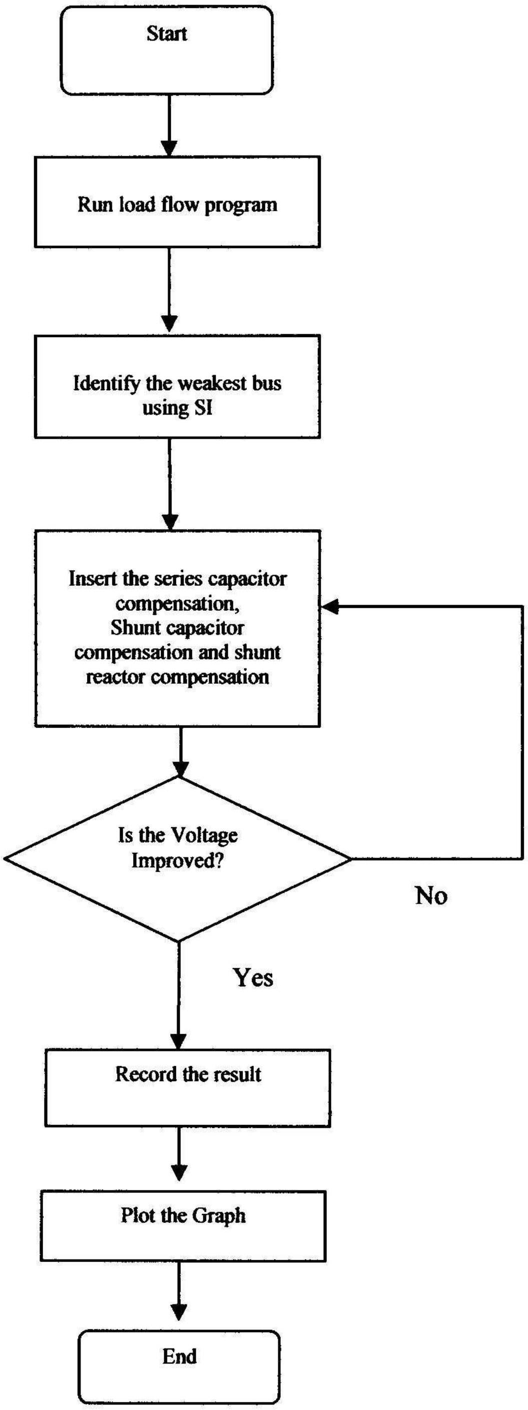

Figure 3.1: The Flow Chart for the Implementation of compensation In Transmission Line

## 4.0 RESULTS AND DISCUSSION

From the load flow program line 1 to 2, 2 to 5 and 1 to 3 gives the highest losses. These three lines are chosen for further studies. The voltage regulations between these three lines are calculated to show its stability.

### 4.1 Bus Voltage without Inserting Compensation

Table 4.1 shows the simulation results of the load flow program without inserting the compensation. The values of voltage regulation are computed.

| Line | Capacitor Value(p.u) | | Vs | Vr(p.u) | V.R |
|---|---|---|---|---|---|
| | X | B/2 | (p.u) | | (%) |
| 1-2 | 0.5 | 0.02640 | 1.06 | 1.023 | 3.6168 |
| 2-5 | 0.7 | 0.02090 | 1.033 | 0.980 | 5.4082 |
| 1-3 | 0.5 | 0.02040 | 1.06 | 1.012 | 4.7431 |

Table 4.1: Result for line 1 to 2,2 to 5 and 1 to 3.

### 4.2 Series Capacitor Compensation

Series capacitor was injected at the highest transmission line losses. The capacitor value was varied and the bus voltage was recorded.

| Line | Capacitor value(p.u) | Vs (p.u) | Vr(p.u) | V.R (%) |
|---|---|---|---|---|
| 1-2 | 0.0 | 1.06 | 1.023 | 3.6168 |
| | 0.10 | 1.06 | 1.023 | 2.6137 |
| | 0.20 | 1.06 | 1.023 | 2.6137 |
| | 0.30 | 1.06 | 1.043 | 1.6299 |
| | 0.40 | 1.06 | 1.043 | 1.6299 |
| 2-5 | 0.0 | 1.033 | 0.980 | 5.4081 |
| | 0.10 | 1.033 | 0.980 | 5.4081 |
| | 0.20 | 1.033 | 0.980 | 4.3482 |
| | 0.30 | 1.033 | 0.980 | 3.3333 |
| | 0.40 | 1.033 | 0.990 | 3.3333 |
| 1-3 | 0.0 | 1.06 | 1.012 | 4.7430 |
| | 0.10 | 1.06 | 1.013 | 4.5360 |
| | 0.20 | 1.06 | 1.014 | 4.3307 |
| | 0.30 | 1.06 | 1.015 | 3.8198 |
| | 0.40 | 1.06 | 1.016 | 3.6044 |

Table 4.2: Result for series capacitor compensation of line 1 to 2, 2 to 5 and 1 to 3.

Table 4.2 and figure 4.1 shows the voltage regulation in between lines 1 to 2, 2 to 5 and 1 to 3.

As the size of series compensation increases the voltage regulation in line 1 to 2 decreases. Similar for line 2 to 5 and 1 to 3 as the value of capacitor increases the voltage regulation decreases.

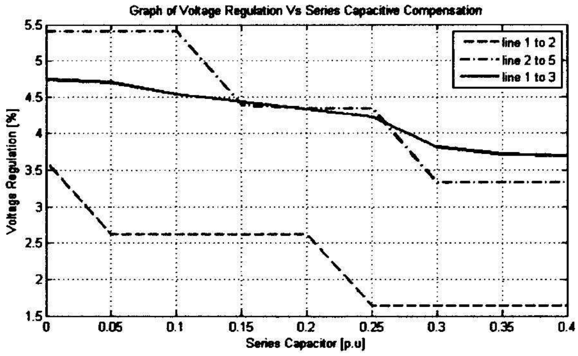

Figure 4.1: Graph VR versus Series Capacitor Compensation

### 4.3 Shunt Capacitor Compensation

With shunt capacitor in the circuit and the decreasing value of inductor. Results obtained were tabulated in table 4.3.

| Line | Inductor value(p.u) | Vs (p.u) | Vr(p.u) | V.R (%) |
|---|---|---|---|---|
| 1-2 | 0.42640 | 1.06 | 1.093 | 3.0192 |
| | 0.62640 | 1.06 | 1.093 | 3.0192 |
| | 0.82640 | 1.06 | 1.083 | 2.1237 |
| | 1.02640 | 1.06 | 1.073 | 2.1237 |
| | 1.22640 | 1.06 | 1.053 | 1.2116 |
| | 1.82640 | 1.06 | 1.043 | 0.6648 |
| 2-5 | 0.42640 | 1.093 | 1.06 | 4.2574 |
| | 0.62640 | 1.083 | 1.06 | 3.2673 |
| | 0.82640 | 1.083 | 1.06 | 3.1130 |
| | 1.42640 | 1.073 | 1.06 | 2.1698 |
| | 1.62640 | 1.063 | 1.06 | 0.2830 |
| | 1.82640 | 1.053 | 1.06 | 1.2264 |
| 1-3 | 0.22640 | 1.06 | 1..135 | 8.4629 |
| | 0.42640 | 1.06 | 1.113 | 6.6619 |
| | 0.62640 | 1.06 | 1.092 | 2.9304 |
| | 0.82640 | 1.06 | 1.076 | 2.9304 |
| | 1.22640 | 1.06 | 1.060 | 0.0000 |
| | 1.62640 | 1.06 | 1.045 | 1.4354 |

Table 4.3: Result for shunt capacitor compensation for line 1 to 2, 2 to 5 and 1 to 3

Table 4.3 and figure 4.2 show the voltage regulation in between lines 1 to 2, 2 to 5 and 1 to 3. With increased value of compensation in line 1 to 2, 2 to 5 and 1 to 3 the voltage regulation is not constant. At first, voltage regulation decrease and suddenly increase.

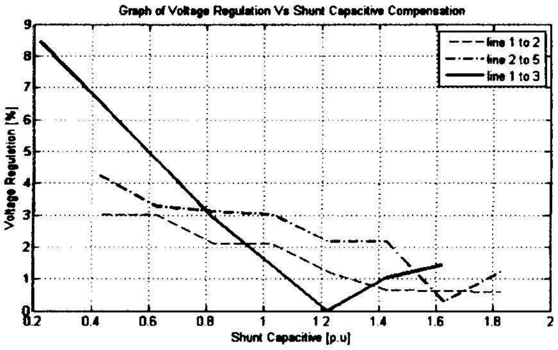

Figure 4.2: Graph VR versus Shunt Capacitor Compensation

### 4.4 Shunt Reactor Compensation

With shunt reactor in the circuit and an increment value of reactor, result obtained was tabulated in table 4.4

| Line | B/2 value(p.u) | Vs (p.u) | Vr(p.u) | V.R (%) |
|---|---|---|---|---|
| 1-2 | 0.12640 | 1.06 | 1.033 | 2.6137 |
| | 0.22640 | 1.06 | 1.043 | 1.6299 |
| | 0.42640 | 1.06 | 1.043 | 1.6299 |
| | 0.62640 | 1.06 | 1.043 | 1.6299 |
| | 0.82640 | 1.06 | 1.043 | 1.6299 |
| | 1.02640 | 1.06 | 1.063 | 0.2822 |
| 2-5 | 0.02090 | 1.033 | 0.98 | 5.408 |
| | 0.22090 | 1.043 | 1.01 | 3.267 |
| | 0.42090 | 1.043 | 1.01 | 3.267 |
| | 0.62090 | 1.043 | 1.01 | 3.267 |
| | 0.82090 | 1.073 | 1.06 | 1.226 |
| | 1.02090 | 1.093 | 1.08 | 1.204 |
| 1-3 | 0.02040 | 1.06 | 1.021 | 3.8198 |
| | 0.22040 | 1.06 | 1.031 | 2.8128 |
| | 0.42040 | 1.06 | 1.039 | 2.0212 |
| | 0.62040 | 1.06 | 1.049 | 1.0486 |
| | 0.82040 | 1.06 | 1.059 | 0.0944 |
| | 1.02040 | 1.06 | 1.060 | 0.0000 |

Table 4.4: Result for shunt reactor compensation of line 1 to 2, 2 to 5 and 1 to 3

Table 4.4 and figure 4.3 show the voltage regulation in between lines 1 to 2, 2 to 5 and 1 to 3. With increases value of compensation in line.

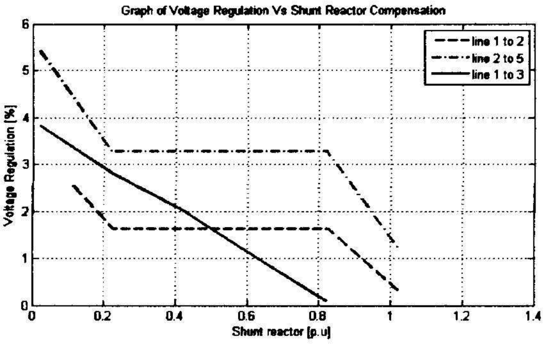

Figure 4.3: Graph VR versus Shunt Reactor Compensation.

### 4.5 Voltage Stability Index (L)

From the load flow program line 1 to 2, 2 to 5 and 1 to 3 gives the biggest losses. These three lines are chosen for further studies. The voltage stability indexes (L) at these two lines are calculated to show its stability.

#### 4.5.1 Bus Voltage without Compensation

Table below shows the simulation result of the load flow program without inserting the compensation. The values of voltage stability (L) are computed.

| Line | Capacitor Value(p.u) | | Vo (p.u) | $V_L$ (p.u) | L |
|---|---|---|---|---|---|
| | X | B/2 | | | |
| 1-2 | 0.0575 | 0.0264 | 1.043 | 1.083 | -0.1593 |
| 2-5 | 0.1983 | 0.0209 | 1.01 | 1.04 | -0.1223 |
| 1-3 | 0.7 | 0.0204 | 1.00 | 1.0215 | -0.0879 |

Table 4.5: Result for line 1 to 2, 2 to 5 and 1 to 3.

### 4.5.2 Stability Index After Inserting Series Capacitor Compensation

The good performance in the system when the value of voltage stability (L) must be kept less than 1.0 to maintain voltage stability.

| Line | Capacitor value(p.u) | Vo (p.u) | $V_L$ (p.u) | L (%) |
|---|---|---|---|---|
| 1-2 | 0.10 | 1.043 | 1.083 | 0.1593 |
| | 0.15 | 1.043 | 1.083 | 0.1593 |
| | 0.20 | 1.043 | 1.083 | 0.1593 |
| | 0.25 | 1.043 | 1.083 | 0.1184 |
| | 0.30 | 1.043 | 1.073 | 0.0006 |
| | 0.35 | 1.043 | 1.063 | 0.0781 |
| | 0.40 | 1.043 | 1.053 | 0.0800 |
| 2-5 | 0.10 | 1.01 | 1.06 | 0.1420 |
| | 0.15 | 1.01 | 1.06 | 0.1420 |
| | 0.20 | 1.01 | 1.06 | 0.1420 |
| | 0.25 | 1.01 | 1.06 | 0.1323 |
| | 0.30 | 1.01 | 1.05 | 0.1222 |
| | 0.35 | 1.01 | 1.04 | 0.1222 |
| | 0.40 | 1.01 | 1.04 | 0.1000 |
| 1-3 | 0.10 | 1.00 | 1.04 | 0.1220 |
| | 0.15 | 1.00 | 1.04 | 0.1220 |
| | 0.20 | 1.00 | 1.03 | 0.1210 |
| | 0.25 | 1.00 | 1.03 | 0.1150 |
| | 0.30 | 1.00 | 1.02 | 0.1150 |
| | 0.35 | 1.00 | 1.02 | 0.1150 |
| | 0.40 | 1.00 | 1.02 | 0.0842 |

Table 4.6: Result for series capacitor compensation line 1 to 2, 2 to 5 and 1 to 3.

Table 4.6 and figure 4.4 show the result at three lines after the compensation. After inserting series capacitive compensation the voltage stability index (L) showed dropped at 0.0006 and smaller increase to 0.0781. The voltage stability index equal to zero means that the voltages are stable. Line 2 to 5 and 1 to 3 shows the decreasing of voltage stability index. This mean the stability in the system has improved by inserting series capacitor.

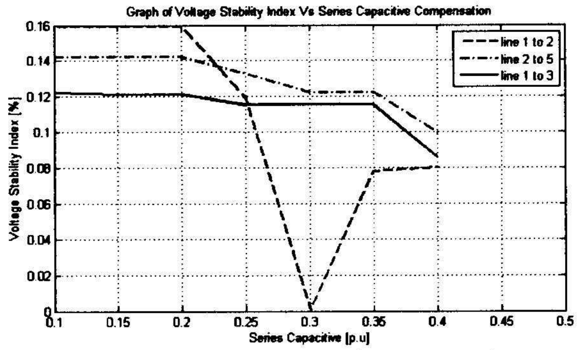

Figure 4.4: Graph L versus Series Capacitor Compensation.

### 4.5.3 Stability Index After Inserting Shunt Capacitor Compensation

With shunt capacitor in the circuit and the decreasing value of inductor. The values of voltage stability were recorded. Results obtained were tabulated in figure 4.5.

| Line | Inductor value(p.u) | Vo (p.u) | $V_L$ (p.u) | L (%) |
|---|---|---|---|---|
| 1-2 | 0.82640 | 1.043 | 1.083 | 0.1593 |
| | 1.02640 | 1.043 | 1.083 | 0.1593 |
| | 1.22640 | 1.043 | 1.076 | 0.1404 |
| | 1.42640 | 1.043 | 1.076 | 0.1404 |
| | 1.62640 | 1.043 | 1.076 | 0.0605 |
| | 1.82640 | 1.043 | 1.050 | 0.0605 |
| 2-5 | 0.82640 | 1.01 | 1.05 | 0.1323 |
| | 1.02640 | 1.01 | 1.05 | 0.1323 |
| | 1.22640 | 1.01 | 1.05 | 0.1323 |
| | 1.42640 | 1.01 | 1.04 | 0.1222 |
| | 1.62640 | 1.01 | 1.03 | 0.0850 |
| | 1.82640 | 1.01 | 1.03 | 0.0850 |
| 1-3 | 0.82640 | 1.00 | 1.025 | 0.1420 |
| | 1.02640 | 1.00 | 1.025 | 0.1420 |
| | 1.22640 | 1.00 | 1.022 | 0.1225 |
| | 1.42640 | 1.00 | 1.022 | 0.1225 |
| | 1.62640 | 1.00 | 1.020 | 0.1151 |
| | 1.82640 | 1.00 | 1.020 | 0.1151 |

Table 4.7: Result for shunt capacitor compensation line 1 to 2, 2 to 5 and 1 to 3.

Table 4.7 and figure 4.5 shows the result of three lines when inserting the shunt capacitor compensation. Line 1 to 2, 2 to 5 and 1 to 3 voltage stability index drop. This means the stability also improved by inserting shunt capacitor.

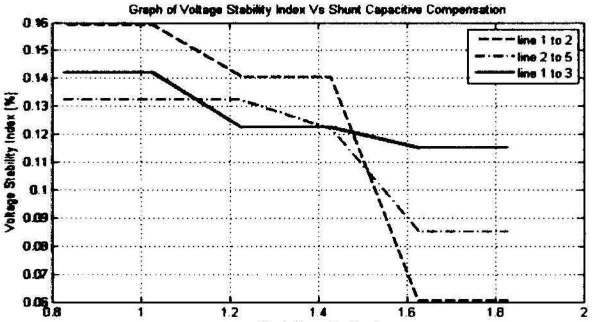

Figure 4.5: Graph L versus Shunt Capacitor Compensation

### 4.5.4 Stability Index after Inserting Shunt Reactor Compensation.

With shunt reactor in the circuit and the decreasing value of inductor. The values of voltage stability were recorded. Results obtained were tabulated in figure 4.6.

| Line | B/2 value(p.u) | Vo (p.u) | $V_L$ (p.u) | L (%) |
|---|---|---|---|---|
| 1-2 | 0.82640 | 1.043 | 1.083 | 0.1593 |
| | 1.02640 | 1.043 | 1.083 | 0.1593 |
| | 1.22640 | 1.043 | 1.083 | 0.1593 |
| | 1.42640 | 1.043 | 1.073 | 0.1184 |
| | 1.62640 | 1.043 | 1.073 | 0.1184 |
| | 1.82640 | 1.043 | 1.064 | 0.1120 |
| 2-5 | 0.82640 | 1.01 | 1.06 | 0.1420 |
| | 1.02640 | 1.01 | 1.06 | 0.1420 |
| | 1.22640 | 1.01 | 1.06 | 0.1420 |
| | 1.42640 | 1.01 | 1.05 | 0.1323 |
| | 1.62640 | 1.01 | 1.04 | 0.1222 |
| | 1.82640 | 1.01 | 1.04 | 0.1222 |
| 1-3 | 0.82640 | 1.00 | 1.030 | 0.1211 |
| | 1.02640 | 1.00 | 1.030 | 0.1211 |
| | 1.22640 | 1.00 | 1.030 | 0.1211 |
| | 1.42640 | 1.00 | 1.025 | 0.1184 |
| | 1.62640 | 1.00 | 1.025 | 0.1184 |
| | 1.82640 | 1.00 | 1.020 | 0.1151 |

Table 4.8: Result for shunt capacitor compensation line 1 to 2 , 2 to 5 and 1 to 3 .

Table 4.8 and figure 4.6 shows the result when inserting shunt reactor compensation at three transmission lines. Line 1 to 2 (bus 2) the voltage stability index decreases from 0.1593 to 0.1120.Line 2 to 5 (bus 5) voltage stability index also decreases, from 0.1420 to 0.1222.Line 1 to 3 (bus 3) voltage stability index decrease from 0.1211 to 0.1151.

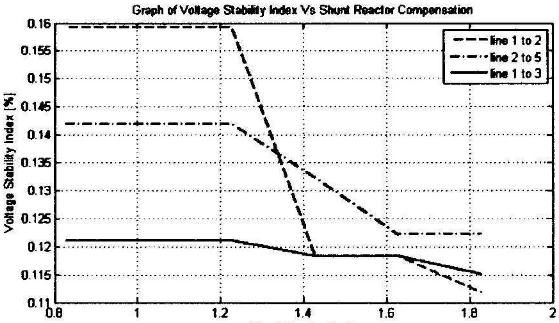

Figure 4.6: Graph L versus Shunt Reactor Compensation

## 5.0 CONCLUSION

This project demonstrates the performance of transmission line using series and shunt compensation to improve the system stability. The result shows that the most stable system is by using shunt capacitor compensation, when the value of shunt capacitor increases, the voltage regulations will decreases. For transmission line 1-2 and 2-5, the voltage regulations are 0.6648p.u and 0.2830p.u. For transmission line 1-3, voltage regulation is equal to 0 which means the system is stable. Voltage stability also shows the decreasing in value to almost zero. For transmission line 1-2, 2-5 and 1-3 the voltage stability are 0.0605p.u, 0.0850p.u and 0.1511p.u which means the system become stable when approaching zero.

## 6.0 FUTURE DEVELOPMENT

For future development, others method of compensation could be observed. This project can be used to calculate the Sensitivity Index (SI). This technique will used to determine the suitable location of the compensation. This index indicates the suitable location of compensation where the highest value of SI will be the best location to insert the compensation.

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## References

[1] A. Arunagiri, B.Venkatesh, "Simulation of Voltage Stability and Alleviation Through Knowledge Based System" Faculty of Engineering, Faculty of Engineering and Technology Multimedia University,Cyberjaya,63100, Malaysia.

[2] Carson W. Taylor, "Power System Voltage Stability", McGraw Hill, USA, 1994.

[3] Lukman D. Blackburn, T.R and Walshe, K, Loss Minimization in Industrial Power System operation, Proceeding of the Australian Universities Power Engineering Conference (AUPEC'94), Brisbane, Australia.

[4] Transmission and Distribution Committee of the IEEE Power Engineering Society,"IEEE Guide for Application of Shunt Power Capacitors", Approved September 17 1992,IEEE Standards Board, IEEE Std 1036-1992.

[5] Hadi Saadat, *Power System Stability and Control,* Mc. Graw Hill, usa, 1999.

[6] T.K Abdul Rahman and G.B Jasmon (1995) "A New Technique for VoltageStability in Power System and Improve LoadFlow Algorithm for Distribution Network "Energy Management and Power Delivery Conference, Singapore, Vol 2, pp, 714-719.

[7] S.S Venkata, C.S Indulkar, B.Vishwanathan, Maximum Power Transfer Limited by Voltage Stability in Series abd Shunt Compensation Schemes for A.C Transmission System."IEEE Transaction on Power Deliver, Vol 4 no 2, April 1989.

[8] Sterling, M.J.H., Chebbo, A.M., and Irving, M.R.: 'Reactive power dispatch incorporating voltage stability', *IEE Proc. C,* 1992,139, (3), pp. 253-260

[9] Jasmon, G.B., and Lee, L.H.C.C.: 'Maximizing voltage stability in distribution networks via loss minimization', *J. Electr. Power Energy Syst.,* 1991, 13, (3), pp. 148 – 152

[10]Stagg, G.W. and El-Abiad, A.H. 1968, Computer Methods in Power System Analysis, McGraw-Hill Book Company, New York.