Technical-Economic Analysis in the Application of Series Capacitor Compensation for Distribution Networks

by

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CERTIFICATION OF APPROVAL

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Approved by,

____

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UNIVERSITI TEKNOLOGI PETRONAS

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JANUARY 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Wagdy Ahmed Moustafa Mansour

ABSTRACT

Series capacitor compensation has been widely known as a successful technique of increasing the overall transmission efficiency in power systems by reducing the line reactance by a certain ratio which is defined by the term degree of compensation (K). In this paper, a new approach is suggested and further discussed where the series compensation mechanism is to be used for distribution networks as a method of reducing network losses, increasing power transfer capability and reducing reactive power input to the grid. Furthermore, the study economically justified the application of the proposed technique. The study is divided into two phases. During this phase of the project, a 14 Bus network is constructed and modelled using Simulink to verify the concept. The simulation results obtained proved the ability of the series compensation technique in achieving the mentioned objectives.

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LIST OF ABBREVIATIONS

PTC power transfer capability

P value or amount of money at a time designated as the present or time 0. Also P is referred to as present worth (PW), present value (PV); monetary units, such as dollars.

F value or amount of money at some future time. Also F is called future worth (FW) and future value (FV); dollars

A series of consecutive, equal, end-of-period amounts of money. Also A is called the annual worth (AW); dollars per year, euros per month.

n number of interest periods; years, months, days

i interest rate per time period; percent per year, percent per month

t time, stated in periods; years, months, days

CHAPTER 1 : INTRODUCTION

1.1 Background Study

Series capacitor is a reactive power compensation device. Capacitor is installed in series with the line or cable to reduce reactance of the network. Series capacitor is widely used in high voltage transmission system known as flexible AC transmission systems (FACTS) devices. However, in distribution system, the use of series capacitors is not very common. The concept is illustrated as follows;

Series Compensation Operation Mechanism:

In Figure 1, a series compensated radial network is shown, where R is the line resistance, X_L is the line reactance and X_C is the reactance of the series capacitor respectively [1].

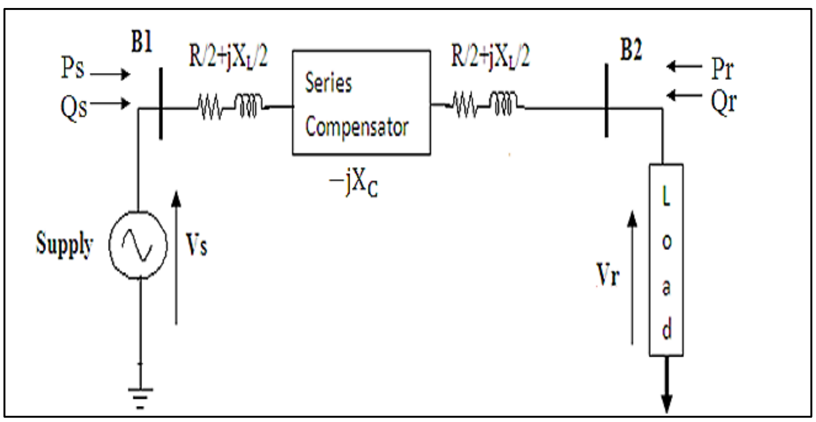

Figure 1: Series capacitor compensated power system

The phase voltage drop from source to load obtained from phasor diagram in Figure 2 can be written as in Equation 1.0.

$$\Delta V = (R * I_L * \cos\delta) + ((X_L - X_C) * I_L * \sin(\delta)) \qquad \text{Equation (1.0)}$$

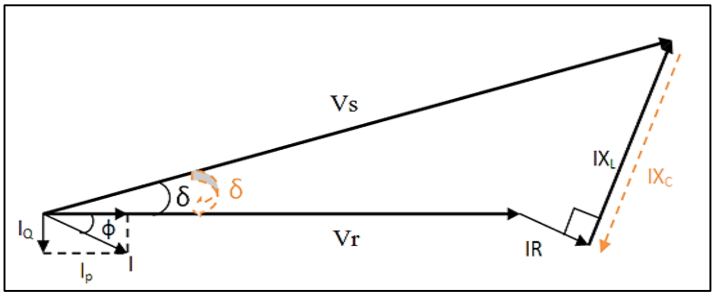

Figure 2: Phasor diagram

Equation 1.1 and 1.2 are the active and reactive power at the sending end while equation 1.3 and 1.4 are the active and reactive power at the receiving end.

$P_S = V_S * I_S * \cos\delta$ Equation (1.1)

$Q_S = V_S * I_S * \sin\delta$ Equation (1.2)

$P_R = V_R * I_R * \cos\delta$ Equation (1.3)

$Q_R = V_R * I_R * \sin\delta$ Equation (1.4)

On the other hand, the voltage regulation provided by the series capacitor is steady and immediate [2]. Also, in case of voltage fluctuations due to large variations of the load, a series capacitor will improve the quality at the load downstream from the series capacitor. The impact of the series capacitor on the voltage profile of a radial power distribution line with inductive load is introduced in Figure 3. In fact, the increase of the receiving end voltage caused by the series capacitor will result in a current reduction which will lead to reduction in the reactive power input from the system. Eventually, the power transfer capability will be increased.

Additionally, another important factor - the degree of compensation (K) – which is the ratio of line reactance to be compensated in order to enhance the overall performance of the line. Moreover, the degree of compensation has limitations that need to be considered carefully for a proper operation. First of all, K should be kept less than 100% as if it exceeds this limit, the line would be overcompensated. If the overcompensation occurs, the line current and power flow would be extremely sensitive to changes in the relative angles of terminal voltages.

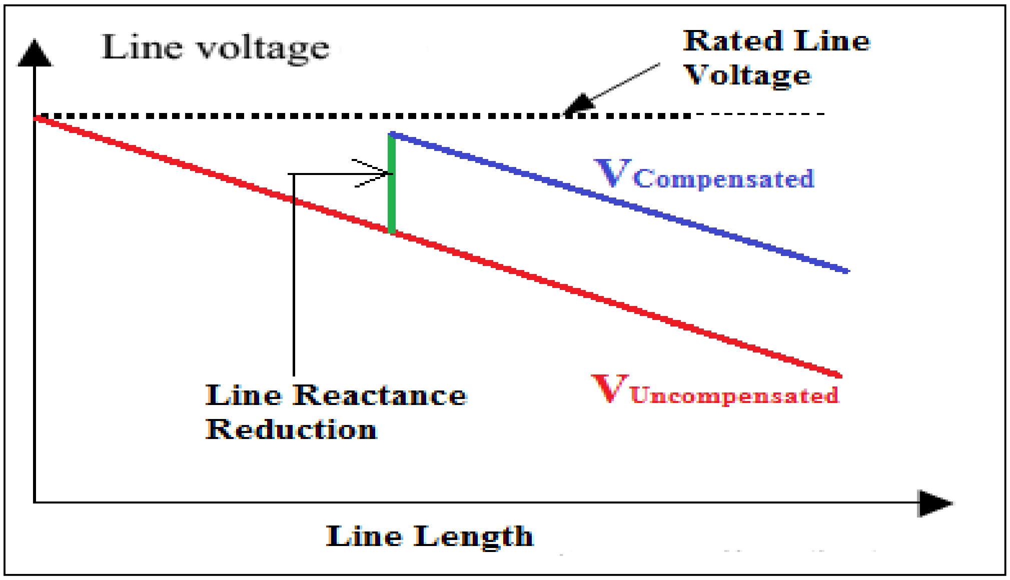

Figure 3: Impact of series compensation on voltage profile

1.2 Problem Statement

Series capacitor compensation is not widely used in distribution systems due to unfamiliarity in the design, operation, negative effects such as sub-synchronous resonance, and ferroresonance. There are no recent studies analyzing the technical effects along with the economic effects of applying series capacitor compensation method with respect to:

- The ability to increase power transfer capability of the system.
- Reduction in reactive power input from the grid system and the reduction in network losses.
- The enhancement of voltage profile.
- Adjusting parallel feeder load distribution by altering the parallel circuit reactance.

1.3 Objectives

- To compare two proposed alternatives for increasing Power transfer capability in a typical distribution system. The two alternatives are; series capacitor compensation and network upgrading by modelling and simulation of typical distribution system
- To analyse the impact of the proposed technique on voltage profile.

- To analyse reactive power input reduction from the grid system and its line losses reduction for both alternatives.
- To determine the optimum location of series capacitor compensation on the distribution network.

1.4 Scope of Study

The project starts by studying the mechanism of series compensation and how it affects a distribution network. The resources that will be used are various such as, journal articles, books, conference papers, manufacturers' brochures and handbooks. Moreover, research studies about applying the series compensation will be analysed to determine any possible advantages and disadvantages that might arise when applying the compensation technique. By doing this, a wide knowledge about the topic can be gained which will help with the second and most important phase of the project which is the simulation.

After that, a small testing model will be built to validate the methodology. Then, the final network model will be defined taking into consideration the distribution system limitations. After modelling and simulating the system with and without the series capacitor module, results will be obtained about the impact of using the series compensation. Furthermore, an economic analysis will take place to justify the two alternatives given in the problem statement. Based on the results, analysis and discussion can be made to conclude the performance and cost efficiency of using series compensation in distribution networks.

CHAPTER 2 : LITERATURE REVIEW

2.1 Series Capacitor Compensation

Series capacitor compensation is a widely used method for both transmission lines and distribution networks. In general, series compensation is achieved by reducing the reactance value on the line between the supply bus and load. This is done by adding a voltage in series to maintain a fixed voltage value at the load side despite any fluctuations or disturbances that may occur to the voltage supply source and so, any voltage drops in the line can be compensated [3] . Moreover, the theory can be further explained as the injected value of the capacitor negative reactance will eliminate a huge amount of the line positive reactance and as a result the line impedance is reduced in total. By doing that, the voltage profile will be greatly improved and at the same time, the line losses are reduced [4].

In addition, for a utility distribution network, the variable loads can impose fluctuations on the network which will lead to voltage profile problem. An example is when running a motor, its initial current is usually larger than the rated one. This is because the motor will need more power to create enough torque to rotate its shaft. As a result, an instantaneously drop in voltage value will occur at the feeder line. That voltage drop is sudden and usually lasts for a few seconds until the motor reaches the operating speed and then the motor current will decrease to its rated value [5].

Generally, a series capacitor unit needs to have additional sub- systems to maintain proper functioning. For example, a series compensation unit requires control, protection and monitoring systems to enable it to perform in a compatible way within a power distribution network. Also, since the series capacitor is operating at the same voltage level as the rest of the system, it needs to be fully grounded to prevent any kind of faults that may occur [6].

In addition, the design phase of a series capacitor unit for a utility system is quite critical concerning the chosen design factors. For example, the capacitor unit location needs to be accurately chosen to achieve the required compensation ratio [2]. Generally, the location of capacitor can be anywhere along the line but certain elements such as power transfer capability improvement, installation cost, accessibility for maintenance purposes, fault level protection and voltage profile [1, 5]. Also, sub-synchronous resonance which can lead to a generator failure and may increase instability of the system at oscillation frequencies lower than the network rated frequency [7]. Furthermore, compensation ratio has to be considered as high compensation level increases the complexity of protection circuit and probability of sub synchronous resonance [1].

2.2 Impacts of Using Series Capacitor Compensation

Line losses and voltage fluctuations issues are rather common in distribution networks due to the heavy duty loads. To solve this problem, many alternatives can be proposed such as reconductoring the feeder, uprating the feeder voltage, constructing a parallel feeder, and constructing a new substation [5].

When considering reconductoring the feeder, big investments needed to cover the expenses for replacing the current carrying cables with higher rating ones. An accurate cost optimization can be made to reduce the total expenses by reusing some of the existing elements (poles or structures) and replacing only the conductor itself. however, such an investment may still not be economically justified [8].

On the other hand, uprating the feeder voltage to the next utility standard system voltage will result in a better voltage profile improvement with a significant reduction in line losses. However, additional cost will be required to implement this option such as purchasing electrical equipment, replacing line cables and performing environmental and technical studies to highlight the impact on the surrounding area and on the overall performance of the network. Besides, inaccuracy may happen when predicting the load growth that demands such a huge investment [9]. So, uprating the feeder cannot be verified as a cost effective solution for the voltage profile problems.

In addition, an analytical study done by ABB Sweden proved the cost efficiency of series capacitor application. In the study, an existing 1300 MW transmission network using two parallel 500 kV lines is to be upgraded to a 2000 MW system due to load growth. The suggested options are to series compensate the two existing lines or build a third parallel line. The study showed that the total investment for compensating the two existing lines will be approximately 10 percent of building a third parallel line. Moreover, the study did not consider the time being saved by not constructing a new parallel feeder as it will take several years added for the construction, depending on the route and distance of the new line [6].

As a result, series capacitor compensation is proposed to provide a proper, cost effective and environmentally acceptable solution to help enhance the voltage profile and reduce line losses. The mechanism of series compensation is rather effective and its positive impacts on the line are highly observed. When installing the series capacitor units, most of the downstream systems will experience an increased short-circuit power [9] which defines the ability of a utility grid to supply varying loads without experiencing high flicker levels [10]. In addition, series capacitor units require low maintenance during its operation which will reduce the operation and maintenance expenses.

2.3 Economic Evaluation of Alternatives

The project's main aim is to increase power transmission quality and capability in electrical distribution networks. Such investments are usually managed by the government because of the high criticality of the power networks on society and the country's economy in general. In fact, the economic calculation reflects not only investment costs but also other items –operational costs, deprecations, reducing of costs of supply interruptions and the time value of the money [11]. In the cash flow analysis, there are three main terms to be introduced which are present worth, annual worth and future value [12]. The present worth is the value of an expected income flow determined as of the date of the project's appraisal and it can be calculated as in Equation 2.0. As for the annual worth, it is defined as the yearly cost of owning and operating an asset over its entire lifespan and can be calculated by Equation 2.1. Finally, the future worth is the value of an asset at a specific date along the project's lifespan and can be calculated as in Equation 2.3.

$P = (F/P, i\ \%, n)$ Equation (2.0)

$A = (A/P, i\ \%, n)$ Equation (2.1)

$F = (F/P, i\ \%, n)$ Equation (2.2)

As a public sector project, there are significant differences in its characteristics comparing to private sector alternatives. Initially, size of investment may greatly vary as alternatives required to serve public needs demand large initial investments with a possibility of its distribution over years. Power plants, public transportation systems, and flood control systems are examples [13]. In addition, the project’s life estimates is important as the long lifespans of public projects often prompt the use of the capitalized cost method

In addition, publicly owned projects have costs that are paid mostly by the government unit; and they benefit the citizens. Public sector projects often have undesirable consequences, as interpreted by some sectors of the public. It is these consequences that can cause public controversy about the projects. That’s why the economic analysis should consider these consequences in financial terms [13]. To perform a benefit/cost economic analysis of public alternatives, the costs, benefits and disbenefits must be estimated as accurately. The project’s costs can be identified as the estimated expenditures to the government entity for construction, operation, and maintenance of the project while the project’s benefits are the advantages to be experienced by the public. In fact, one of the financial analysis main purposes is to compute the overall project cost which is made up of construction cost and operation cost. The construction cost consists of variable cost and fixed cost. Variable cost differs according to length of line but fixed cost is constant [14]. On the other hand, the disbenefits are the expected negative consequences to the public if the alternative is implemented. However, it is problematic to estimate the economic impact of benefits and disbenefits for a public sector alternative because their bases are difficult to establish and verify. Generally, public meetings and debates are held in association with public sector projects to address and gather the various interests of citizens.

The capital used to finance public sector projects is commonly acquired from taxes, bonds, and fees. As for the project’s interest rate, many of the funding methods for public sector projects are categorized as low-interest as the interest rate is lower than for private sector alternatives. This results in interest rates in the 4% to 8% range [12]. As a matter of standardization, directives to use a specific interest rate are beneficial because different government agencies are able to obtain varying types of funding at different rates [13].

2.4 Alternative Selection Using Incremental Benefit-Cost Ratio Analysis:

The incremental benefit-cost analysis is used to choose the best option from a list of mutually exclusive alternatives [15] . Mutually exclusive alternatives can be defined as the business proposals of a certain project. However, only one of these proposals can be selected. For terminology purposes, each possible proposal is called an alternative [13]. The incremental benefit-cost analysis is applicable for all types of investment projects. Its main aim is the improvement of the current business schemes. The examples of this improvement may vary along wide range of courses of action from a simple replacement in a certain project to the full construction of new plants or factories.

CHAPTER 3 : METHODOLOGY

3.1 Research Methodology

Figure 4 describes the steps taken to conduct the technical-economic analysis.

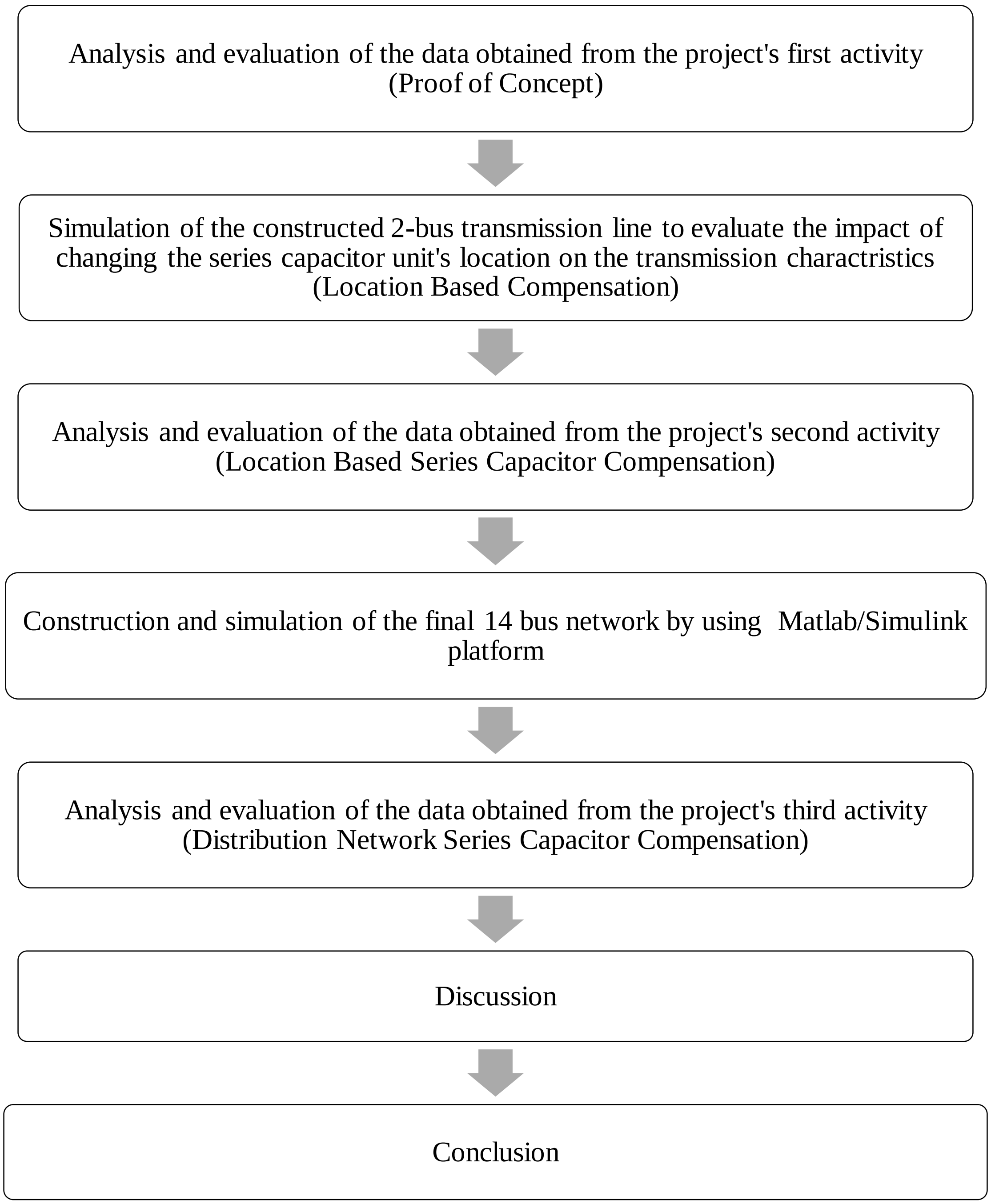

Figure 4: Research methodology

3.2 Project Activities

3.2.1 Proof of Concept (Project activity 1)

The main aim of this activity is to prove the technical concept of series capacitor compensation technique and its impacts on the network's active power, reactive power and voltage profile.

After carrying out the initial research on the series capacitor compensation technique, a model was chosen for the first phase simulation purposes. The 2 bus model [16], chosen for the study is illustrated as follows;

- Generator Parameters:

  Rms Voltage Value: 500 kV

  Angle: 16.1 degree

- Line Parameters:

  Length: 300 km

  Resistance: $10^{-13}\Omega$ per km

  Inductance: 0.97 mH per km

  Capacitance: 0.0115 µF per km

- Load Parameters:

  Rating: 1000 MVA

  Type: Inductive series RLC load

  Power Factor: 0.8 lagging

The system is built by using Matlab/Simulink platform where SimPowerSystems toolbox is used. Then, the simulation process is focused on:

- Voltage profile at the receiving end of the line (load side)
- The reactive power input to the system
- The power transfer capability from the sending end of the line to the load.

Accordingly, measurements were taken for the system parameters when no compensation is applied as a reference for the compensated line results. Rms values of the generated and load voltages were measured besides the active and reactive power values transferred along the line. In applying the proposed technique, a specific series capacitor unit was followed after being proven successful with similar case studies. The model and its implementation in Simulink are highlighted in Figure 5.

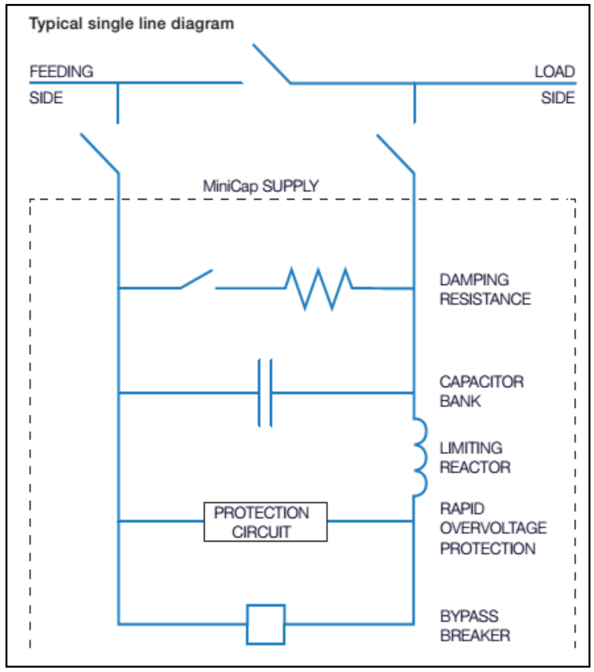

Figure 5: ABB MiniCap internal structure (single line diagram)

I. Main Components of the Series Capacitor Unit

- Capacitor Bank

The capacitor bank consists of capacitor units connected in series to provide the required total MVAR ratings. The capacitor bank is connected in parallel with the unit as in Figure 5. Also, the capacitor units are equipped with internal discharge resistors to fulfill the discharge requirements according to applicable standards.

- Metal Oxide Varistor

The Metal Oxide Varistor (MOV) overvoltage protection is made from individual MOV blocks that are connected in series in order to achieve the desired protective level. The MOV is then connected in parallel with the capacitor unit to obtain the required energy absorption capability. The MOV blocks are assembled in stacks with high strength silicone housing according to specification.

- Damping Circuit

The purpose of the current limiting damping circuit is to limit and damp the discharge current caused by spark gap operation or closing the bypass switch. The current limiting damping circuit normally consists of an air core reactor. In case of high damping of the discharge current is required, a damping resistor is connected across the reactor.

- By-Pass Switch

Allow the series capacitor to be bypassed in cases of internal faults and reinsert the faulted line after fault is cleared.

II. Capacitor Unit Implementation in Matlab/Simulink:

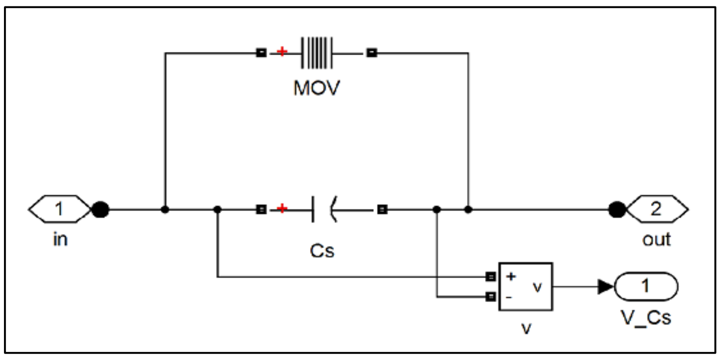

Figure 6: Series Capacitor Model

The MOV block implements a highly nonlinear resistor used to protect power equipment against overvoltages. When high power dissipation is required, several columns of metal-oxide discs are connected in parallel inside the same porcelain housing. The protection voltage obtained with a single column is specified at a reference current (usually 500 A or 1 kA). Default parameters given for the block were maintained as their effect on the protection voltage is negligible. However, the required protection voltage is obtained for the rated generated voltage. Additionally, the capacitor block is a simple block where the capacitance value is entered to match the degree of compensation (K) required for the system.

The capacitance value depends on the compensation ratio (K) which has been chosen to range from 25% to 75% of the total line reactance [17]. The line impedance is calculated in equation 3.0.

$Z_{Line} = R + X_L$ Equation (3.0)

The compensation ratio (K) has a limit, then the following equations are used to calculate the capacitance needed for each (K)

$0 \leq K \leq 1$

$K = X_C / X_L$ Equation (3.1)

$X_C = \frac{1}{2\pi f C}$ Equation (3.2)

$C = \frac{1}{2\pi f * Xc}$ Equation (3.3)

The following table shows the original line impedance with no compensation applied and then it shows the different values of the line impedance associated with different compensation ratios.

Table 1: Compensation ratio and it correspondent capacitance

Percentage of Compensation (K)	Line Reactance (X_L)	X_C	Correspondent Capacitance Value ($\boldsymbol{F}$)
($K = 0\%$)	$107.1i$	0	0
($K = 25\%$)	$80.325i$	$26.775i$	$9.90694 * 10^{-5}$
($K = 30\%$)	$74.97i$	$32.13i$	$8.25578 * 10^{-5}$
($K = 40\%$)	$64.26i$	$42.84i$	$6.19184 * 10^{-5}$
($K = 50\%$)	$53.55i$	$53.55i$	$4.95347 * 10^{-5}$
($K = 60\%$)	$42.84i$	$64.26i$	$4.12789 * 10^{-5}$
($K = 70\%$)	$32.13i$	$74.97i$	$3.53819 * 10^{-5}$
($K = 75\%$)	$26.775i$	$80.325i$	$3.30231 * 10^{-5}$

3.2.2 Location Based Compensation Analysis (Project activity 2)

The location where the capacitor unit is positioned to give its highest performance is to be studied based on the simulation results of the model. The unit's location is critical as it may affect the overall efficiency of the concept and also it plays an important part for the economic point of view especially regarding maintenance expenses.

In order to perform a location analysis, the total length of the line is divided into twelve (12) sections to investigate the impacts of location varying series compensation on the line. Two PI models are used to simulate the line parameters. The length of each PI model is determined by the following equations:

$L_1 = D * \text{Total line length}$ Equation (3.4)

$L_2 = (1 - D) * \text{Total line length}$ Equation (3.5)

Where;

L_1 Length of the first PI Model (km)

L_2 Length of the second PI Model (km)

D Ratio of the total line length

3.2.3 Distribution Network Series capacitor compensation (Project activity 3)

In this phase of the project, a technical analysis is conducted in applying the series compensation technique on an electrical distribution network which is constructed and simulated using Matlab/Simulink. The parameters of the network are in accordance with IEEE 14 bus test network which has been decided for evaluating the proposed technique. The IEEE14 bus system was chosen as a test system as it is considered for large scale simulations [18].

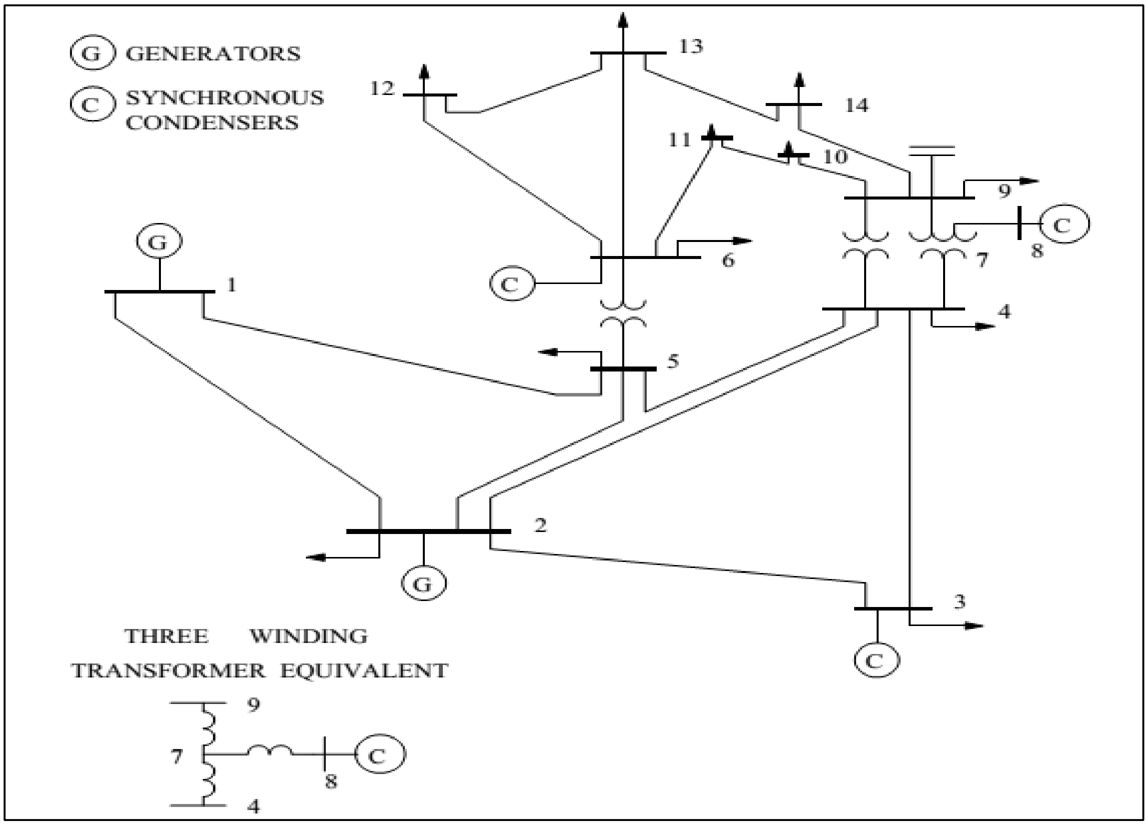

Figure 7: IEEE 14 Bus test network [19]

The system parameters can be found in [20], [21]. As seen in Figure 7, the network consists of two (2) main generators, three (3) synchronous compensators, two (2) two-windings three phase transformers, one (1) three-windings three phase transformer and twenty (20) transmission lines.

The network is constructed in Matlab/Simulink platform considering the main differences between single phase and three phase simulations. The transmission lines are modelled using three phase series RLC branches. However, the Matlab/Simulink platform does not provide the ability to define line lengths for those specific blocks which is an essential requirement for pursuing the technical analysis as the unit's location is an important parameter for the evaluation process. This issue is resolved as the 14 bus network parameters (reactance, susceptance and resistance) are given per 10 km and so, their values are multiplied by the distance to obtain the line's parameters. The same method is followed when dividing the total line length for applying the series compensation technique.

In addition, the voltage magnitudes are represented in per unit values for a more comprehensive analysis. In the location based compensation analysis, the series capacitor unit's location for the 14 bus network is varied along the compensated lines at three different locations. First, the unit is located at half distance of the total line's length at $D = 1/2$, then at a distance of $D = 3/4$ and finally, at a distance of $D = 2/3$ of the total line's length. The study concept is to apply the series capacitor compensation technique for a distribution network in which shorter length lines are proposed. For the simulation purposes, three different line's lengths are considers; 10 km, 30 km and 50 km. On the other hand, two degrees of compensation K = 40 %, K = 75 % are used to show the impact of varying the compensation degree (K) on the network performance.

Generally, the series compensation is applied to the lines with high reactance values. Therefore, line 9 – 14 is chosen to undergo the series compensation analysis. First of all, the uncompensated line parameters are calculated. Then, the line is divided into two parts namely part A and part B between which the capacitor unit is positioned. In the simulation, all the network lines are assumed to have the same length.

Table 2: Capacitor unit's locations on line 9 - 14

Ratio of the total Line Length D	Total Length (Km)	Part A Length (Km)	Part B Length (Km)
$D = 1/2$ $D = 3/4$ $D = 2/3$	10	5 7.5 6.67	5 2.5 3.33
$D = 1/2$ $D = 3/4$ $D = 2/3$	30	15 22.5 20	15 7.5 10
$D = 1/2$ $D = 3/4$ $D = 2/3$	50	25 37.5 33.3	25 12.5 16.67

After that, the parameters for each part are calculated as shown in Figure 8.

Line 9 - 14 Series Compensation			XL	L	XL	L	XL	L
Line 9 - 14 (10 Km)		RLC Branch Block	D = 3/4		D = 2/3		D = 1/2	
0.000717205	0.27038	9 - 14 B	0.067595	0.000215162	0.09003654	0.000286595	0.13519	0.000430323
		9 - 14 A	0.202785	0.000645485	0.18034346	0.000574051	0.13519	0.000430323
		Line 9 - 14 Total Reactance	0.27038	0.000860646				
Line 9 - 14 (30 Km)		RLC Branch Block	D = 3/4		D = 2/3		D = 1/2	
0.000717205	0.27038	9 - 14 B	0.202785	0.000645485	0.27038	0.000860646	0.40557	0.001290969
		9 - 14 A	0.608355	0.001936454	0.54076	0.001721293	0.40557	0.001290969
		Line 9 - 14 Total Reactance	0.81114	0.002581939				
Line 9 - 14 (50 Km)		RLC Branch Block	D = 3/4		D = 2/3		D = 1/2	
0.000717205	0.27038	9 - 14 B	0.337975	0.001075808	0.45072346	0.001434697	0.67595	0.002151616
		9 - 14 A	1.013925	0.003227424	0.9003654	0.002865952	0.67595	0.002151616
		Line 9 - 14 Total Reactance	1.3519	0.004303231				

Figure 8: Parameters calculations for line 9 – 14 (part A, B)

3.2.4 Economic Analysis (Project activity 4)

By using the incremental benefit-cost ratio analysis, the benefits and costs differences between the alternatives are calculated and then the ratio of the equivalent worth of benefits to that of costs is found out. After that, the alternative with large cost is selected, if the incremental benefits justify the extra cost associated with it. In other words if the incremental B/C ratio is greater than or equal to 1.0, then the larger cost alternative is selected. If incremental B/C ratio is less than 1.0, then lower cost alternative is selected [13].

The incremental benefit-cost ratio analysis for comparison of mutually exclusive alternatives is carried out in the following steps;

1. First, all the alternatives are arranged in increasing order of equivalent worth of costs. The equivalent worth of cost of alternatives may be determined either by present worth method, annual worth method or future worth method.
2. The alternative with lowest equivalent cost is now compared with do-nothing alternative (initial base alternative). In other words the B/C ratio of lowest equivalent cost alternative on its total cash flow is calculated. If calculated B/C ratio is greater than or equal to 1.0, then the lowest equivalent cost alternative becomes the new base alternative. On the other

hand if B/C ratio is less than 1.0, then this alternative is removed from further analysis and the acceptability of the next higher equivalent cost alternative as base alternative is found in the same manner as that was carried out for the alternative with lowest equivalent cost. This process is continued till the base alternative (acceptable alternative for which B/C ratio is greater than or equal to 1.0) is obtained. If no alternative is obtained in this manner, then do-nothing alternative is selected i.e. none of the alternatives are selected, if this is an option.

3. Now the incremental benefit, DB and incremental cost, DC (i.e. difference in benefits and costs) between next higher equivalent cost alternative and the base alternative are calculated and then incremental B/C ratio (DB/DC) i.e. ratio of the equivalent worth of incremental benefits to that of incremental costs is obtained. If the incremental B/C ratio (DB/DC) is greater than or equal to 1.0, then the base alternative is removed from further analysis and the next higher equivalent cost alternative becomes the new base alternative. On the other hand if DB/DC is less than 1.0, then the higher equivalent cost alternative is eliminated form further analysis and base alternative remains the as the base. Then the incremental B/C ratio is calculated between the next higher equivalent cost alternative and the base alternative. This process is continued till the last alternative is compared and in this way the best alternative is selected which justifies the extra cost associated with it from the incremental benefits.

3.3 Key Milestone

No.	Item/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Preparing the Progress Report														
2	Submission of Progress Report														
3	Poster Presentation														
4	Submission Final Report's Dratft														
5	Submission of Final Report														

3.4 Gantt Chart

No.	Item/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Analysis of Project's First Activity Data														
2	Project's Second Activity														
3	Analysis of Project's Second Activity Data														
4	Project's Third Activity														
5	Analysis of Project's Third Activity Data														

CHAPTER 4 : RESULTS AND DISCUSSION

4.1 Proof of Concept

After calculating the capacitance value required for each degree of compensation as shown in Table 1, the model [16] for the project's first activity is constructed and simulated using Matlab/Simulink . Measurements blocks are added to the module to monitor and record the parameters values (voltage, current, active and reactive power). The simulated models with and without the series capacitor unit as in Figure 9 and 10.

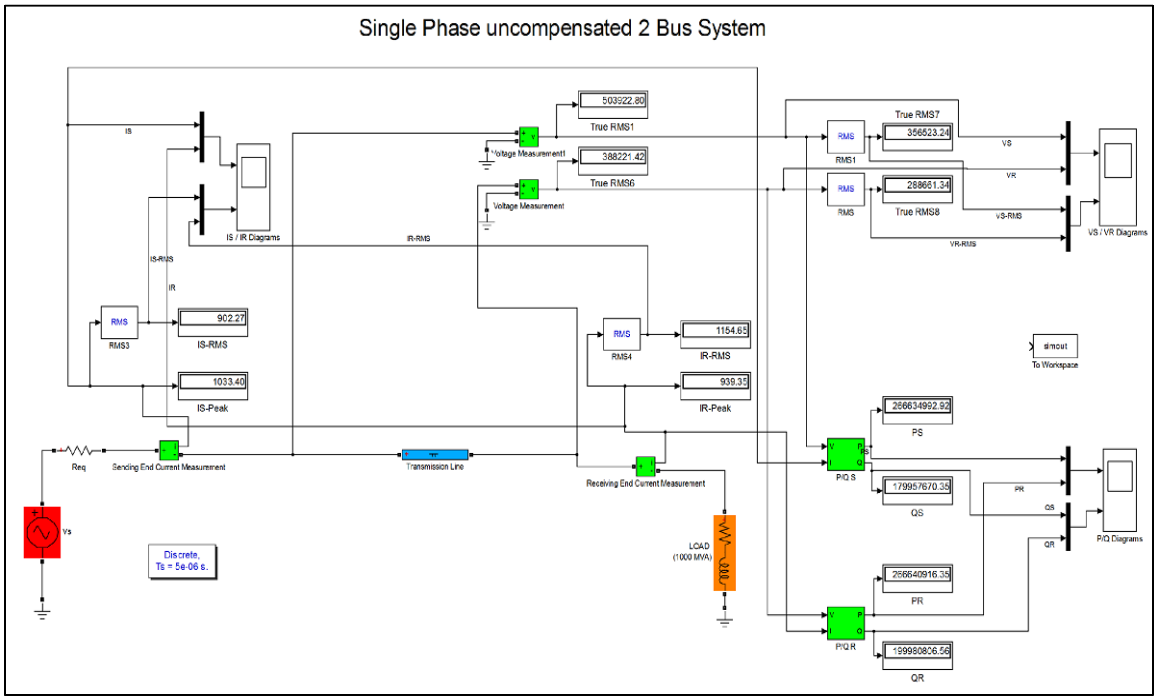

Figure 9: 2-Bus system with no compensation applied

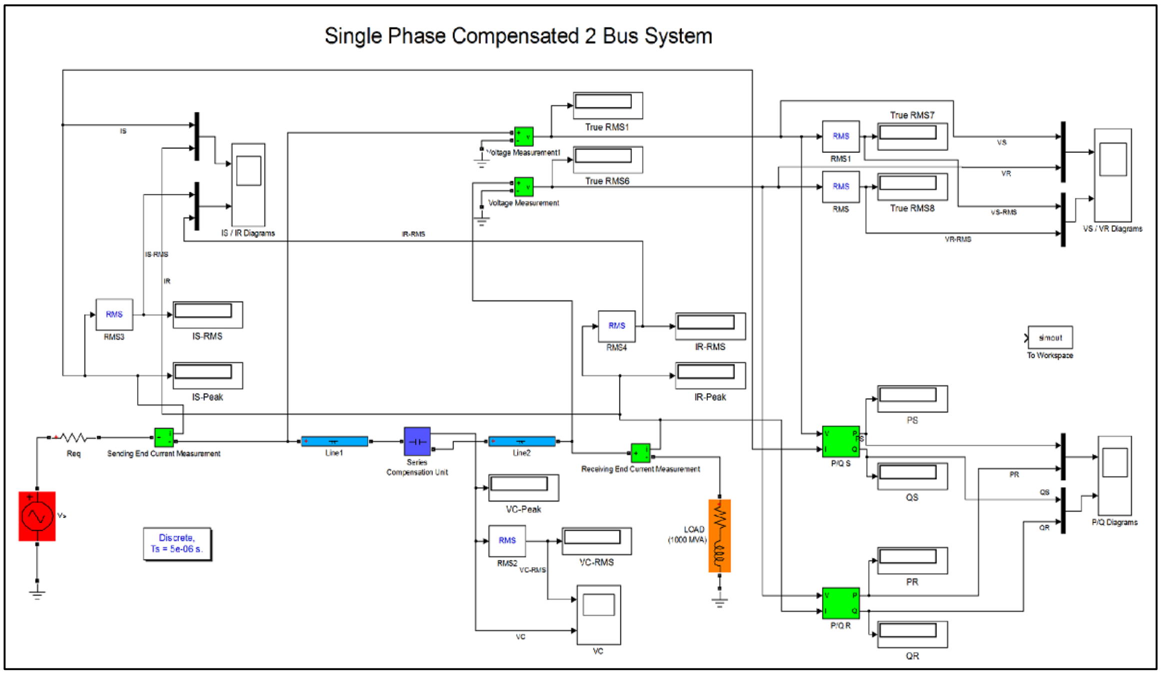

Figure 10: 2-Bus system with series capacitor compensation applied

For the 1st project activity, the initial results obtained after the simulation showed that using the series compensation technique has improved active power transfer capability, reduced reactive power input from the grid and enhanced the voltage profile in total.

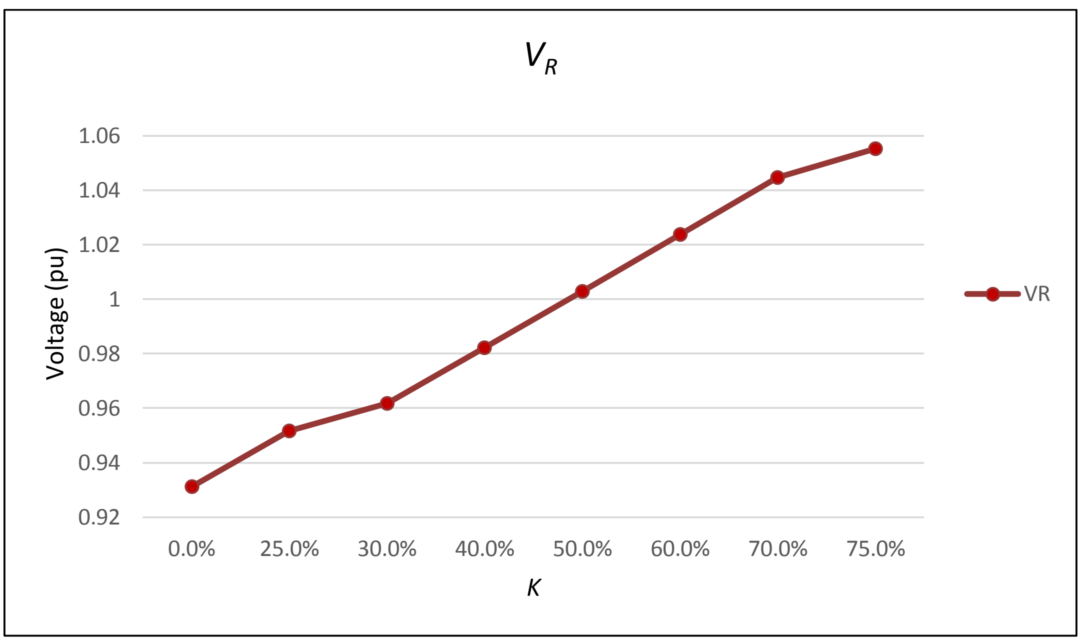

Figure 11: Enhancement in receiving end voltage profile

Figure 11 shows how the voltage at the receiving end side is improved by the addition of the series capacitor unit which compensates all the losses occurred due to the line parameters. It can be concluded that by increasing the degree of compensation (K), the voltage profile at the load side will be more stable.

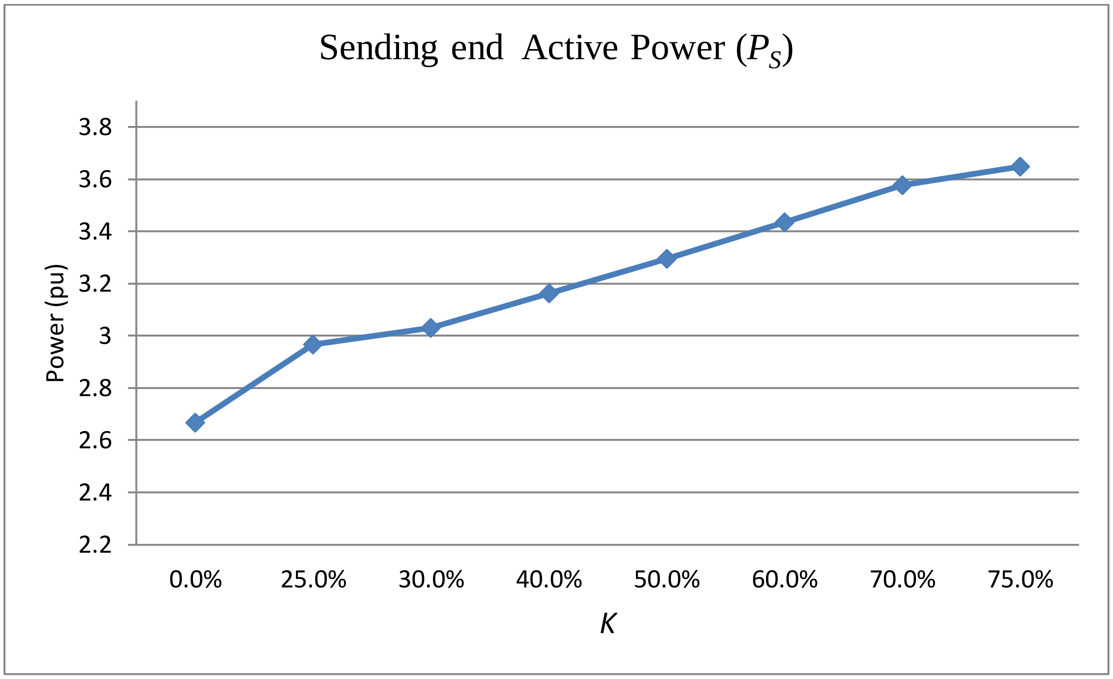

Figure 12: Increase in active power transfer capability

Figure 12 points out that the amount of active power that can be transferred from the generator side to the load side is gradually increased after the insertion of the series capacitor unit. Also, by increasing (K), the amount of power to be transferred is also increased.

On the other hand, Figure 13 shows the relationship between the receiving end and the sending end active power which have almost the same magnitude despite the line losses. This indicates that the insertion of the series capacitor unit has reduced the line losses and as a result increased the transmission efficiency of the line.

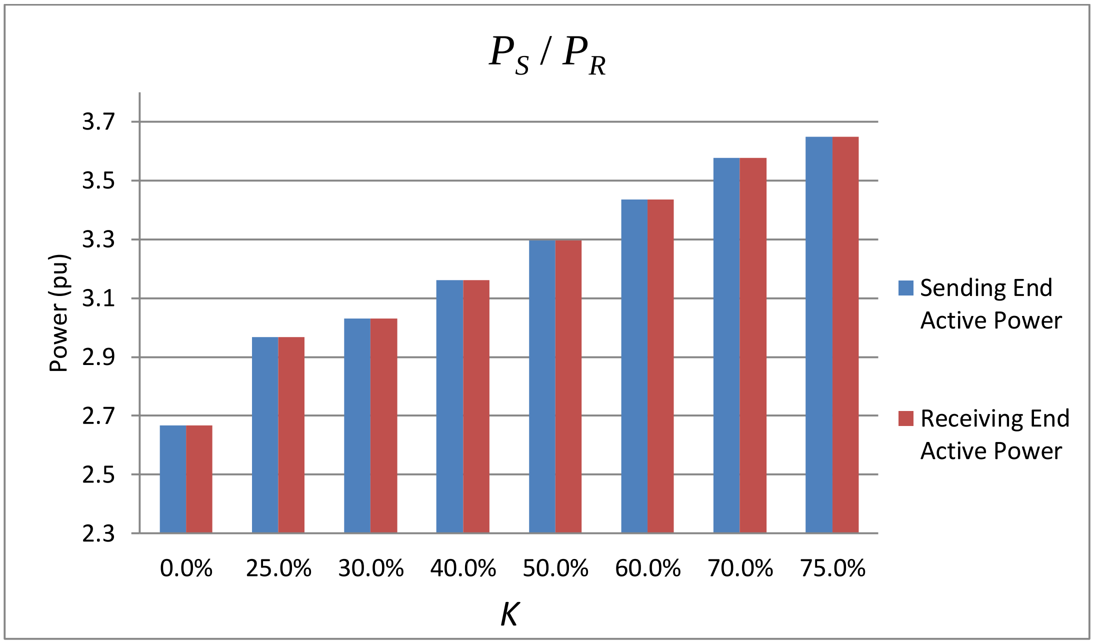

Figure 13: Sending end and receiving end active power

Furthermore, Figure 14 indicates that the reactive power input to the grid is decreased as a result of applying the series compensation system.

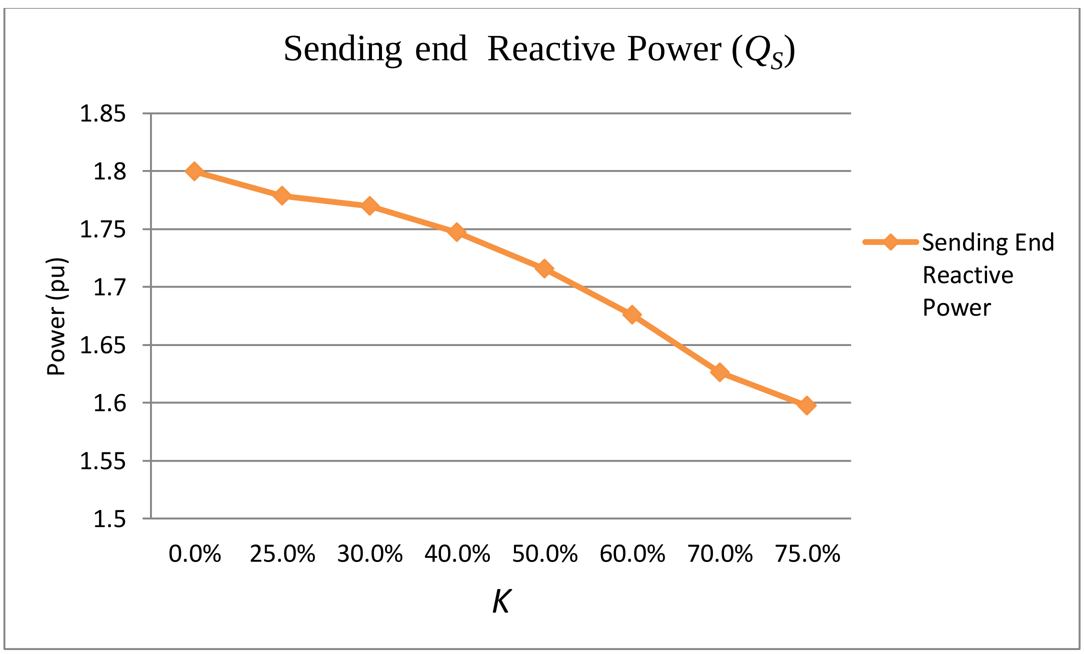

Figure 14: Reduction in sending end reactive power

4.2 Location Based Compensation Analysis

For the 2nd project activity, K was varied for the same location during the first stage of the simulation. Then, the location is changed and again K is varied.

Initially, the capacitor unit was placed at a distance of 25 km and capacitance value was changed inside the capacitor unit to reflect the different degrees of compensation.

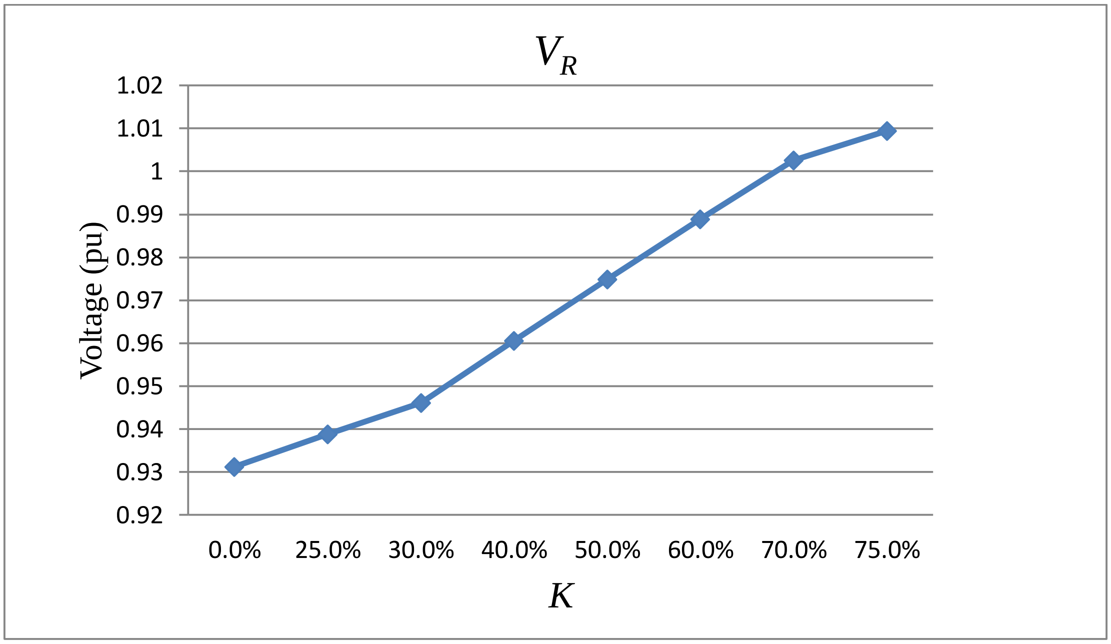

Figure 15: Receiving end voltage profile - capacitor unit is at 1/12 (25 km) of the total line length

Figure 15 shows that the voltage at the receiving end side (V_R) is improved by inserting the series capacitor unit which compensates the losses occurred due to the line parameters. Based on the graph, it can be concluded that by increasing K, the voltage profile at the load side is enhanced.

Furthermore, Figure 16 indicates that the amount of active power that can be transferred from the generator side to the load side (P_R) is gradually increasing by increasing K. Also, the reactive power input to the grid (Q_S) is reduced as a result of applying the series compensation technique.

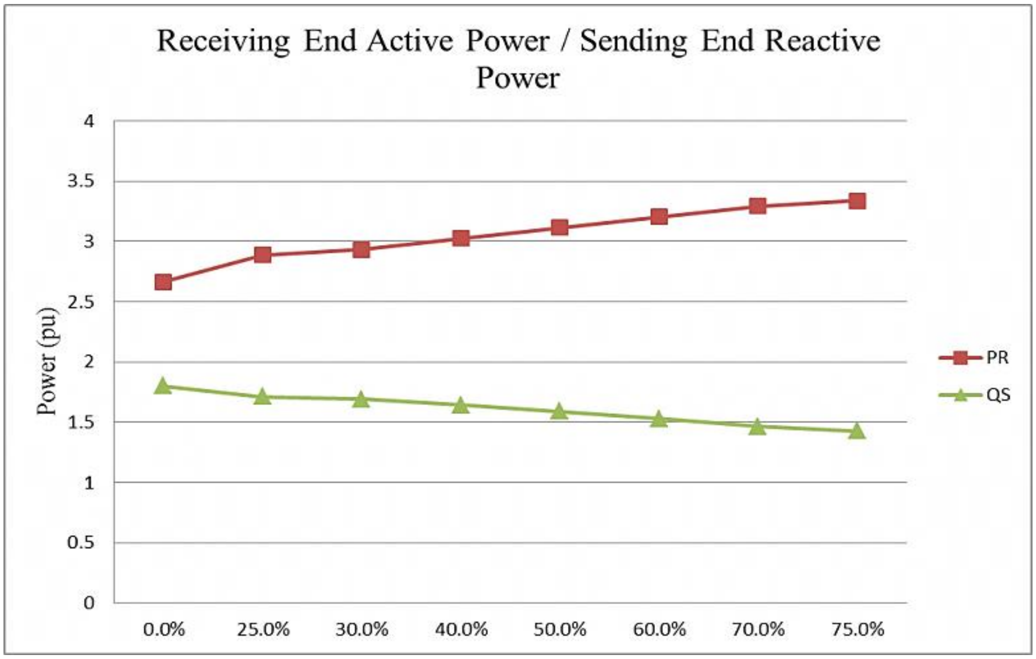

Figure 16: Receiving end active power P_R / sending end reactive power Q_S - capacitor unit is at 1/12 (25 km) of the total line length

Figure 17 shows the relationship between the receiving end and the sending end active power where the magnitude is almost maintained despite the line losses. This indicates that the addition of the series capacitor unit has diminished the line losses thus the transmission efficiency of the line is enhanced.

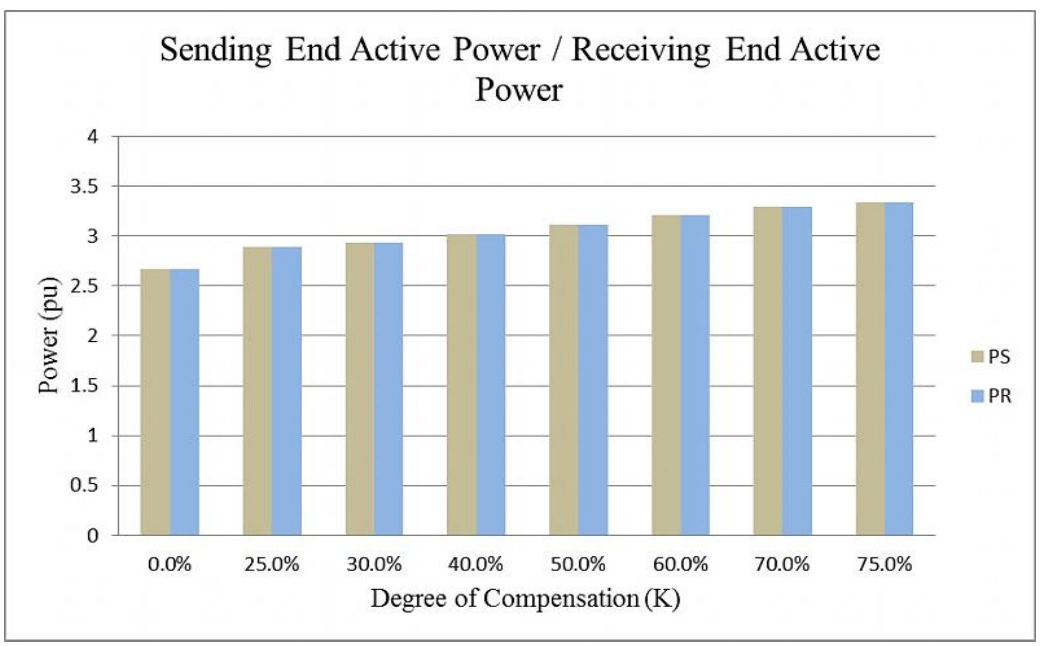

Figure 17: Sending end and receiving end active power - Capacitor Unit is at 1/12 (25 km) of the total line length

Broadly, the initial simulation results signified that using the series compensation technique has improved active power transfer capability, reduced reactive power input from the grid and enhanced the voltage profile. Specifically, with the unit being positioned at $D = 1/12$, by increasing K from 0 % to 75 %, the receiving end voltage magnitude (V_R) is increased by 9.63% as in Figure 15. Also, in Figure 17 the power transfer capability of the line (P_R) is enhanced by 67.2% while the generator's reactive power (Q_S) is reduced by 37.03% as in Figure 16.

In the simulation's Second Phase, different values of D were applied to examine the location-varying impacts on the line. Table 3 contains the locations at which the series capacitor unit is positioned.

Table 3: Capacitor unit's locations on the line

Ratio of the total Line Length D	Capacitor Unit's Location (Km)
$D = 1/12$	25
$D = 1/6$	50
$D = 1/4$	75
$D = 1/3$	100
$D = 5/12$	125
$D = 1/2$	150
$D = 7/12$	175
$D = 2/3$	200
$D = 3/4$	225
$D = 5/6$	250
$D = 11/12$	275

As a matter of fact, the voltage profile at the receiving end side (V_R) is highly enhanced as a result of varying the unit's location while maintaining the same degree of compensation (K) as noticed in Figure 18. For example, the voltage regulation at K = 60 % is increased by 6 % by changing the unit's location from 25 km ($D = 1/12$) to 275 km ($D = 11/12$) as in Figure 19.

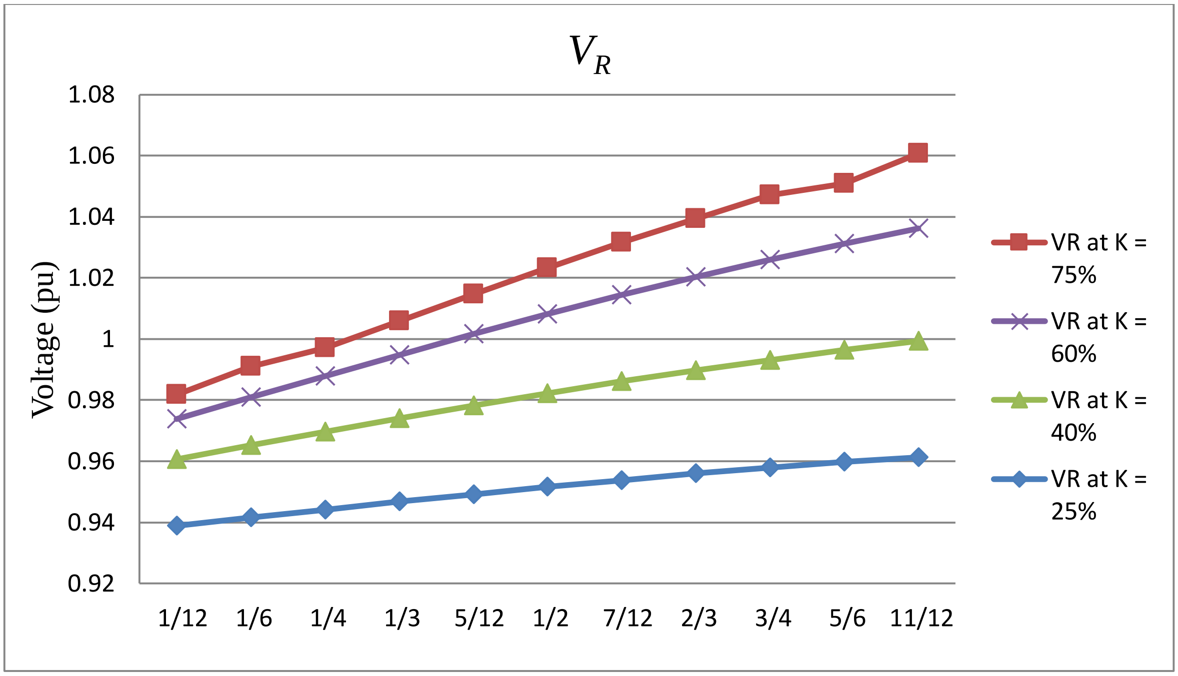

Figure 18: Receiving end voltage profile V_R with multiple degrees of compensation (K = 25 % - 75 %) – capacitor unit positioned at different locations

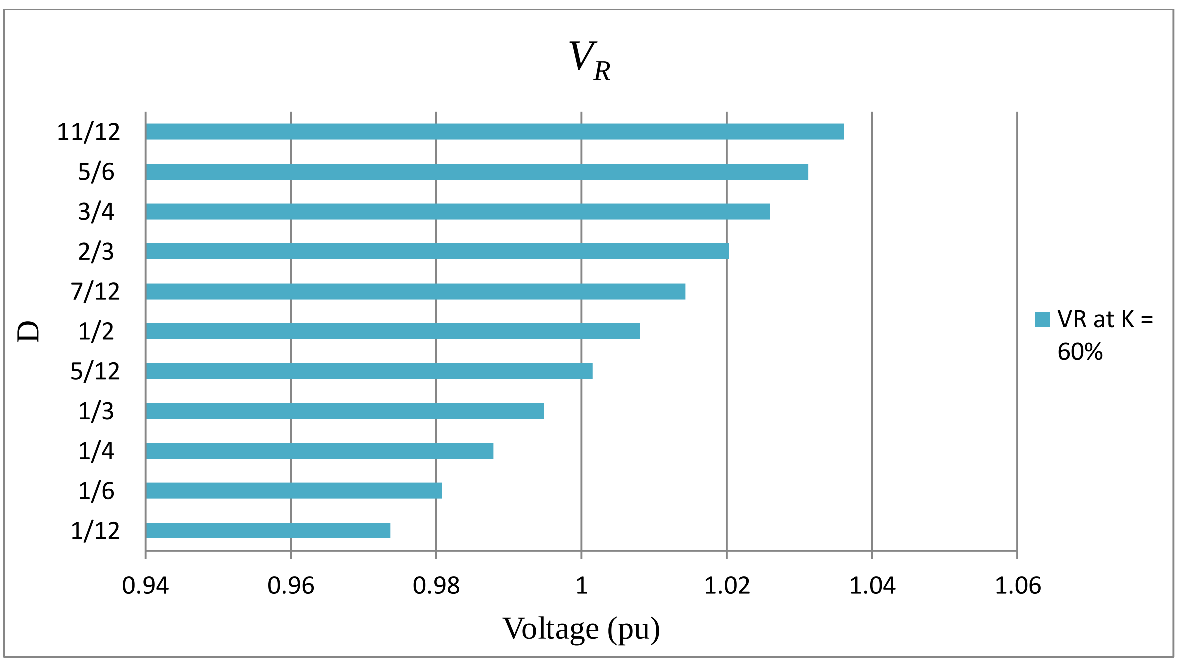

Figure 19: Receiving end voltage profile V_R with degree of compensation K = 60 % - capacitor unit positioned at different locations

Figure 20 shows that the most enhanced voltage profile might be achieved by applying a compensation degree of K = 75 % while placing the unit at a distance of 275 km ($D = 11/12$). In that case, a voltage regulation of 7.58 % is realized as compared to the voltage magnitude V_R before compensation.

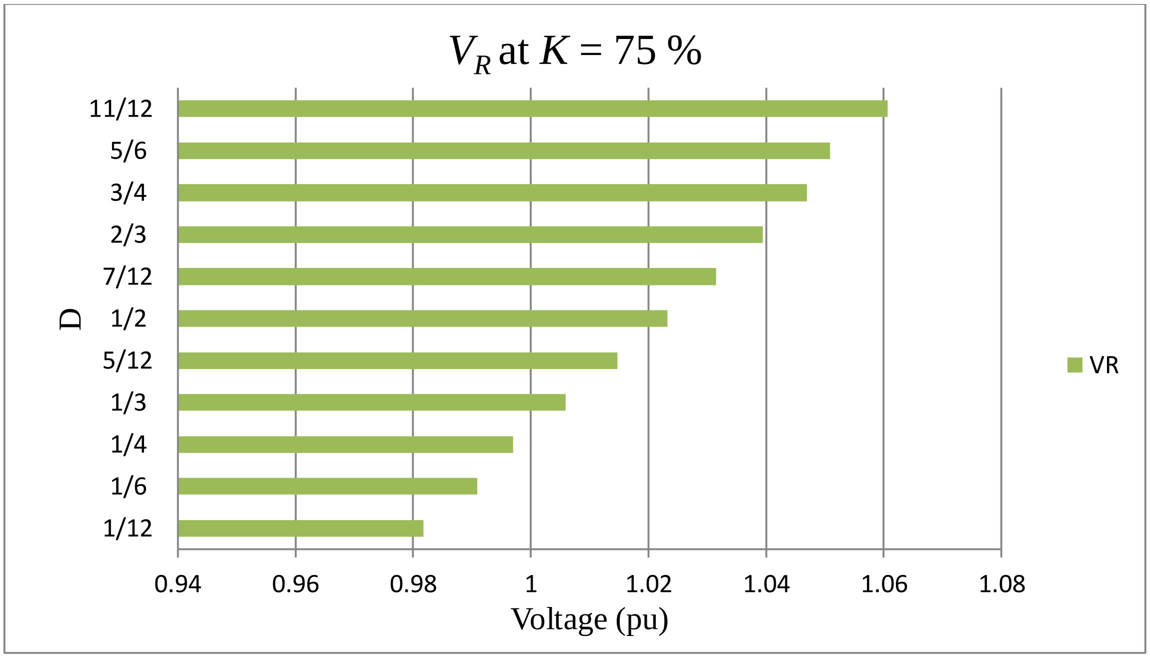

Figure 20: Receiving end voltage profile V_R with degree of compensation K = 75 % - capacitor unit positioned at different locations

Figure 21 demonstrates the location changing impact of the series capacitor compensation unit on the power transfer capability (*PTC*) of the transmission line. The indexes of the chart show that the active power transmitted through the line has been greatly raised by using a high K with varying location. It is also observed that the closer the capacitor unit to the load, the higher the *PTC* of the system.

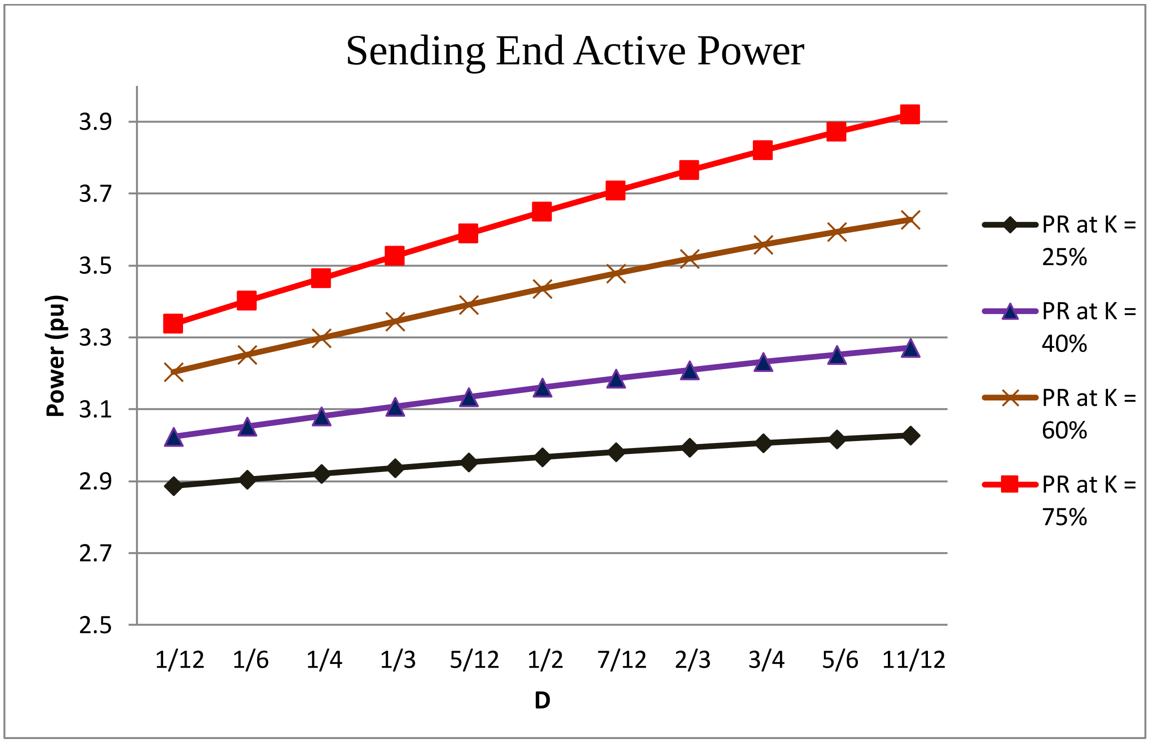

Figure 21: Receiving end active power P_S with multiple degrees of compensation (K = 25 % - 75 %) – capacitor unit positioned at different locations

The simulation results showed that by using a compensation degree of K = 75 % with positioning the series capacitor unit at a distance of 275 Km ($D = 11/12$), the active power transmission capability will be increased by 47 % as in Figure 21. However, other considerations shall be highlighted before deciding on the final location of the capacitor compensation unit.

Another important variable that needs to be considered when finalizing the capacitor's unit location is the sending end reactive power (Q_S). The reactive power input to that system shall be reduced for enhancing the overall transmission efficiency of the line.

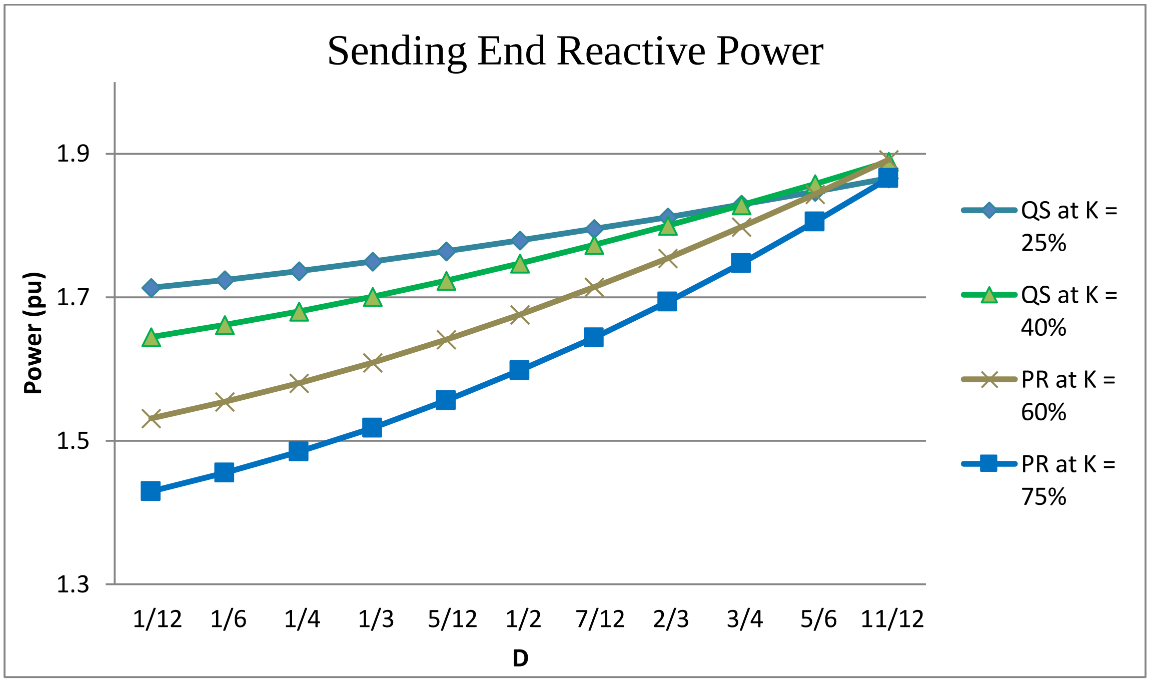

Figure 22: Sending end reactive power Q_S with multiple degrees of compensation (K = 25 % - 75 %) – capacitor unit positioned at different locations

In Figure 22, different compensation levels (K) are used with changing the unit's location when applying each of them. It can be seen that the reactive power input to the grid is increasing by narrowing the distance between the capacitor's unit and the load side. This shall negatively affect the transmission efficiency. Therefore, an optimization analysis is done to come up with the most suitable location for the series capacitor unit to achieve the highest possible (PTC) and reduce the reactive power input to the grid (Q_S) while maintaining a convenient (V_R).

By reviewing the simulation results, it is decided to use a compensation degree of K = 75 % which has been proven as the most suitable for enhancing the transmission efficiency. On the other hand, the series capacitor unit's location is estimated at a distance of $D = 2/3$ or $D = 3/4$ of the total length of the line.

As per the optimization analysis, by locating the unit at $D = 2/3$ (200 Km) and at $D = 3/4$ (225 Km), the (PTC) is increased by 12 % and 17 % respectively comparing to compensating at the midpoint of the line ($D = 1/2$) as in Figure 23. Moreover, the reactive power input (Q_S) is decreased by 13 % and 17 % respectively comparing to compensating at the end of the transmission line ($D = 11/12$) as in Figure 24.

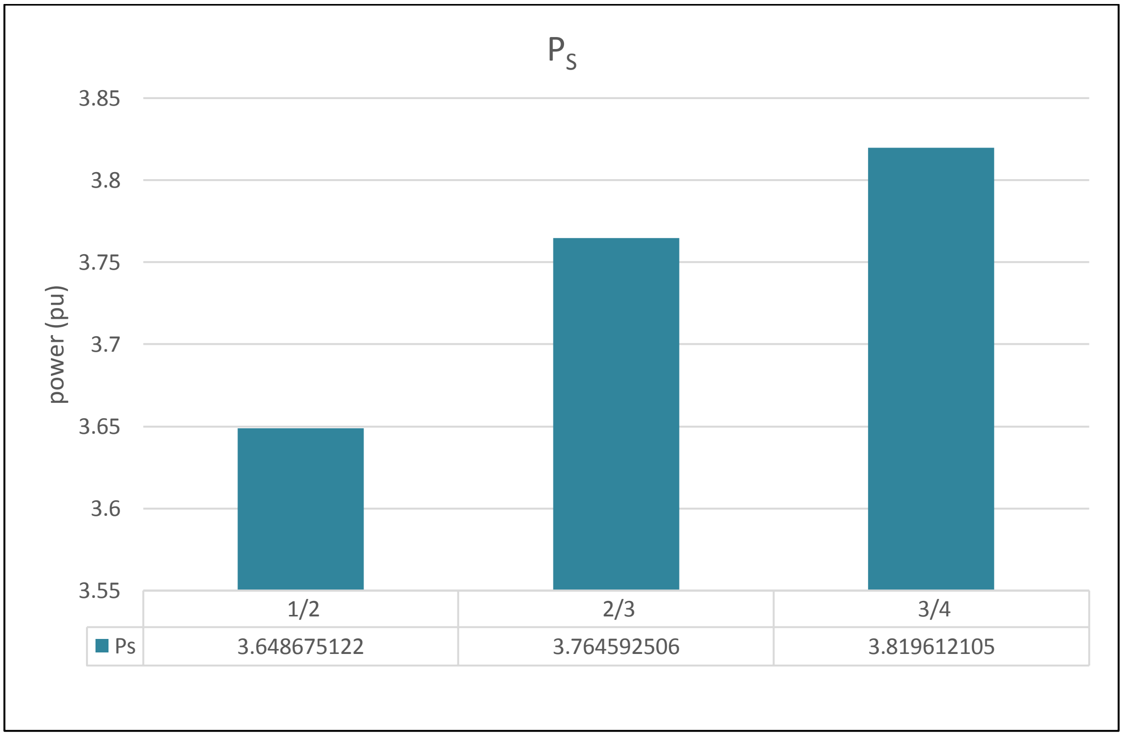

Figure 23: Sending end active power P_S at K = 75 % – capacitor unit positioned at different locations

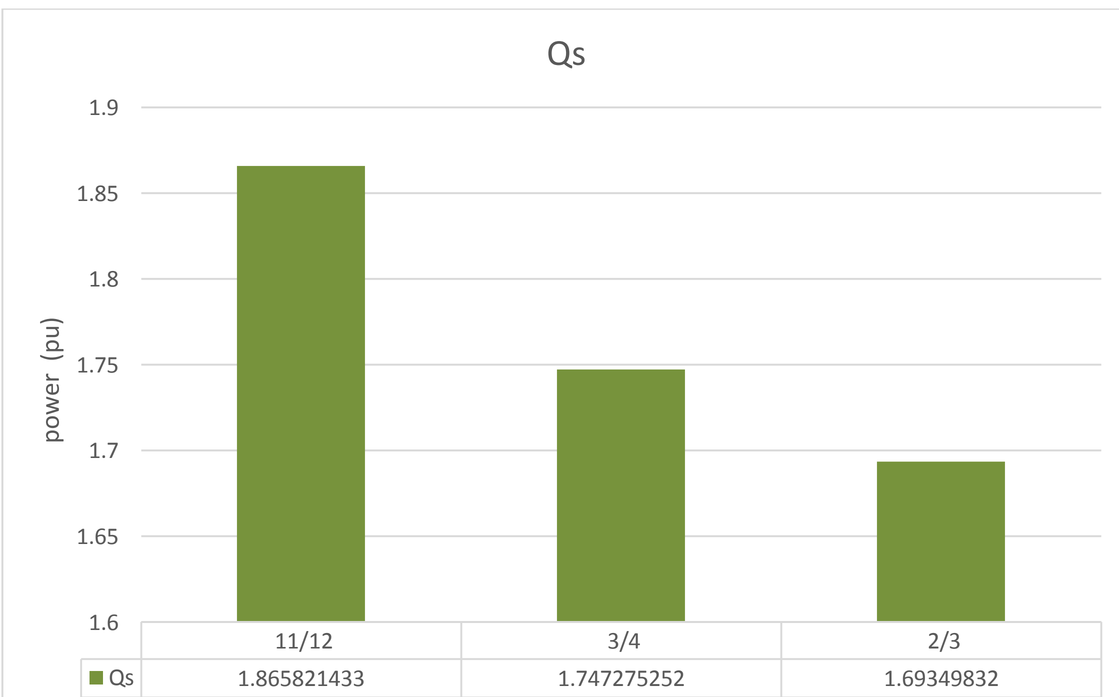

Figure 24: Sending end reactive power Q_S at K = 75 % – capacitor unit positioned at different locations

4.3 Distribution Network Series capacitor compensation

For the 3rd project activity, the network models in Figure 25, 26 and 27 are constructed and simulated after calculating the parameters for the compensated and the uncompensated lines.

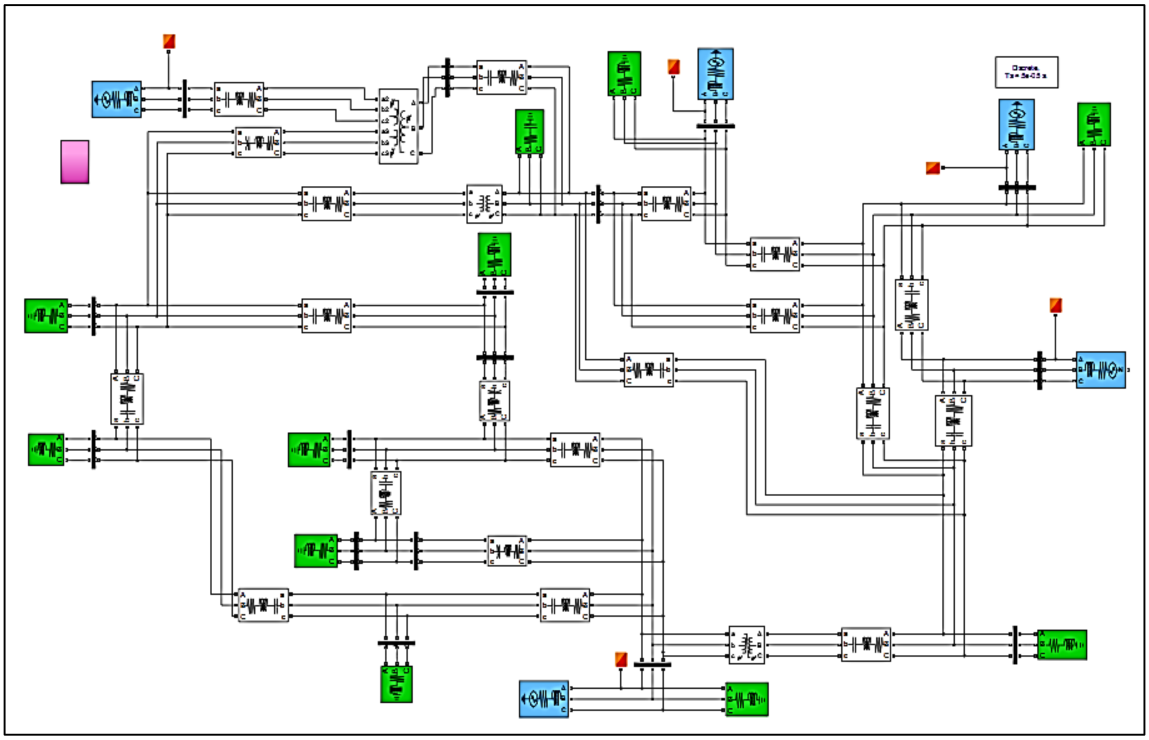

Figure 25: The 14 bus network without series compensation

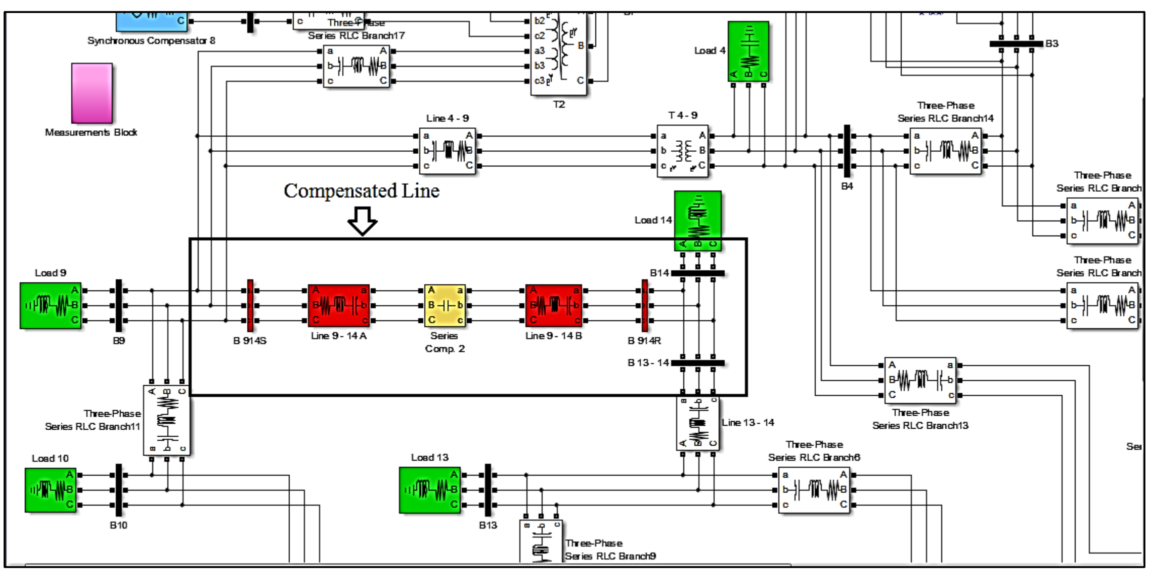

Figure 26: The series compensated line in the 14 Bus Network

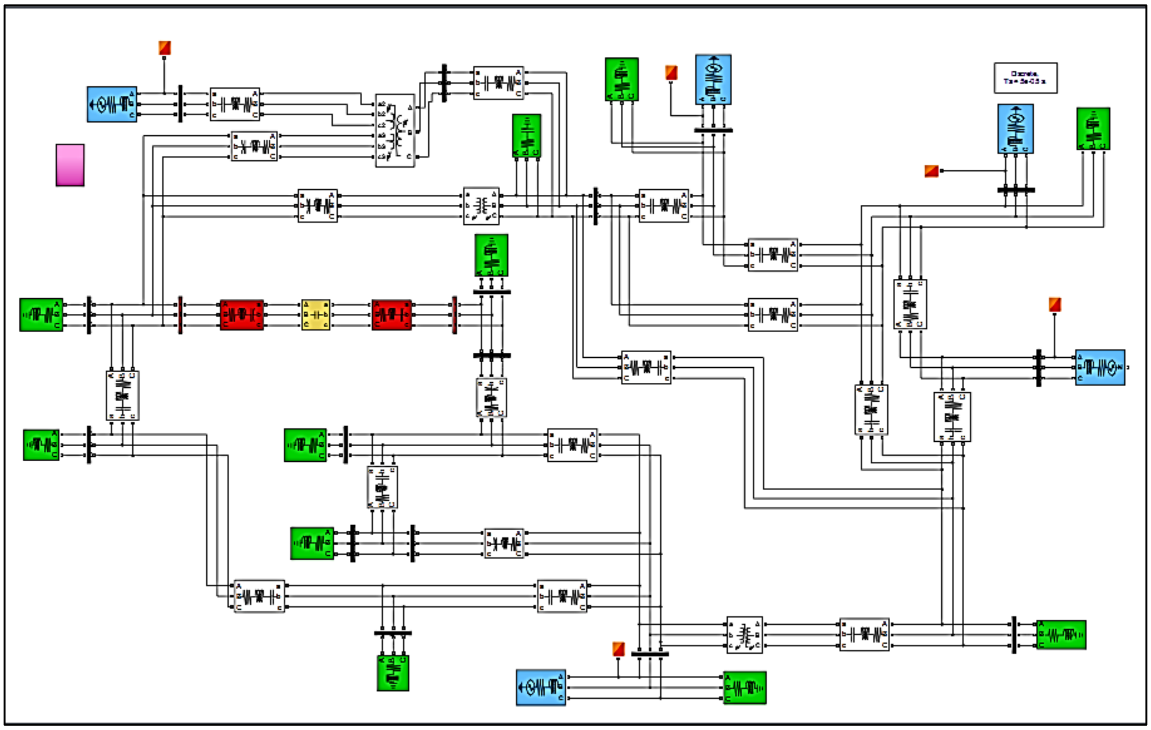

Figure 27: The 14 bus network with series capacitor compensation applied

For a 10 km transmission line, the capacitor unit along line 9 - 14 is placed at different locations $(D = 1/2, D = 2/3, D = 3/4)$ and two degree of compensations are used K = 40 % and K = 75 %. After running the simulation, the results showed a slight enhancement in the receiving end voltage profile V_R after compensating the line with K = 40 % and the profile enhanced when using K = 75 %.

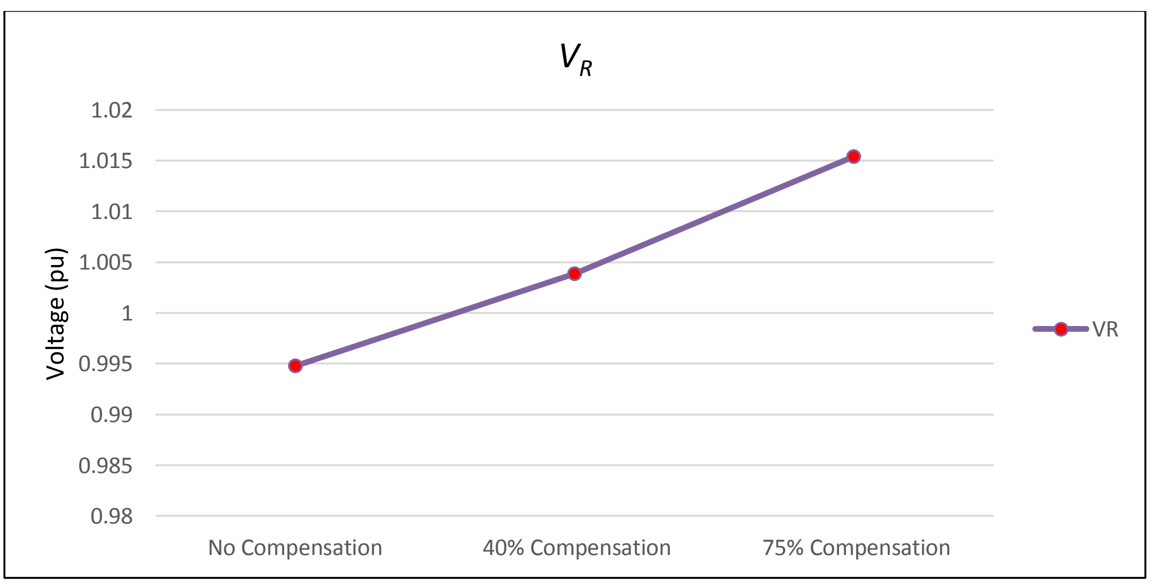

Figure 28: Receiving end voltage profile enhancement

After compensating line 9 – 14 with a series capacitor unit, the receiving end voltage profile V_R is slightly enhanced by 5.6 % compared to the uncompensated value with K = 75 % as in Figure 28.

Furthermore, the sending end active power P_S is increased by 1.33 pu when compensating the line with K = 75 % as in Figure 29.

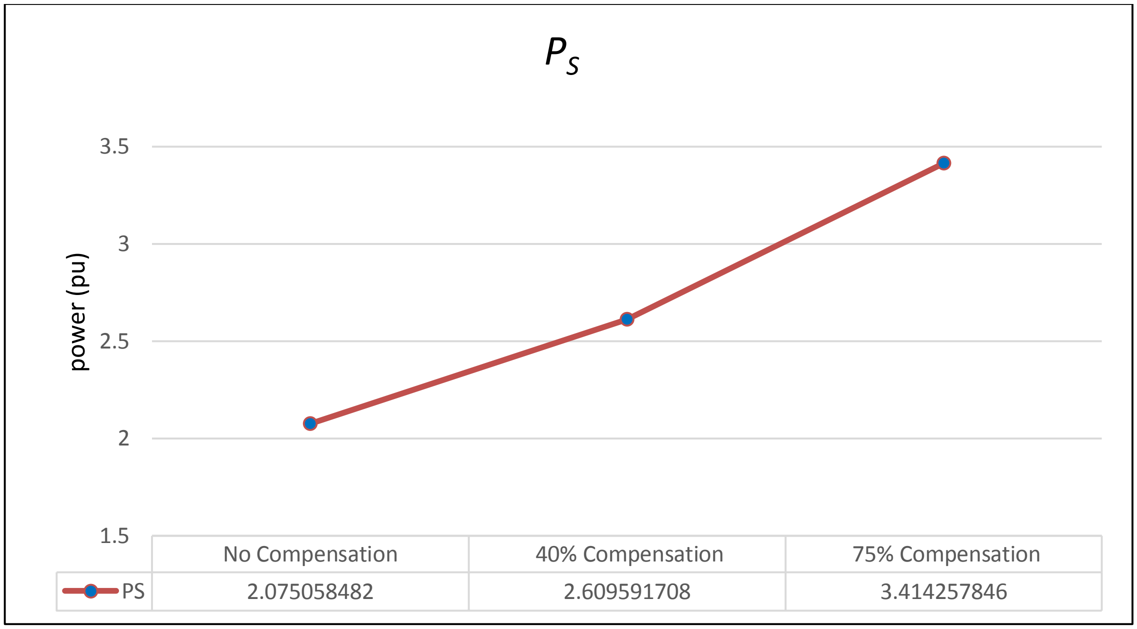

Figure 29: Enhancement in active power transmission over the line

As per the results, the location varying impact on the receiving end voltage profile V_R and the sending end active power P_S is not significant as in Figure 30 and 31. In fact, at the same degree of compensation (K), the voltage magnitude and the amount of active power to be transmitted over the line have the same values despite changing the capacitor unit's location.

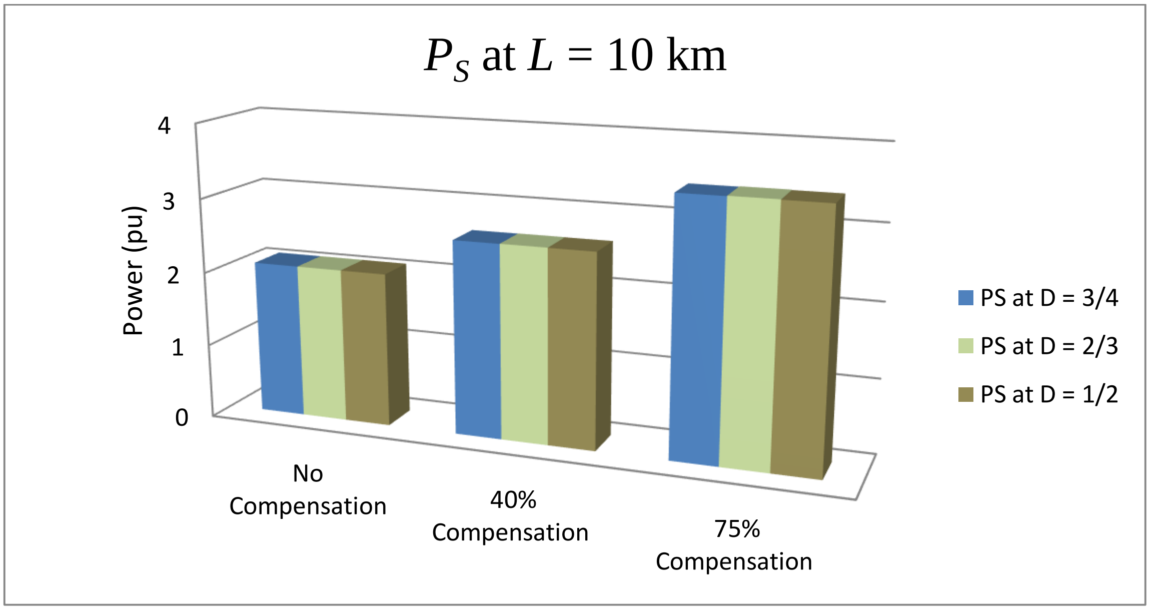

Figure 30: Sending end active power P_S at line 9 - 14 with total length of 10 km – capacitor unit placed at different locations

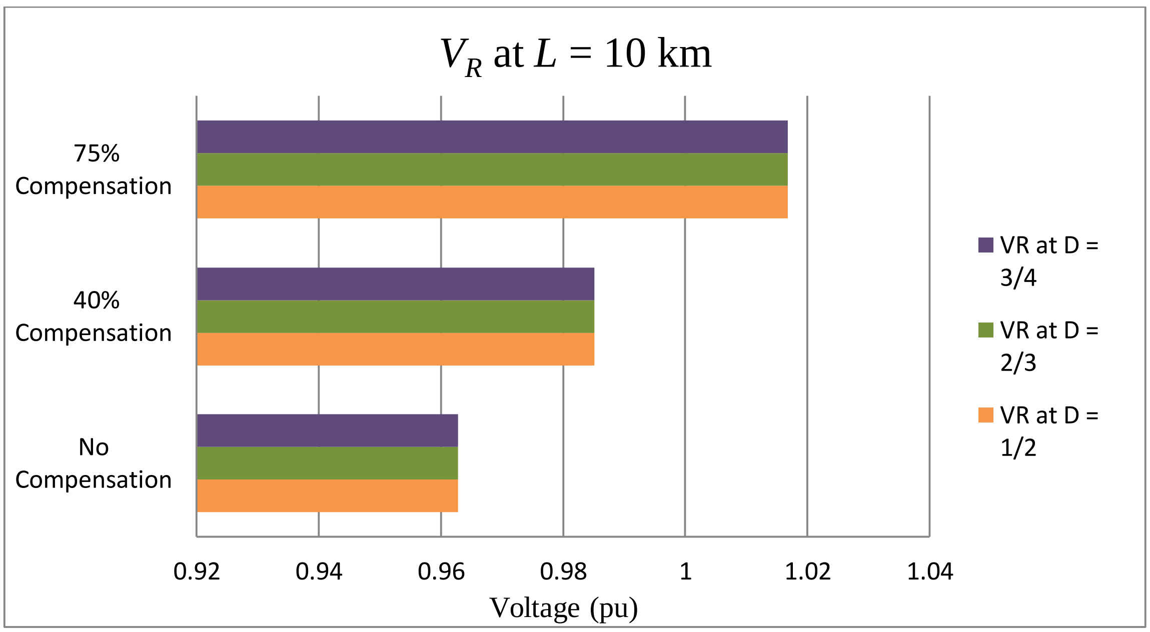

Figure 31: Receiving end voltage profile V_R at line 9 - 14 with total length of 10 km – capacitor unit placed at different locations

For a 30 Km Transmission Line, the capacitor unit along line 9 - 14 has contributed in enhancing the receiving end voltage profile V_R by 6 % of the uncompensated value as in Figure 32.

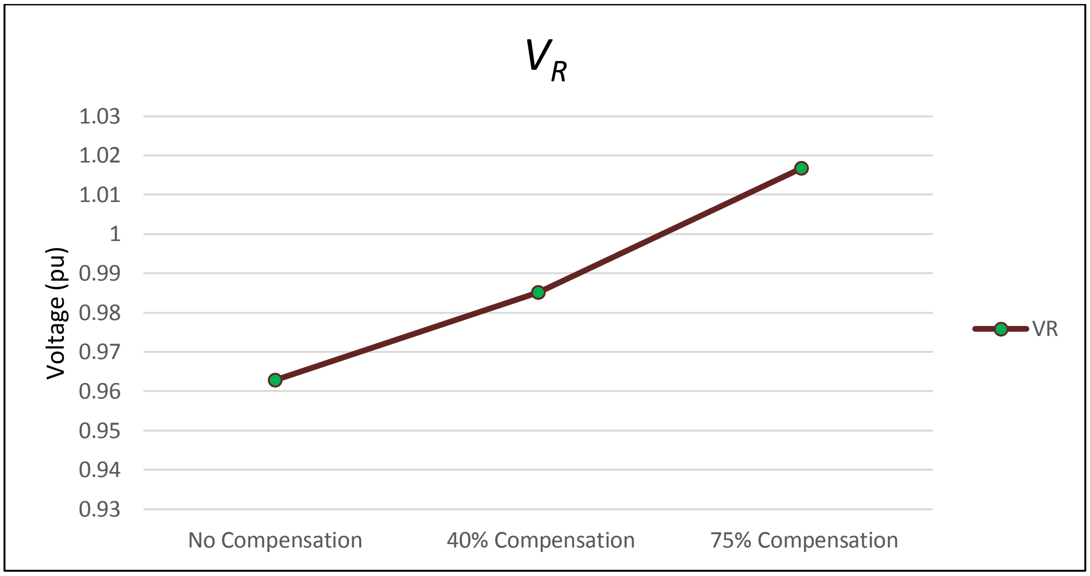

Figure 32: Receiving end voltage profile V_R with total length of 30 km

On the other hand, the sending end active power P_S has improved by 1.09 pu as in Figure 33.

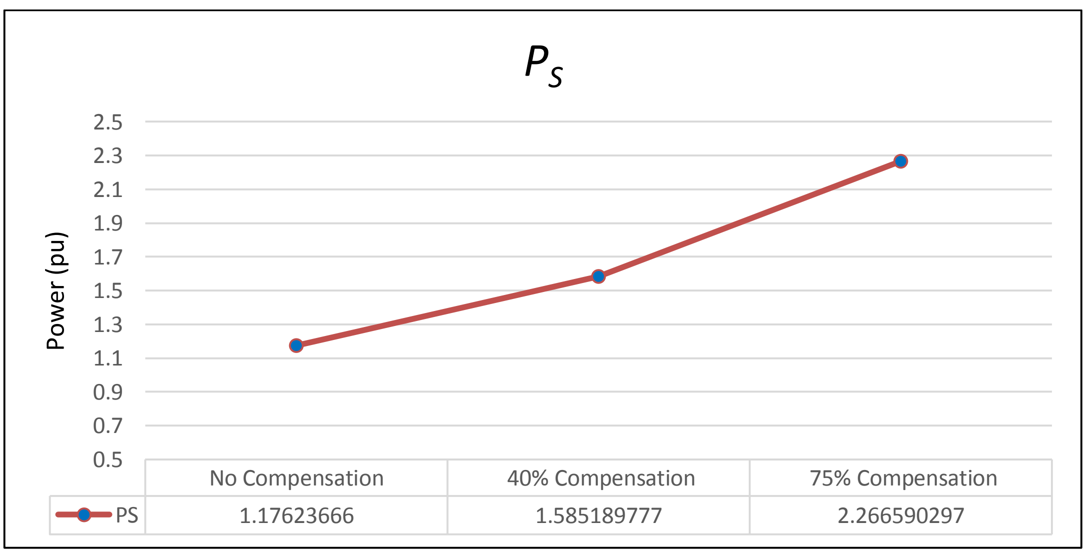

Figure 33: Sending end active power P_S with total length of 30 km

In Figure 34 and 35, the location impact on the distribution characteristics is not clear. There is no significant differences in the values as a result of varying the capacitor unit's location over the line.

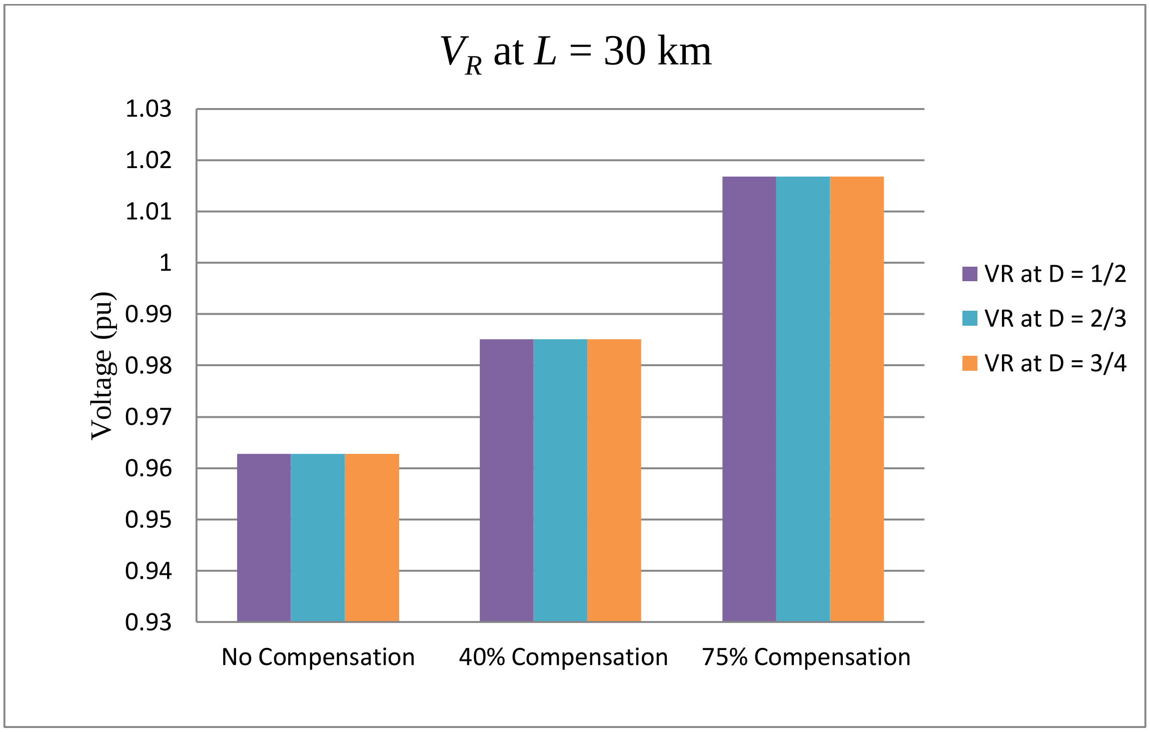

Figure 34: Receiving end voltage profile V_R at line 9 - 14 with total length of 30 km – capacitor unit placed at different locations

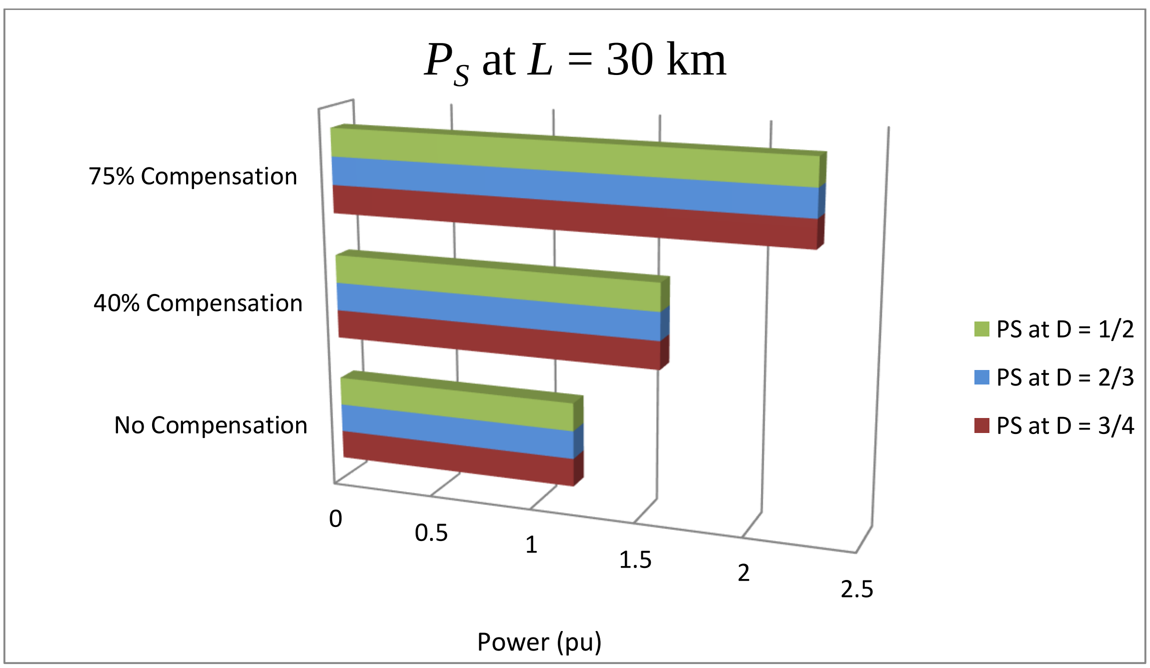

Figure 35: Sending end active power P_S at line 9 - 14 with total length of 30 km – capacitor unit placed at different locations

<u>For a 50 Km transmission line</u>, After running the simulation at line 9 - 14, the results showed a slight enhancement in the receiving end voltage profile V_R after compensating the line with K = 40 %. V_R showed a better enhancement when using K = 75 % where it was increased by 5.6 %.

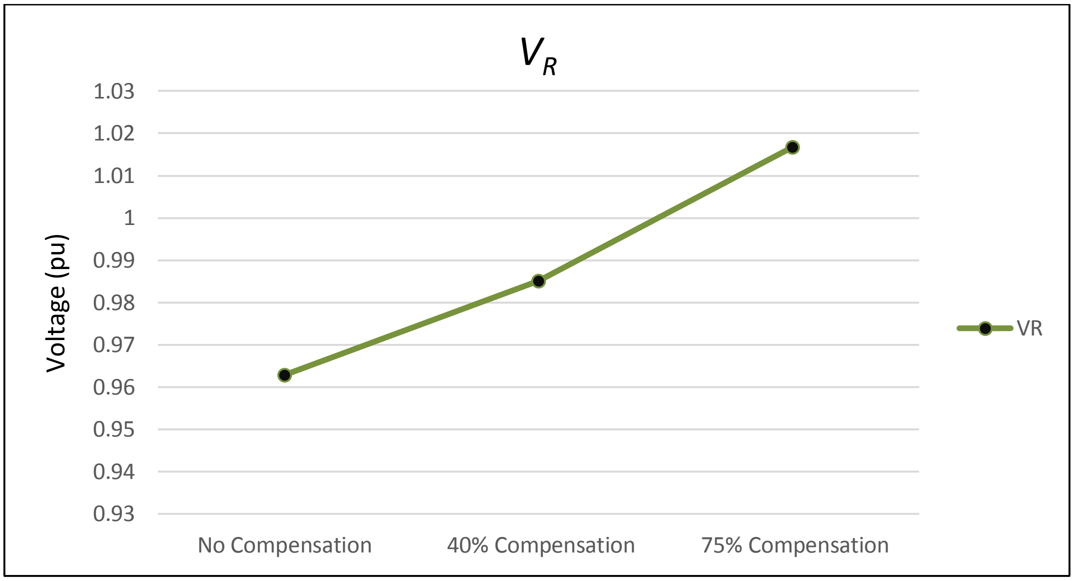

Figure 36: Receiving end voltage profile V_R at line 9 - 14 with total length of 50 km

On the other hand, P_S has increased by 1.09 pu when compensating the line with K = 75 %.

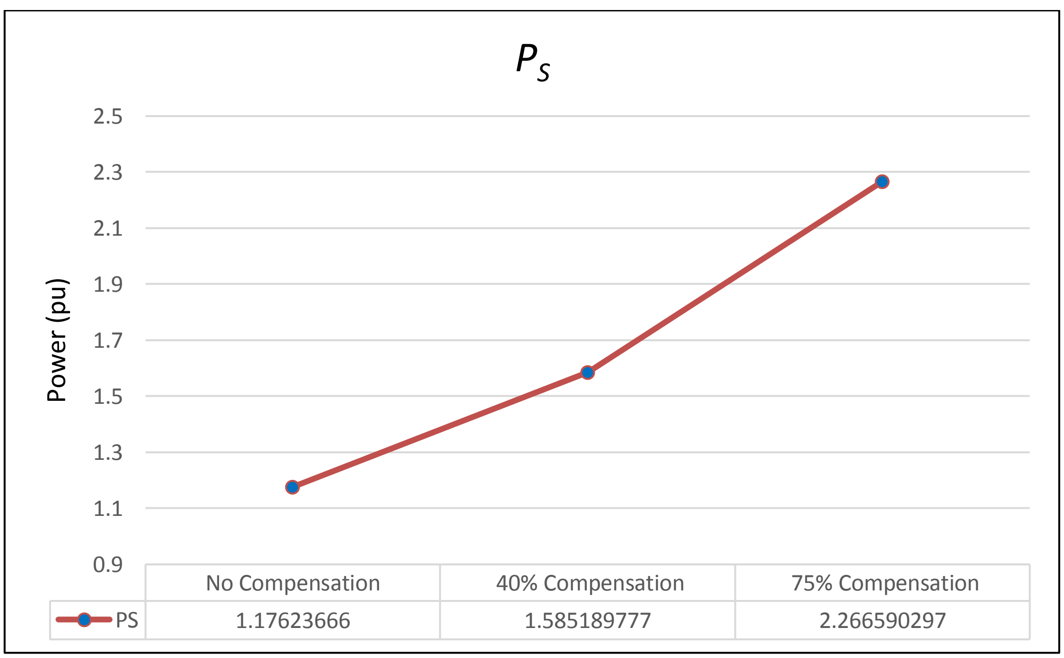

Figure 37: Sending end active power P_S at line 9 - 14 with total length of 50 km

Furthermore, the location varying impact is still not obvious despite the relative long length of the line. In Figure 39 and 40 the voltage magnitude V_R and the sending end active power P_S have the same values although the capacitor unit location has varied at ($D = 1/2, D = 2/3, D = 3/4$).

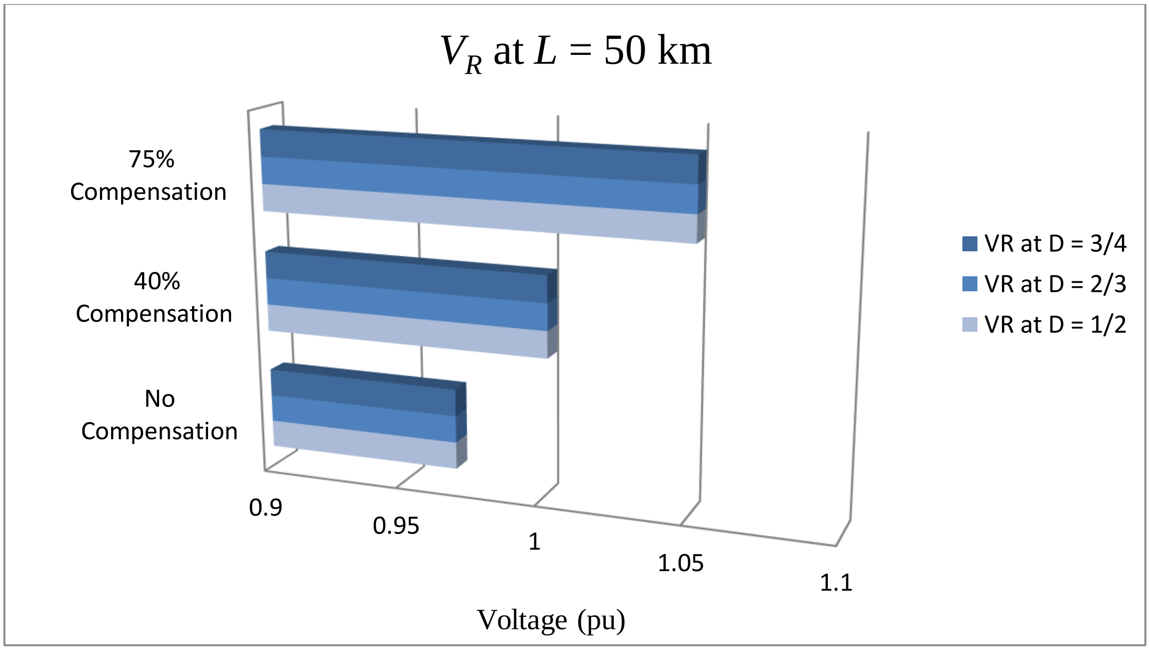

Figure 38: Receiving end voltage profile V_R at line 9 - 14 with total length of 50 km – capacitor unit placed at different locations

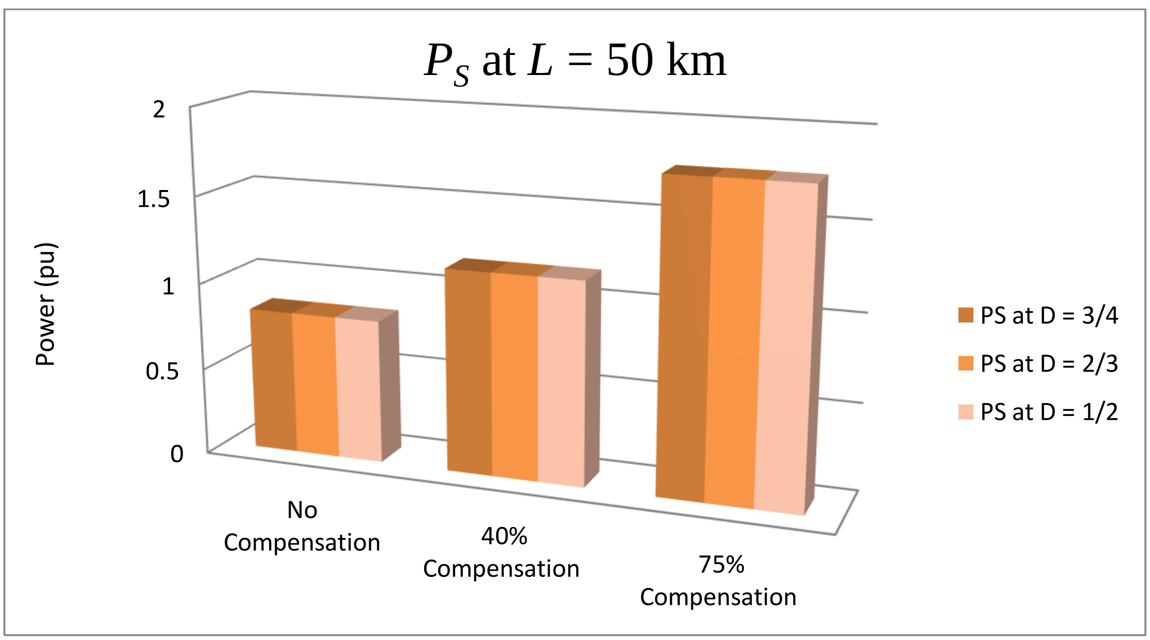

Figure 39: Sending end active power P_S at line 9 - 14 with total length of 50 km – capacitor unit placed at different locations

As per the previous simulation results, two compensation levels (*K*) are used with changing the unit's location (three different locations) when applying each of them. The results showed more stability regarding the receiving end voltage profile V_R and an increase in the total power transfer capability (*PTC*). It is also observed that the series capacitor unit's location neither has impact on the (*PTC*) nor the V_R. In fact, as the location varies among ($D = 1/2, D = 2/3, D = 3/4$), the effect was negligible. So, changing the unit's location will only depend on the considerations being made during installation stage as placing the capacitor unit at any of those locations will give the same transmission enhancements. Moreover, the compensation degree of K = 75 % has been proven the most suitable for enhancing the network efficiency.

Alternative Comparison (Technical):

As per the 14 bus network analysis, the use of a series capacitor unit will have a significant enhancement regarding the transmission characteristics of high reactance lines. As an application, the second alternative proposed in this study to increase the overall (*PTC*) which is to construct a new line is analysed by Matlab/Simulink as in Figure 40.

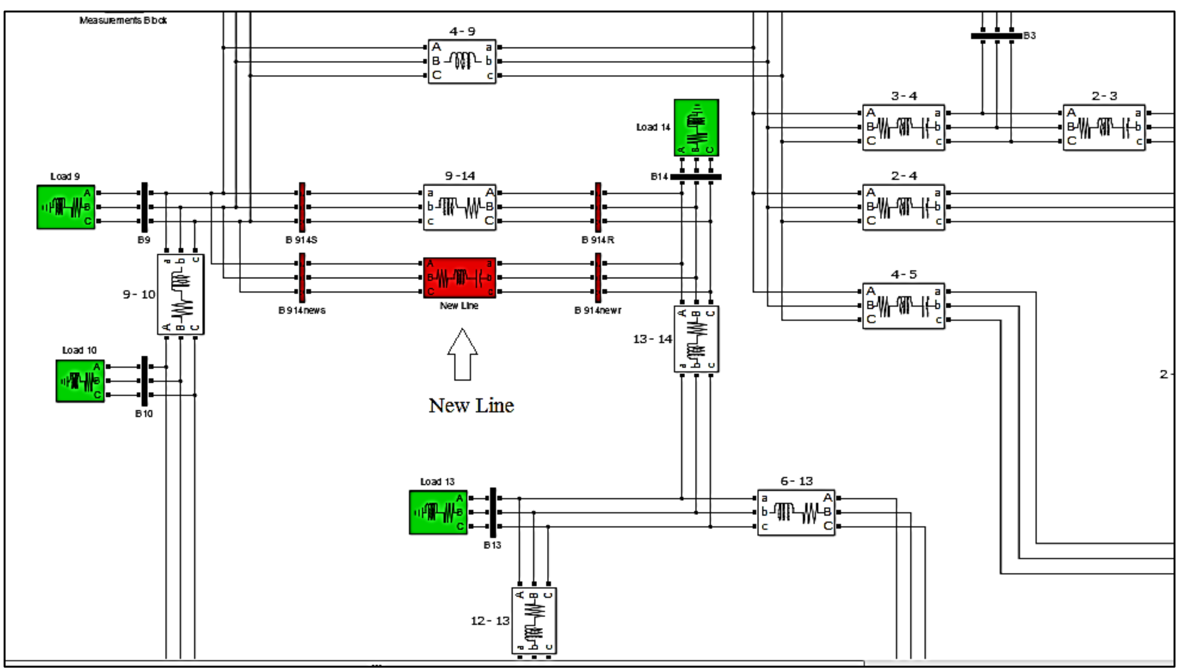

Figure 40: Matlab/Simulink model of alternative 2

Then, a thorough analysis is conducted between the two alternatives (series capacitor compensation and construction of a new line) to justify -technically and economically- the use of either of them. The results showed that using a series capacitor unit to compensate the line will result in a better enhancement of the voltage profile V_R than the construction of the new line as in Figure 41. As per the Figure, V_R will enhance by 5.6 % with the use of series capacitor compensation while it will only increase by 0.0004 % with the construction of a new line.

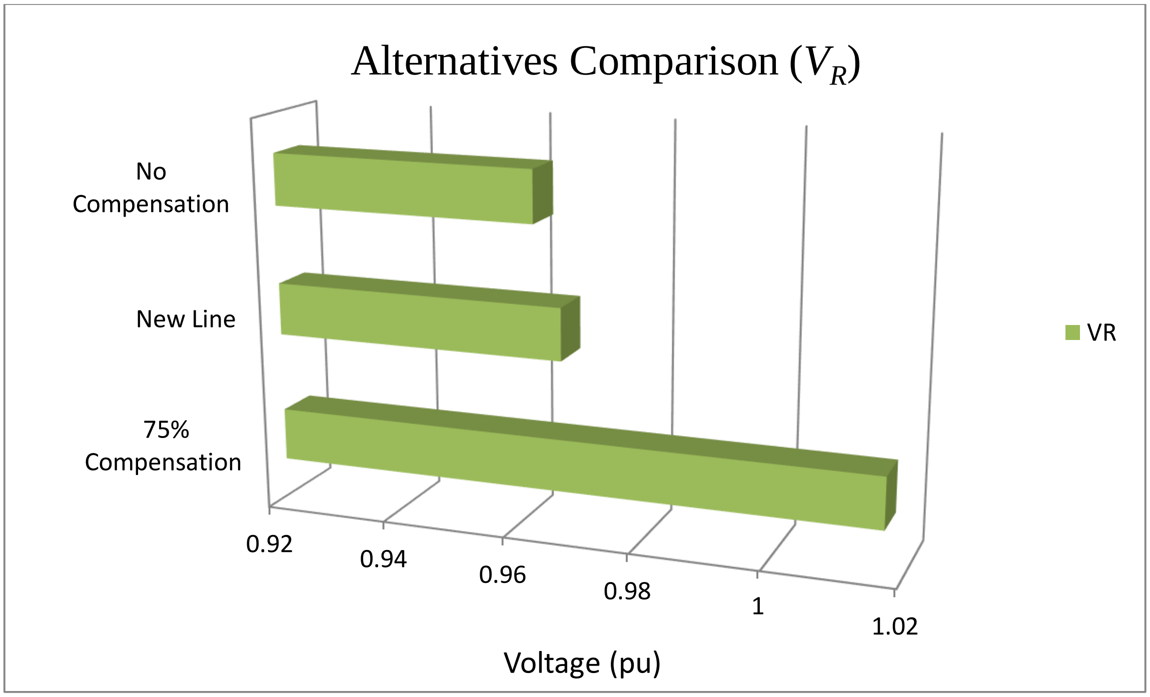

Figure 41: Impact of alternatives on receiving end voltage profile (V_R)

Additionally, the power transfer capability (*PTC*) will increase by 1.09 pu (93 %) when using a series capacitor unit comparing to 0.22 pu (18 %) with the alternative of constructing a new line as in Figure 42.

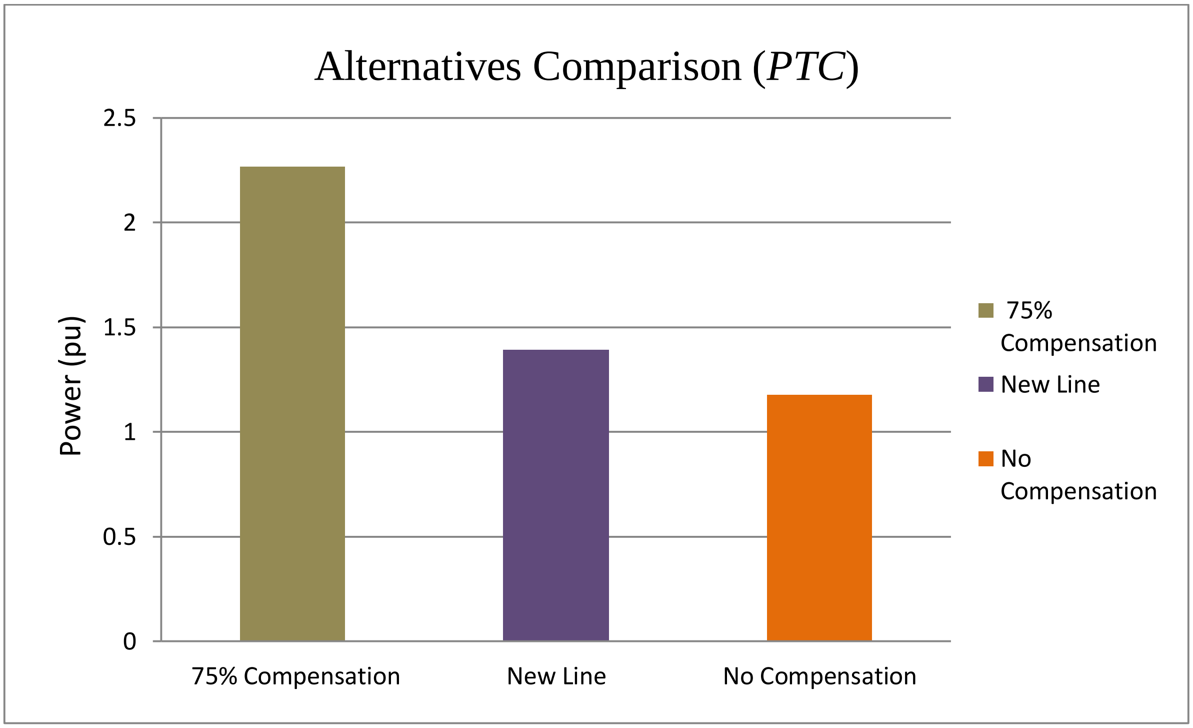

Figure 42: Impact of alternatives on power transfer capability (*PTC*)

4.4 Economic Analysis

CASE STUDY:

- Line rating: 33 kv
- Total length: 30 km
- Current power transfer capability: 117 MVA
- Line reactance: 0.7 + j2.901 MΩ / per km

Alternative 1: Series capacitor compensation

- Benefits: an increase in ***PTC*** by 1.09 pu (119 MVA) at base power of 100 MVA.
- Estimated annual value of benefits = 47742000 USD per year at MW/h price of 50 USD.
- Capacitor reactance = Total line reactance * 0.75 = 87 * 0.75 = 65.25 MVAR
- Suggested capacitor unit: ***ABB MiniCap (***12 MVAR per unit***)***
- N = 65.25 / 12 = 6 units
- Unit price = 70000 USD
- Shipping and installation cost = 10000 USD

- Total initial cost = 70000 * 6 + 10000 * 6 = 480000 USD
- Maintenance and operation per year = 10 % of initial cost = 48000 USD per year

Suggested capacitor unit: ***ABB MiniCap***

- Technical specifications:
  - Maximum system voltage: 36 kV
  - Maximum rated current: 600 A
  - Maximum Short-circuit current: 10 kA
  - Capacitor ratings: Up to 12 Mvar
  - Basic Impulse Insulation level: Up to 170 kV
  - Ambient air temperature range: from -50 °C to +40 °C

Table 4 shows the cash flow for alternative 1:

Table 4: Cash flow for alternative 1

	Price per Mwh	MW	Hourly Benefits	Daily Benefits	Annual Benefits	Initial investment	Annual Cost (O&M)
Alternative 1	50	109	5450	130800	47742000	480000	48000

Alternative 2: Construction of a new line

- Benefits: an increase in ***PTC*** by 0.22 pu (22 MVA) at base power of 100 MVA.
- Estimated annual value of benefits = 9636000 USD per year at MW/h price of 50 USD.
- Construction cost per km = 180000 USD
- Total initial cost = 180000 * 30 = 5400000 USD
- Maintenance and operation per year = 10 % of initial cost = 540000 USD per year

Table 5 shows the cash flow for alternative 2:

Table 5: Cash flow for alternative 2

	Price per Mwh	MW	Hourly Benefits	Daily Benefits	Annual Benefits	Initial investment	Annual Cost (O&M)
Alternative 2	50	22	1100	26400	9636000	5400000	540000

The incremental benefit-cost ratio analysis is used to select the most suitable alternative. The interest rate is chosen to be 5 % while the expected lifespan is 30 years. On the other hand, no disbenefits are considered. The calculations is following Equation 4.0.

$$\Delta B/C = \frac{\Delta \text{B (Difference in benefits)}}{\Delta \text{C (Difference in costs)}} \qquad \text{Equation (4.0)}$$

The present worth analysis is chosen to estimate ΔB and ΔC

$$\Delta B/C = \frac{\Delta \text{(PW of benefits)}}{\Delta \text{ (Initial investment+PW of O\&M costs)}} \qquad \text{Equation (4.1)}$$

PW_{1B} is the present worth of annually estimated benefits for alternative 1:

- PW_{1B} = 47742000 (*P/A*, 5%, 30) = 3105617.1 USD

PW_{2B} is the present worth of annually estimated benefits for alternative 2:

- PW_{2B} = 9636000 (*P/A*, 5%, 30) = 626821.8 USD

ΔB is the difference in benefits between alternative 1 and 2:

- ΔB = 3105617.1 - 626821.8 = 2478795.3 USD

PW_{1C} is the present worth of estimated costs for alternative 1:

- PW_{1C} = Initial cost for alternative 1 + PW of annual operation and maintenance cost
- PW_{1C} = 480000 + 48000 (*P/A*, 5%, 30) = 1121880 USD

PW_{2C} is the present worth of estimated costs for alternative 2:

- PW_{1C} = Initial cost for alternative 2 + PW of annual operation and maintenance cost
- PW_{1C} = 5400000 + 540000 (*P/A*, 5%, 30) = 12621150 USD

ΔC is the difference in costs between alternative 1 and 2:

- ΔC = 12621150 – 1121880 = 11499270 USD

$\therefore\ \Delta B/C = \frac{2478795.3}{11499270} = 0.215$

Because the B/C ratio is less than 1.0, the extra costs associated with alternative 2 are not justified. Therefore, alternative A is selected for increasing the power transfer capability of the line.

CHAPTER 5 : CONCLUSION AND RECOMMENDATIONS

In this study, the using of series capacitor compensation method in distribution networks is suggested to reduce line losses, enhance voltage profile and gain the ability to increase power transfer capability through the network. The series capacitors compensation technique has been proven most effective for load variations involving high reactive content The analysis done on simulation basis proved that the technique can increase the power transfer capability and enhance voltage profile. The series capacitor compensation has shown high efficiency with the simulation results for the 14 Bus Electrical distribution network. The study recommends that overcompensation should be avoided which means that K = 100 % is not advised for compensating the line. Also, the possibility of oscillations with the downstream loads and transformers can be reduced by bypassing the capacitor bank prior to the energizing or reclosing of the distribution circuit The series capacitor unit's location impact has been proven to be slight regarding short distance lines and will not have an important impact on the network. It is recommended that the protection of the capacitor bank must be ensured by the use of overvoltage protective schemes. Economically, the technique has been justified by the use of incremental cost benefit ratio analysis.

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