

Optimal Location of Facts Device for Improved Power Transfer Capability and System Stability

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Abstract: The work entailed in this paper is to develop a model for the optimal location of shunt Flexible Alternating Current Transmission System (FACTS) along a transmission line so as to enhance controllability and increase power transfer capability of the transmission network. Mathematical models for maximum power transfer and transmission angles for transmission line were developed. The investigation was done for both lossless and actual transmission lines. MATLAB software was used for the simulation of the models. Aloaji – Itu transmission 132 KV transmission line in South-eastern Nigeria was used as a case study. Performance analysis was conducted on the various maximum power and transmission angles data for different degree of series compensation and FACTS locations along the transmission lines to determine the optimal location of the FACTS device for both lossless and actual transmission lines. The results obtained showed that the optimal location of the shunt FACTS device is not fixed, but changes with the change in degree of series compensation. Both the power transfer capability and stability of the system can be improved much more if the shunt FACTS device is placed at the new optimal location instead of the mid-point of the line.

Keywords: FACTS Devices, Transmission Line, Switching Device, Maximum Power, Transmission Angle

1. Introduction

It is an axiomatic fact that power supply is one of the indispensable arrowheads of every country's development. Although, Nigeria is renowned for the availability of vast amounts of natural resources in the country, yet, its development has been bedevilled by avalanche of factors but leading the chart is epileptic power supply. This acute power crisis in the country has offered horrendous and inexplicable impedance to the country's development. The effects of this include, inter alia, the demoralisation of foreign and local industrialists or manufacturers to invest confidently in the country and hence, increase in rate of unemployment most especially amongst the teeming Nigerian youths; poor research outcomes from researchers both within and outside the universities; increase in dependencies on electric generators and the concomitant increase in noise and air pollutions; widening of socioeconomic gaps among Nigerians and so on. Motivated by the aforementioned implications, several steps have been taken by both government and

individuals, especially researchers, in bringing to its barest minimum these scourge of epileptic power supply in Nigeria. One of such steps is the deregulation in power sector tailored to reshape the monopolistic and government-controlled power sector to a competitive power market. Furthermore, several suggestions had been made on the need for Nigeria to step up its power generation to a scale that will commensurate with its teeming population. In essence, attention to generation of adequate power alone will not do enough in addressing the issues of epileptic power supply in Nigeria holistically. Suffice it to say that, if equal attention is not given to the power transmission system in the country, the attempts to increase energy generation will tantamount to unrealistic efforts due to issues of power losses suffered by the transmission systems.

The transmission of power from the generation stations to the final consumers via transmission and distribution stations encounters a lot of power losses due to several technical reasons. This has stimulated several researches and as such many suggestions as to strategies to ameliorate these losses have been made. Observably, one of the most popularly

employed strategies to this end is the placement of switching devices at optimal locations along transmission lines. In this paper, mathematical models of both lossless and actual transmission lines were developed. The switching devices considered for optimisation in this paper are the Flexible Alternating Current Transmission System (FACTS) controllers. FACTS is a system composed of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. This work seeks to ensure maximum power transfer, improve on system reliability and minimise cost. MATLAB program was used to simulate the models based on the data obtained from Aloaji – Itu transmission 132 KV transmission line in South-eastern Nigeria and the results are presented in tables and graphs.

2. Literature Review

The characteristics of any given power system evolve with time, as load grows and generation is added. If the transmission facilities are not upgraded sufficiently the power system becomes vulnerable to steady-state and transient stability problems, as stability margins become narrower [1]. Furthermore, ageing and lack of maintenance are some of the problems facing the transmission lines in Nigerian power system. Ikorodu-Ayede-Osogbo 132kV line was constructed around 1964. There are quite a few transmission lines like this and they are poorly maintained. Akangba-Ojo 132kV line is a typical example of a poorly maintained line. Another problem is the length of the transmission lines. The Gombe Maiduguri 132kV line is about 310km long with the consequent large voltage drop. The New Haven-Oturkpo-Yandev 132kV line is 330km long. The voltage drop between New Haven and Yandev is about 20kV. Also, the Nigerian grid system suffers from lack of alternative route for primary transmission lines. Benin-Onitsha-Aloaji 330kV line is a typical example. If there is a trip on this line for whatever reason, the situation will be very grave. This single line contingency is also applicable to the Aloaji – Itu 132 KV line. The Aloaji – Itu line serves Itu, Calabar, Uyo and Eket and all these areas will be affected in the event of any outage [2]. Moreover, the ability of transmission system to transmit power becomes impaired by one or more of the following steady-state and dynamic limitations: angular stability, voltage magnitude, thermal limits, transient stability and dynamic stability. These limits define the maximum electrical power to be transmitted without causing damage to transmission lines [3] and electric equipment.

In principle, limitations on power transfer can always be relieved by addition of new transmission and generation facilities. Alternatively, FACTS controllers can enable the same objectives to be met with no major alterations to system layout. The demand of lower power losses, faster response to system parameter change, and higher stability of system have stimulated the development of the Flexible AC Transmission systems (FACTS) [4]. Based on the success of research in power electronics switching devices and advanced control

technology, FACTS has become the technology of choice in voltage control, reactive power flow control, transient and steady-state stabilisation that improves the operation and functionality of existing power transmission [5-10]. The potential benefits brought about by FACTS controllers include reduction of operation and transmission investment cost, increases system security and reliability, increased power transfer capabilities, and an overall enhancement of the quality of the electric energy delivered to customers [11-14].

Aloaji transmission station is a 330/132kV substation located in Aba township. Among the existing facilities at the station are series line reactor, two 330-132kV transformer of 150 MVA and number of circuit breakers. The existing switch at the station is a line REACTOR which is used to regulate power flow and short-circuit levels at the station; it is switched on or off according to load and voltage conditions. For instance, the reactor is bypassed during minimum loading in order to avoid transmission line overvoltage due to excessive capacitive effects in the system. Conversely, it is fully utilised during maximum loading, aiming at increasing the transfer of the power without subjecting transmission lines to overloads. One major problem that beset this reactor is that it is weak with voltage limit violation and high power loss. This problem, if not properly addressed, can lead to station collapse and may consequently warrant building of a new transmission station. This can be costly to implement and involves long construction period. FACTS controllers can be introduced in power systems to solve the above problems.

3. Methodology

The parameters of the transmission line are considered to be uniformly distributed. The line can be modeled by a 2-port, 4-terminal network as shown in Figure 1.

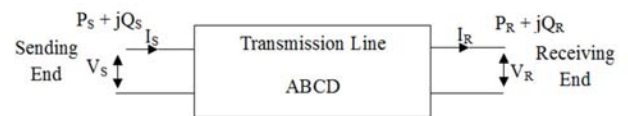


Figure 1. 2-port, 4-terminal model of a transmission line.

The relationship between the sending and receiving quantities of the line are given by equations (1) and (2).

$$V_S = AV_R + BI_R \tag{1}$$

$$I_S = CV_R + DI_R \tag{2}$$

The ABCD constants of a line of length l , having a series impedance $z \Omega/\text{km}$, and a shunt admittance of $y \text{ S}/\text{km}$ are by equations (3) - (5).

$$A = D = \cosh(\gamma l) = |A| \angle \alpha \tag{3}$$

$$B = Z_C \sinh(\gamma l) = |B| \angle \beta \tag{4}$$

$$C = \frac{\sinh(\gamma l)}{Z_c} \quad (5)$$

Where,

$$Z_c = \sqrt{\frac{z}{y}}, \quad (6)$$

$$\gamma = \sqrt{zy} \quad (7)$$

Where Z_c = characteristic impedance of the line, γ = propagation constant of the line, z = series impedance per unit length per phase, y = shunt admittance per unit length per neutral, l = transmission line length, α = attenuation constant, and β = phase constant.

Considering a sending end voltage as a reference phasor ($|V_S| \angle 0$) and that the receiving end lags it by an angle δ known as transmission angle, the real and reactive powers at the sending and receiving ends are given in equations (8) – (11).

$$P_S = C_1 \cos(\beta - \alpha) - C_2 \cos(\beta + \delta) \quad (8)$$

$$Q_S = C_1 \sin(\beta - \alpha) - C_2 \sin(\beta + \delta) \quad (9)$$

$$P_R = C_2 \cos(\beta - \delta) - C_3 \cos(\beta - \alpha) \quad (10)$$

$$Q_R = C_2 \sin(\beta - \delta) - C_3 \sin(\beta - \alpha) \quad (11)$$

Where,

$$C_1 = \frac{|A|V_S^2}{|B|} \quad (12)$$

$$C_2 = \frac{V_S V_R}{|B|} \quad (13)$$

$$C_3 = \frac{|A|V_R^2}{|B|} \quad (14)$$

Substituting equation (14) into equations (8) – (11), the real and reactive powers at the sending and receiving ends are given as:

$$P_S = \frac{|A|V_S^2}{|B|} \cos(\beta - \alpha) - \frac{V_S V_R}{|B|} \cos(\beta + \delta) \quad (15)$$

$$Q_S = \frac{|A|V_S^2}{|B|} \sin(\beta - \alpha) - \frac{V_S V_R}{|B|} \sin(\beta + \delta) \quad (16)$$

$$P_R = \frac{V_S V_R}{|B|} \cos(\beta - \delta) - \frac{|A|V_R^2}{|B|} \cos(\beta - \alpha) \quad (17)$$

$$Q_R = \frac{V_S V_R}{|B|} \sin(\beta - \delta) - \frac{|A|V_R^2}{|B|} \sin(\beta - \alpha) \quad (18)$$

Considering a simplified model of the transmission line where the line is lossless, i.e. resistance and capacitance are neglected. The ABCD constants of the line are given as

$$A = D = |A| \angle \alpha = 1 \angle 0 \quad (19)$$

$$B = |B| \angle \beta = |xl| \angle 90^\circ \quad (20)$$

$$C = 0 \quad (21)$$

Hence, the real and reactive powers at the sending and

receiving ends of the simplified model are derived by substituting equations (19) and (20) into equations (15) – (18):

$$P_S = \frac{V_S V_R}{|xl|} \sin \delta \quad (22)$$

$$Q_S = \frac{V_S^2}{|xl|} - \frac{V_S V_R}{|xl|} \cos \delta \quad (23)$$

$$P_R = \frac{V_S V_R}{|xl|} \sin \delta \quad (24)$$

$$Q_R = \frac{V_S V_R}{|xl|} \cos \delta - \frac{V_R^2}{|xl|} \quad (25)$$

Power Flow in a Transmission Line with FACTS Device

Considering that a transmission line equipped with series capacitor at center and a shunt FACT device at point 'm' is transferring power from a large power source station to an infinite bus at the receiving end and as shown in Figure 2.

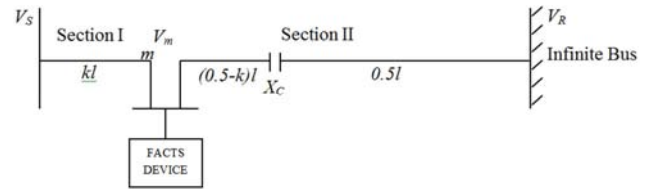


Figure 2. Series compensated transmission line with a shunt FACT device.

Parameter k is used to show the fraction of the line length at which the shunt FACTS device is placed. The transmission line is divided into 2 sections (I and II) and section II is further divided into subsections of length $[(0.5-k) \& \text{half-line length}]$. Each section is represented by a separate 2-port, 4-terminal network with its own ABCD constants considering the actual line model. It is assumed that the rating of the shunt FACTS device is large enough to supply the reactive power required to maintain a constant voltage magnitude at bus m and the device does not absorb or supply any active power.

a) For a Simplified Transmission Line Model

Applying equation (18) on section I of Figure 2, the sending end power transfer through a simplified transmission line model for a given values of sending end voltage (V_S) and voltage at point 'm' (V_m) on the line is given by equation (26).

$$P_S = \frac{V_S V_m}{k|xl|} \sin \delta_S \quad (26)$$

Where maximum sending end power, $P_m^S = \frac{V_S V_m}{k|xl|}$, δ_S = transmission angle between sending end and point 'm' on the line, and k = location of shunt FACTS device along the line.

Also, applying equation (24) on section II of Figure 2, the receiving end power transfer through a simplified transmission line model for a given values of voltage at point 'm' (V_m) on the line and receiving end voltage (V_R) is given by equation (27).

$$P_R = \frac{V_m V_R}{(1-k)|xl| - X_C} \sin \delta_R \quad (27)$$

But, $X_C = k_{se} \times |xl|$

Thus, equation (27) becomes

$$P_R = \frac{V_m V_R}{(1-k-k_{se})|xl|} \sin \delta_R \quad (28)$$

Where maximum receiving end power, $P_m^R = \frac{V_m V_R}{(1-k-k_{se})|xl|}$, δ_R = transmission angle between point ‘m’ on the line and receiving end, and k_{se} = degree of series compensation.

Since, for a simplified model, the line is lossless, sending end power is equal to the receiving end power. Hence,

$$P = \frac{V_S V_m}{k|xl|} \sin \delta_S = \frac{V_m V_R}{(1-k-k_{se})|xl|} \sin \delta_R$$

Taking $P_0 = \frac{V_S V_m}{|xl|} = \frac{V_m V_R}{|xl|}$, and $V_S = V_R = V_m$

$$P = \frac{P_0}{k} \sin \delta_S = \frac{P_0}{(1-k-k_{se})} \sin \delta_R \quad (29)$$

The transmission angle (δ) is given as

$$\delta = \delta_S + \delta_R$$

And from equation (25)

$$\delta = k \times \sin^{-1} \frac{P}{P_0} + (1-k-k_{se}) \times \sin^{-1} \frac{P}{P_0} \quad (30)$$

When a shunt FACTS device is connected to the line both maximum power (P_m) and maximum transmission angle (δ_m) are increased and their values depend on the k factor.

b) For an Actual Transmission Line Model

Section I

Using equations (3) - (5), the ABCD constants of section I of the actual line of length kl, having a series impedance z Ω /km, and a shunt admittance of y S/km are first determined as follows:

$$A^i = D^i = \cosh(\gamma kl) = |A^i| \angle \alpha^i \quad (31)$$

$$B^i = Z_c \sinh(\gamma kl) = |B^i| \angle \beta^i \quad (32)$$

$$C^i = \frac{\sinh(\gamma kl)}{Z_c} \quad (33)$$

Where k = location of shunt FACTS device along the line.

Applying equation (11) on section I of Figure 2, the sending end power transfer (P_S^i) through an actual line model for a given values of sending end voltage (V_S) and voltage at point ‘m’ (V_m) on the line is given by equation (34).

$$P_S^i = \frac{|A^i|V_S^2}{|B^i|} \cos(\beta^i - \alpha^i) - \frac{V_S V_m}{|B^i|} \cos(\beta^i + \delta^i) \quad (34)$$

Where δ^i = transmission angle between sending end and point ‘m’ of section I.

It is clear from equation (34) that the sending end power reaches the maximum value when the angle $\delta^i = \pi - \beta^i$. Hence,

$$P_{Sm}^i = \frac{|A^i|V_S^2}{|B^i|} \cos(\beta^i - \alpha^i) - \frac{V_S V_m}{|B^i|} \cos \quad (35)$$

Also, Applying equation (13) on section I of Figure 2, the receiving end power transfer (P_R^i) through an actual line model for a given values of sending end voltage (V_S^1) and voltage at

point ‘m’ (V_m) on the line is given by equation (36).

$$P_R^i = \frac{V_S V_m}{|B^i|} \cos(\beta^i - \delta^i) - \frac{|A^i|V_m^2}{|B^i|} \cos(\beta^i - \alpha^i) \quad (36)$$

It is clear from equation (32) that the receiving end power reaches the maximum value when the angle δ^i becomes β^i . Hence,

$$P_{Rm}^i = \frac{V_S V_m}{|B^i|} - \frac{|A^i|V_m^2}{|B^i|} \cos(\beta^i - \alpha^i) \quad (37)$$

Section II

Using equations (3) - (5), the ABCD constants of section ii of the actual line of length kl, having a series impedance z Ω /km, a shunt admittance of y S/km and a series compensation $X_C (k_{se}|xl|)$ are first determined as follows:

$$A^{ii} = D^{ii} = \cosh((1-k-k_{se})\gamma l) = |A^{ii}| \angle \alpha^{ii} \quad (38)$$

$$B^{ii} = Z_c \sinh((1-k-k_{se})\gamma l) = |B^{ii}| \angle \beta^{ii} \quad (39)$$

$$C^{ii} = \frac{\sinh((1-k-k_{se})\gamma l)}{Z_c} \quad (40)$$

Applying equation (11) on section II of Figure 2, the sending end power (P_S^{ii}) transfer through a simplified transmission line model for a given values of voltage at point ‘m’ (V_m) on the line and receiving end voltage (V_R) is given by equation (41).

$$P_S^{ii} = \frac{|A^{ii}|V_m^2}{|B^{ii}|} \cos(\beta^{ii} - \alpha^{ii}) - \frac{V_m V_R}{|B^{ii}|} \cos(\beta^{ii} + \delta^{ii}) \quad (41)$$

Where, δ^{ii} = transmission angle between point ‘m’ on the line and receiving end of section II

It is clear from equation (41) that the sending end power reaches the maximum value when the angle $\delta^{ii} = \pi - \beta^{ii}$. Hence,

$$P_{Sm}^{ii} = \frac{|A^{ii}|V_m^2}{|B^{ii}|} \cos(\beta^{ii} - \alpha^{ii}) - \frac{V_m V_R}{|B^{ii}|} \quad (42)$$

Also, Applying equation (17) on section II of Figure 2, the receiving end power transfer (P_R^{ii}) through an actual line model for a given values of receiving end voltage (V_R) and voltage at point ‘m’ (V_m) on the line is given by equation (43).

$$P_R^{ii} = \frac{V_m V_R}{|B^{ii}|} \cos(\beta^{ii} - \delta^{ii}) - \frac{|A^{ii}|V_R^2}{|B^{ii}|} \cos(\beta^{ii} - \alpha^{ii}) \quad (43)$$

It is clear from equation (43) that the receiving end power reaches the maximum value when the angle δ^{ii} becomes β^{ii} . Hence,

$$P_{Rm}^{ii} = \frac{V_m V_R}{|B^{ii}|} - \frac{|A^{ii}|V_R^2}{|B^{ii}|} \cos(\beta^{ii} - \alpha^{ii}) \quad (44)$$

Since it is assumed that the shunt FACTS device does not absorb or supply any active power, at ‘m’, the receiving end power of section I must equal to the sending end power of section II, i.e. $P_R^i = P_S^{ii}$.

The transmission angle (δ) is given as

$$\delta = \delta^i + \delta^{ii}$$

4. Performance Analysis

MATLAB software was used for the simulation of the maximum power (P_m) and corresponding angle (δ_m) were determined for various values of location (k) for both lossless and actual transmission lines. Aloaji – Itu 132KV transmission line was used as a case study for this work. The length (l) of the transmission line is about 100km. The series and shunt admittance of the line is $z = (.02986 + j.2849) \Omega/\text{km}$ and $y = (j3.989 \cdot 10^{-6}) \text{ S/km}$ respectively, at 50Hz. The result of the line is presented in p. u. on a 100MVA, 132KV base.

Lossless Transmission Line

Figures 3 and 4 show the variation in maximum power (P_m) and transmission angle (δ_m) against various values of location (k) for different series compensation levels ($\%S$). It should be noted that for a lossless transmission line, the maximum sending power (P_m^S) and maximum receiving end power (P_m^R) are equal.

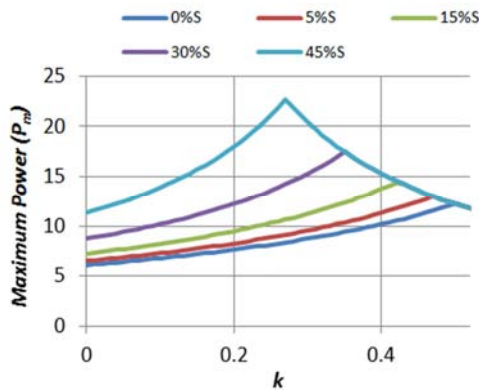


Figure 3. Variation of Maximum power (P_m) in a lossless line against location of shunt FACTS device (k).

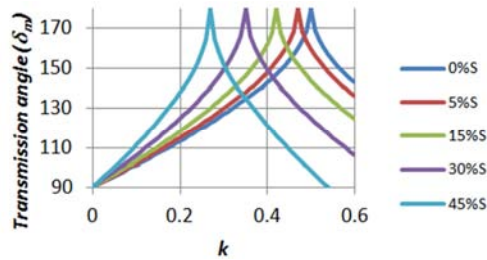


Figure 4. Variation of Transmission angle (δ_m) in a lossless line against location of shunt FACTS device (k).

From Figure 3, it can be noted that when $\%S = 0$, the value of maximum power (P_m) increases from 6.1 p. u. as the value of k is increased from zero and reaches the maximum value of 12.2 p. u. at $k = 0.5$ (at the centre of line). Slope of P_m curve suddenly changes at $k = 0.5$ and the value of P_m decreases when $k > 0.5$. When $\%S = 5$, P_m increases from 6.5 p. u. at $k = 0$ to its maximum value of 13.2 p. u. at $k = 0.475$. When k is further increased then P_m decreases. It means that, for maximum power transfer capability, the optimal location of the shunt device will change when series compensation level changes. Similarly, when $\%S = 45$, the optimal location of the shunt device at $k = 0.275$.

In Figure 4, it can be observed that for all degrees of series compensation, the transmission angle at the maximum power

(δ_m) increases from 90° at $k = 0$ to its maximum value of 180° . The optimal location (k) of the shunt FACTS devices at which the maximum transmission angle ($\delta_m = 180^\circ$) depends on the degree of series compensation ($\%S$).

Actual Transmission Line

Figures 5 – 7 show the variation in maximum sending power (P_m^S), maximum receiving end power (P_m^R), and transmission angle (δ_m) against various values of location (k) for different series compensation levels ($\%S$). It can be noticed from Figures 5 and 6 that $P_m^S > P_m^R$ for any series compensation level ($\%S$) because of the loss in the line.

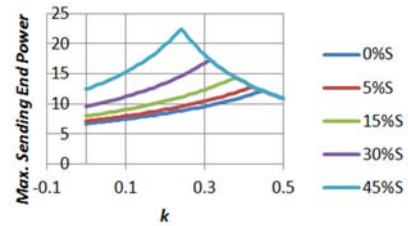


Figure 5. Variation of Maximum sending end power (P_m^S) in an actual line against location of shunt FACTS device (k).

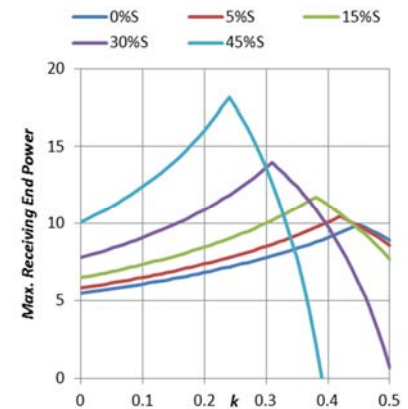


Figure 6. Variation of Maximum receiving end power (P_m^R) in an actual line against location of shunt FACTS device (k).

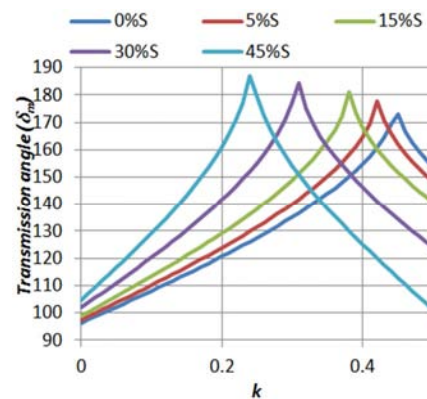


Figure 7. Variation of Transmission angle (δ_m) in an actual line against location of shunt FACTS device (k).

From Figure 5, it can be noted that when $\%S = 0$, the value of maximum sending end power (P_m^S) increases from 6.7 p. u. as the value of k is increased from zero and reaches the maximum value of 12.1 p. u. at $k = 0.448$ (but not at $k = 0.5$ as in the case of lossless line). Slope of P_m^S curve suddenly

changes at $K=0.448$ and the value of P_m^S decreases when $K > 0.448$. A similar pattern for maximum receiving end power (P_m^R) can be observed from Figure 6 when $\%S=0$. When $\%S=5$, maximum sending end power (P_m^S) increases from 7.1 p. u. at $k=0$ to its maximum value of 12.8 p. u. at $k=0.425$. When k is further increased then P_m^S decreases. It means that, for maximum power transfer capability, the optimal location of the shunt device will change when series compensation level changes. Similarly, when $\%S=45$, the optimal location of the shunt device at $k=0.246$. A similar pattern for maximum receiving end power (P_m^R) can be observed from Figure 6 for different series compensation levels.

In Figure 7, it can be observed that in the absence of series compensation ($\%S=0$) the angle at the maximum sending end power (δ_m) increases from 96.4° at $k=0$ to its maximum value 172.8° at $k=0.448$. When $\%S=5$, δ_m increases when k is increased and reaches its maximum value 177.7° at $k=0.425$. Similarly, when $\%S=45$, δ_m increases when k is increased and reaches its maximum value 187.1° at $k=0.246$. As the degree of series compensation level ($\%S$) increases, the maximum transmission angle increases.

5. Conclusion

This work investigated the effect of location of a shunt FACTS device on maximum power transfer on a transmission line so as to get the highest possible benefit of maximum power transfer and system stability. Various results were found for both a lossless and an actual line model of a series compensated line. Aloi-Itu 132KV transmission line was used as a study. It has been found that the optimal location of the shunt FACTS device is not fixed, but changes with the change in degree of series compensation. The deviation in the optimal location of the shunt FACTS device from the center point of line depends upon the degree of series compensation and it increases almost linearly from the center point of the transmission line towards the generator side as the degree of series compensation ($\%S$) is increased. Both the power transfer capability and stability of the system can be improved much more if the shunt FACTS device is placed at the new optimal location instead of at the mid-point of the line.

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