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# Effect of Transmission Line Susceptance Modeling on the Steady-State Operation of 115 kV Power Systems

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**ABSTRACT:**The constant increase in the demand for electrical energy around the world has brought with it a continuous growth of the generation and transmission infrastructure of electrical power systems. This growth causes the operating point of the SEPs to change constantly, so energy supply companies must calculate it correctly to carry out the control actions that guarantee the reliable and safe operation of the power systems. Power transmission lines are modeled considering three parameters: series resistance, series reactance, and parallel susceptance. This last parameter is normally disregarded when calculating the steady-state operating point of power systems at the sub-transmission level, since the length of most lines in this type of power system is less than 80 km and calculations are facilitated. However, such consideration can be counterproductive when calculating such steady-state operating point of the power system, because it omits the influence of the parallel susceptance in the nodal voltage profile and in the nodal and global reactive power balance of the system, obtaining an approximate operating point, which is not accurate. For this reason, this paper presents a steady-state analysis that shows the importance of modeling the parallel susceptance when determining the operating point of 115 kV power systems. The power flow formulation is used to carry out several case studies in which the effect of transmission line susceptance modeling on power system operation is clearly observed. By considering the parallel susceptance the steady-state operating point of the EPS is modified, since the susceptance changes the nodal voltage profile, which in turn causes variations in the power flow, and therefore in the power losses of the system. According to the above, it is concluded that by considering the parallel susceptance in the modeling of transmission lines, a more accurate operating point is obtained, which allows taking better control actions in the SEP.

**KEYWORDS:**Transmission line susceptance, power system, steady-state operating point.

## I. INTRODUCTION

Around the world, the steady-state operating point of a power system is mainly determined by two steady-state analysis tools: Power Flow (PF) and Optimal Power Flow (OPF) [1, 2]. Since the first one was introduced to the study of power systems by J. B. Ward and H.W. Hale [3], it has been considered around the world as a routinely used tool for the determination of steady-state operating points of power electric systems. The PF analysis does not consider economic aspects for system operation, while the OPF analysis does [4]. The PF analysis provides information on certain parameters, from which it is possible to determine how the power system operates in a steady state. Among the parameters that are calculated by PF analysis are the magnitudes and phase angle of the load and generation bus voltages, the reactive powers on the generation buses, and the active and reactive power flow on the transmission lines, in addition to other variables that are previously specified [5, 6]. This information is essential for continuous monitoring of the current state of the system and for analyzing the effectiveness of alternative plans for future system expansions to meet the increased load demand [7].

In recent years, there has been a continuous growth of population and industry in the world, which has also led to a steady increase in the demand for electric power around the world. Faced with this scenario, electric power supply companies maintain a constant pace of change to increase generation capacity and strengthen the infrastructure of the transmission system. As a result, the steady-state operating points of power systems are constantly changing, so that power system operators must be calculating such operating point accurately to carry out monitoring and control actions to ensure reliable and safe operation of power systems.

The main elements of power systems are generators, transformers, loads, and transmission lines, although in recent decades the shunt elements and Flexible AC Transmission System devices (FACTS) are also considered as part of power systems [8, 9, 10]. Power transmission lines are modeled considering three parameters: series resistance, series reactance, and parallel susceptance. The susceptance of the lines is due to the capacitive effect and is only considered in transmission lines classified, according to their length, as medium and long lines. This is because the capacitive effect becomes considerable along the length of the line when its length exceeds 80 km, although there is also a consideration that contributes significantly to the capacitive effect and that is rarely taken into account by power system operators: the voltage level of the transmission line. If the voltage level of the transmission line exceeds 69 kV, then the transmission line should be considered as a medium line regardless of the length, since the capacitive effect will have a high value and should be included in the modeling of the transmission line [5].

In this sense, and for reasons of simplicity in the modeling of transmission lines, many power system operators disregard the parallel susceptance in the line model when calculating the steady-state operating point of power systems at sub-transmission level, since the length of most of the lines in this type of networks is less than 80 km. However, the operating voltage of the lines at sub-transmission level is generally 115 kV, so that such consideration is erroneous when calculating the steady-state operating point of this type of system, since an approximate operating point of the power system is obtained which is not accurate because there are inaccuracies in the nodal voltage profile and the reactive power balance at each node and the whole system. It is clear that if the steady-state operating point is incorrect, wrong decisions will be taken at the moment of monitoring and controlling the power system. According to the aforementioned perspective, power flow analysis is used in this work to visualize the importance of modeling parallel susceptance when determining the steady-state operating point of power systems at sub-transmission level, whose length is less than 80 km and the operating voltage is greater than 69 kV.

The paper is organized in five sections. Section II and III describe the transmission line modeling and the power flow analysis, respectively. Numerical examples where it is possible to visualize the importance of the parallel susceptance modeling in the transmission lines are developed in Section IV, whilst in Section V are presented the conclusions about the effect of the susceptance modeling on the steady-state operating point of 115 kV power systems.

## II. TRANSMISSION LINE MODELING

The transmission lines are represented by an equivalent model with the circuit parameters expressed per phase. The voltages at the terminals are expressed from phase to neutral and the currents are per phase so that the three-phase system is reduced to an equivalent single-phase system expressed on a per-phase basis.

The model used to calculate voltages, currents and power flows depend on the length of the line. Transmission lines are classified, according to their length, into short, medium, and long lines. Short transmission lines are represented by the equivalent circuit shown in Fig. 1. It is important to note that in the equivalent circuit of short lines the parallel susceptance is not considered, since the effect of capacitance may often be negligible if the lines have a length is less than 80 km, or if the voltage is not greater than 69 kV.

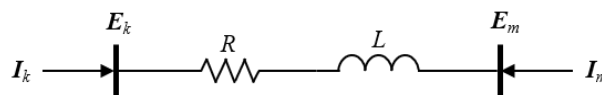


Fig. 1. Equivalent circuit of the short transmission line.

On the other hand, medium and long transmission lines are modeled with the equivalent circuit  $\pi$ , depicted in Fig. 2, where the capacitive effect of the line is considered in this circuit using the parallel susceptance, which is denoted in the figure by  $B_C$ .

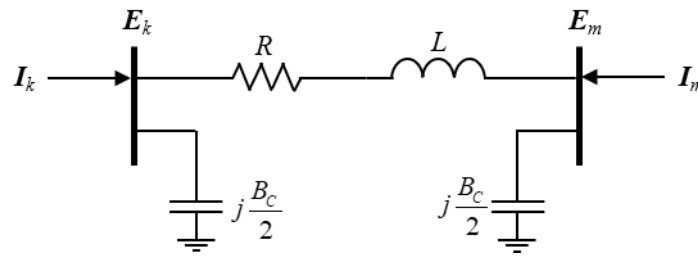


Fig. 2. Equivalent circuit  $\pi$  of medium and long transmission lines.

In the above figures, the term  $I_j$  is the injected current phasor at node  $j$  and  $E_j$  represents the voltage phasor at node  $j$  ( $j=k,m$ ), while  $R$  and  $L$  are the series resistance and inductance of the line, respectively [10]. Regarding the parallel susceptance of the transmission line, the following should be taken into consideration. The capacitive admittance of the transmission line is [5, 6],

$$Y = (g + j\omega C)l \quad (1)$$

The term  $g$  corresponds to the parallel conductance, which represents the leakage currents in the insulators and corona power losses. This value is negligible and, therefore,  $g$  is assumed to be equal to zero. Thus, the parallel admittance results as,

$$Y = j\omega Cl \quad (2)$$

Since the admittance has an only imaginary part, then the parallel susceptance is:

$$B_c = j\omega Cl \quad (3)$$

Parallel susceptance is directly related to the capacitive effect of the transmission line, so it is a purely reactive phenomenon that directly affects the reactive power and voltage level of the power system.

### III. POWER FLOW ANALYSIS

Power flow analysis is a tool commonly used in the analysis of electric power systems to determine the steady-state operating point. This tool is elementary and very important in the analysis of the systems since by knowing the operating point, it is possible to carry out actions of monitoring and control of the operation, as well as the planning and design of the future expansion of the power systems. The information obtained by calculating the steady-state operating point is the nodal voltage phasors, power flows, and power losses in transmission lines [5, 6].

The power flow analysis is based on the energy balance at each substation of the power system, which states that at any node  $i$  of the system the sum of the generated power  $S_{Gi}$ , the demanded power  $S_{Di}$ , and the power injected through the different transmission elements of the system  $\sum S_i^{iny,k}$  is zero. Thus the power balance  $S \{S=P,Q\}$  at node  $k$  can be modeled by equations (4) and (5) as follows,

$$\Delta P_i = P_{Gi} - P_{Di} - \sum_{k=1}^{N_b} P_i^{iny,k} = 0 \quad (4)$$

$$\Delta Q_i = Q_{Gi} - Q_{Di} - \sum_{k=1}^{N_b} Q_i^{iny,k} = 0 \quad (5)$$

The above expression represents a nonlinear system of equations, which is solved here using the Newton-Raphson method as illustrated below. In the first instance, the Taylor Series is applied to the above equations to obtain the linearized system given by equations (6) and (7).



$$\sum_{j=1}^n \left( \frac{\partial P_i}{\partial \delta_j} \right)^k \Delta \delta_j^k + \sum_{j=1}^n \left( \frac{\partial P_i}{\partial |V_j|} \right)^k \Delta |V_j|^k = \Delta P_i^k \quad (6)$$

$$\sum_{j=1}^n \left( \frac{\partial Q_i}{\partial \delta_j} \right)^k \Delta \delta_j^k + \sum_{j=1}^n \left( \frac{\partial Q_i}{\partial |V_j|} \right)^k \Delta |V_j|^k = \Delta Q_i^k \quad (7)$$

In these equations, the active and reactive power increments are obtained by the difference between the scheduled power and the power injected at node  $i$  in each iteration, as shown in Equations (8) and (9).

$$\Delta P_i^k = P_i^{sch} - \Delta P_i^k \quad (8)$$

$$\Delta Q_i^k = Q_i^{sch} - \Delta Q_i^k \quad (9)$$

Solving the above equations for the phase angle and voltage magnitude increments, a compact matrix expression is obtained as given by (10).

$$\begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix}^k = \begin{pmatrix} J_1 & J_2 \\ J_3 & J_4 \end{pmatrix}^k \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^k \quad (10)$$

$$\begin{bmatrix} \delta \\ |V| \end{bmatrix}^{k+1} = \begin{bmatrix} \delta \\ |V| \end{bmatrix}^k + \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix}^k \quad (11)$$

Once the angle and voltage magnitude at the system nodes are calculated, the active and reactive power flows and losses on the transmission lines must be calculated. This is done using the following equations as shown.

$$I_{km} = I_\ell + I_{k0} = y_{km} (V_k - V_m) + y_{k0} V_k \quad (12)$$

$$I_{km} = -I_\ell + I_{m0} = y_{km} (V_m - V_k) + y_{m0} V_m \quad (13)$$

The complex power flow  $S_{km}$  from bus  $k$  to bus  $m$  and from bus  $m$  to bus  $k$  is given by (14) and (15), respectively.

$$S_{km} = V_k I_{km}^* \quad (14)$$

$$S_{mk} = V_m I_{mk}^* \quad (15)$$

While the power losses in transmission lines are,

$$S_{losses} = S_{km} + S_{mk} \quad (16)$$

Finally, the active and reactive power injected by the slack node and the reactive power injected by the generation nodes of the power system is calculated using the power injection equations given by (4) and (5).

#### IV. NUMERICAL EXAMPLES

Next, study cases with the IEEE 5-node test power system are presented to observe the importance of considering the parallel susceptance of transmission lines when determining the steady-state operating point of 115 kV power systems. In all study cases, the PF analysis is used, which is solved using an algorithm implemented in Matlab with a convergence tolerance of  $1 \times 10^{-9}$ .



The IEEE 5-node power system consists of 2 generators, 7 transmission lines, and a total load power of 165 MW and 40 MVAR [11]. For the case study, first, the steady-state operating point of the system is obtained considering the parallel susceptance in the model of the seven lines, and then the operating point is determined without considering the  $B_C$ . A summary of the results obtained with and without parallel susceptance is presented in Table 1.

Table 1. Summary of power flow results.

Parameters	With $B_C$	Without $B_C$
$P_{Gi}$ (MW)	169.5869	169.7271
$Q_{Gi}$ (MVAR)	22.5806	54.1813
$P_{losses}$ (MW)	4.587	4.727
$Q_{losses}$ (MVAR)	-17.419	14.181

The table above shows that when parallel susceptance is not integrated into the modeling of transmission lines, there is a small increase in active power generation and an increase of almost twice the reactive power generation. A similar situation occurs in the case of active power losses since when parallel susceptance is not considered, active power losses are higher. A particular mention deserves the reactive power losses, since when  $B_C$  is considered, the reactive power losses are negative, which means that the transmission lines, instead of having losses, supply reactive power to the system, acting as sources of this type of power. Thus, when parallel susceptance is not considered, the lines present reactive power losses, as shown in Fig.3, causing reactive power generation to increase.

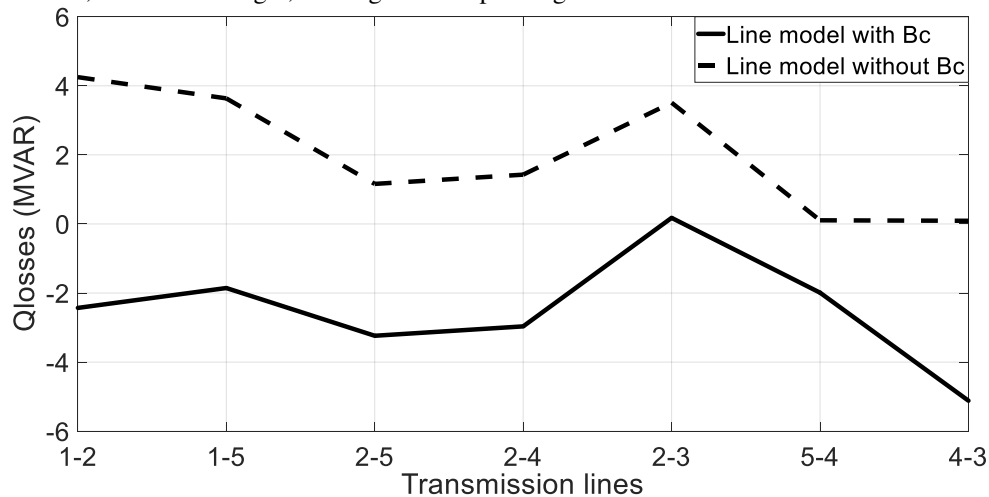


Fig. 3. Reactive power losses in transmission lines with and without  $B_C$ .

Fig.4 presents a 5-node power system voltage profile in which the effect of considering or neglecting the parallel susceptance in the modeling of power system transmission lines is observed.

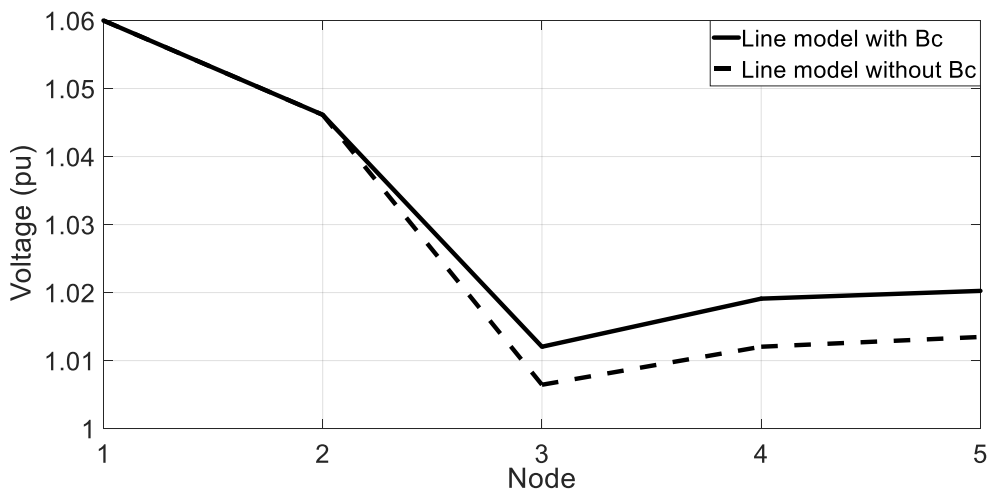


Fig. 4. Nodal voltage profile with the effect of  $B_C$ .

As mentioned before, the parallel susceptance in transmission lines acts as a source of reactive power, therefore, when  $B_C$  is considered, there is an important effect on the nodal voltage magnitude, since the voltage depends directly on the reactive power injected into the power system. It is observed that when the parallel susceptance is considered the nodal voltage profile grows, while if it is not considered the opposite phenomenon occurs. Accordingly, the consideration or not of the  $B_C$  does not have a considerable effect on the active power, as mentioned in the active power generation and as shown in Fig.5.

This figure shows that when the parallel susceptance is considered, active power losses increase slightly, which translates into a higher generated power and generation cost. At this point, the importance of modeling the transmission line considering the parallel susceptance is emphasized, since not doing so results in lower generation costs, which can be detrimental when making operating or planning decisions of the power system, ultimately affecting its profitability.

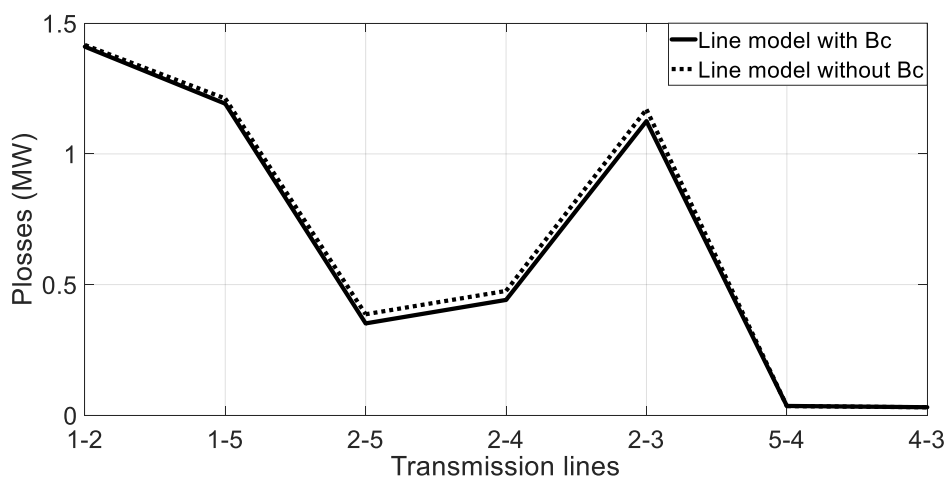


Fig. 5. Active power losses in transmission lines with and without  $B_C$ .

Finally, it should be mentioned that the parallel susceptance, besides affecting the current flowing in the transmission lines, also has a very important effect on the short-circuit currents. If the susceptance is considered, the short-circuit current at a point of the power system is lower than in the case when  $B_C$  is neglected. It is well known that the short-circuit currents are used for relay setting and coordination, therefore, having different short-circuit levels at the same point of the system will result in different relay settings and coordination, which could cause undesirable tripping of the electrical protections, affecting the safety and reliability of the power system.



## V. CONCLUSIONS

An analysis of the effect of the susceptance of transmission lines at the steady-state operating point of 115 kV power systems has been presented. Power flows analysis was used to carry out the study cases in which it was observed that when considering the  $B_C$  the nodal voltage profile is modified, changing the steady-state operating point of the power system, while the reactive power balance nodal and global is fulfilled exactly. If the parallel susceptance is considered in the equivalent circuit of the transmission lines, the short-circuit current decreases, but the nodal voltage profile and the losses and generation of reactive power increase.

It is also important to include the  $B_C$  in the line model because if it is not included, a lower active power generation cost is obtained, which could result in an error that is detrimental when making decisions related to the operation and planning of the power system, ultimately affecting its profitability. In general, it is concluded that by considering parallel susceptance in the modeling of transmission lines, a more accurate steady-state operating point is obtained, through which it is possible to take better actions in the operation, control, planning, and protection of the power system.

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