ISSN: 0975-833X

Available online at http://www.journalcra.com

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

International Journal of Current Research
Vol. 13, Issue, 11, pp.19665-19672, November, 2021

DOI: https://doi.org/10.24941/ijcr.42367.11.2021

RESEARCH ARTICLE

CONTRIBUTION TO THE STUDY OF LONG ELECTRIC POWER TRANSMISSION LINES

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ARTICLE INFO

Article History:
Received 25th August, 2021
Received in revised form
19th September, 2021
Accepted 24th October, 2021
Published online 26th November, 2021

Keywords
Long Lines, Telegraph Equations, Voltage, Current, Joule Losses, Voltage Profile and Compensation Plan.

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ABSTRACT

Studies on long lines of power transmission remain a controversial subject up to this day in view of the unsatisfactory results. These studies often address cases where the line is connected to a node which is perfectly voltage regulated. Likewise, the telegraph equations, reflecting how these lines work, express the voltage and current of the source as a function of the voltage and current along the line. Thus, our study examines the case of a line connected to an unregulated node. Regarding the telegraph equations dedicated to long lines, we will take care to express the voltage, the current and the joule losses according to the length of the line considered as variable while the voltage and the current of the source constitute constant. This way of approaching the study allows us to design an optimal compensation plan in order to maintain an ideal voltage profile.

Citation: Mathurin GOGOM, Afred Raoul MISSESSETE and Désiré LILONGA-BOYENGA. "Contribution to the study of long electric power transmission lines", *2021. International Journal of Current Research, 13, (11), 19665-19672.*

INTRODUCTION

The geographic dispersion and remoteness of convertible hydroelectric sites require the erection of long lines to transport the electrical energy produced to consumption centers. The transport of this electrical energy over long distances is subject to joule losses problems and voltage drops. The joule losses constitute a shortfall for the electricity companies and a factor of degradation of the transit equipment of electrical energy among others lines and transformers. Voltage drops are the cause of instability of electrical networks that can lead to voltage collapse or partial or total blackout. Studies tending to highlight these problems and the solutions found are abundant in the literature [Khefiani Guellil Smail, 2011; Jean-Claude; Mathurin Gogom, 2021]. However, examining the profile of the voltage along a long transport line of the electrical energy and current through that line requires special attention. Studies carried out to date consider the connection point of this line to be a perfectly voltage-regulated node [Khefiani Guellil Smail, 2011; Jean-Claude; Mathurin Gogom, 2021], while in other cases these nodes are not regulated; they can be the load nodes. Thus, the evolution of voltage and current as a function of the length of the line has the shape of a vault, which does not allow the exact location of the connection points of the compensators. In this study, the line is modeled taking into account resistive, inductive, crown and capacitive effects. The telegraphic equations of voltage, current and joule losses are developed and the voltage is appreciated according to the evolution of the length of the line. From the curve, we appreciate the voltage profile to consider the compensation plan of the line. Finally, a check is carried out after compensation using the load flow calculation algorithms to ensure that the line is in good working order.

Modeling long lines

Line types: There are basically three types of lines: short, medium and long lines [Khefiani Guellil Smail, 2011].Short lines of length $l \leq 80\ Km$ can be modeled taking into account only resistive and inductive effects and not crown and capacitive effects. However, the modeling of medium lines of length $80\ Km < l \leq 250\ Km$ takes into account all the effects except thecrown effect.Finally, long lines, with a length of $l > 250\ km$, which are the subject of this study, take into account all the effects.

Long lines model: A transport line of electricity can be represented by circuit elements distributed over its entire length.These circuit elements are: resistance, inductance, conductance and capacitors [4, 5, 6].As we are interested in the balanced steady state, a line is represented by an equivalent single-phase circuit whose parameters are those of the direct sequence figure 1 [Khefiani Guellil Smail, 2011; Jean-Claude; Mathurin Gogom, 2021; Mekhloufi Med Abdelatif, 2012].

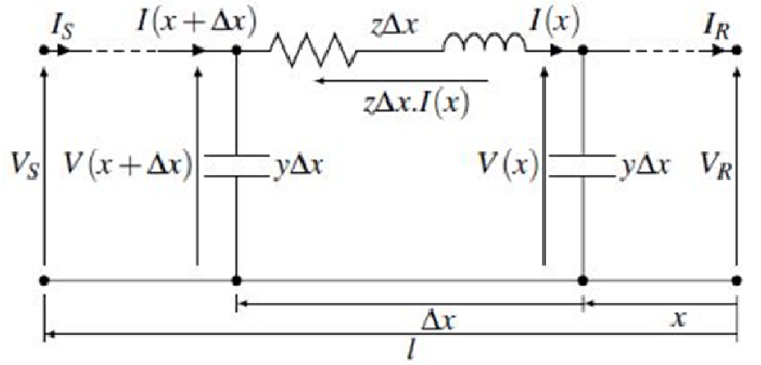

Fig. 1. One line model

With

V(x), I(x) : Voltage and current at position x of the line;
V(x+Δx), I(x+Δx) : Voltage and current at position x + Δx;
VS, IS : Source voltage and current (start);
VR, IR : Voltage and current at the end of the line (reception);
z_o: Line serie impedance per unit length, $z_o = r_o+j\omega l_o$;
y_o: Shunt admittance per unit length, $y_o = g_o+j\omega C_o$;
l : Line length.

Characteristic equations of long lines: By applying Kirchhoff's laws on the circuit of figure 1, the voltage V (x + Δx) is [Khefiani Guellil Smail, 2011; Jean-Claude; Mathurin Gogom, 2021]:

$$V(x+\Delta x) = V(x) + z\Delta(x)I(x) \quad (1)$$

After some transformations, we have:

$$\frac{V(x+\Delta x)-V(x)}{\Delta x} = zI(x) \quad (2)$$

Or

$$\lim_{\Delta x \to 0} \frac{V(x+\Delta x)-V(x)}{\Delta x} = \frac{dV(x)}{dx}$$

then

$$\frac{dV(x)}{dx} = zI(x) \quad (3)$$

Equation (3) is the first derivative of the voltage as a function of the length of the power transmission line.Likewise, the current I (x + Δx) can also be written [Khefiani Guellil Smail, 2011; Jean-Claude; Mathurin Gogom, 2021]:

$$I(x+\Delta x) = I(x) + y\Delta(x)V(x) \quad (4)$$

After some transformations, we have:

$$\frac{I(x+\Delta x)-I(x)}{\Delta x} = yV(x) \quad (5)$$

Or

$$\lim_{\Delta x \to 0} \frac{I(x+\Delta x)-I(x)}{\Delta x} = \frac{dI(x)}{dx}$$

Then

$$\frac{dI(x)}{dx} = yV(x) \quad (6)$$

By further deriving equations (3) and (6) with respect to x we obtain:

$$\frac{d^2V(x)}{dx^2} = z\frac{dI(x)}{dx} \quad (7)$$

$$\frac{d^2I(x)}{dx^2} = y\frac{dV(x)}{dx} \quad (8)$$

By substituting equations (3) and (6) in equations (7) and (8) we obtain the wave equations of the voltage and the current along the line:

$$\frac{d^2V(x)}{dx^2} = zyV(x) \quad (9)$$

$$\frac{d^2I(x)}{dx^2} = yzI(x) \quad (10)$$

By setting $\gamma^2 = zy$then$\gamma = \sqrt{(r + jl\omega)(g + jc\omega)} = \alpha + j\beta$called the propagation constant and equations (9) and (10) become:

$$\frac{d^2V(x)}{dx^2} - \gamma^2V(x) = 0 \quad (11)$$

$$\frac{d^2I(x)}{dx^2} - \gamma^2I(x) = 0 \quad (12)$$

Resolution of these second order differential equations gives [1, 2, 3] :

$$V(x) = A_1e^{\gamma x} - A_2e^{-\gamma x}$$

$$I(x) = \frac{1}{z}\frac{dV(x)}{dx} = \frac{1}{z}(\gamma A_1e^{\gamma x} - \gamma A_2e^{-\gamma x}) = \frac{\gamma}{z}(A_1e^{\gamma x} - A_2e^{-\gamma x})$$

By setting :$z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{r+jl\omega}{g+jc\omega}}$called characteristic impedance, we have:

$$I(x) = \frac{1}{z_c}(A_1e^{\gamma x} - A_2e^{-\gamma x})$$

We thus obtain the system of equations:

$$V(x) = A_1e^{\gamma x} - A_2e^{-\gamma x} \quad (13)$$

$$I(x) = \frac{1}{z_c}(A_1e^{\gamma x} - A_2e^{-\gamma x}) \quad (14)$$

Of unknown A1 and A2 which must be determined taking into account the line operation limit conditions.When x takes the value 0, under these conditions we have:

$V(0) = V_R \ et \ I(0) = I_R$

V (0) = $A_1 + A_2$et I(0) = $\frac{1}{z_c}(A_1 - A_2)$

That is

$V_R = A_1 + A_2$

$I_R = \frac{1}{z_c}(A_1 - A_2)$

The resolution of this system gives:

$A_1 = \frac{V_R+z_cI_R}{2} \ et \ A_2 = \frac{V_R-z_cI_R}{2}$by replacing A1 and A2 in equations (13) and (14), we obtain:

$$V(x) = \frac{e^{\gamma x}+e^{-\gamma x}}{2}V_R + \frac{e^{\gamma x}-e^{-\gamma x}}{2}z_cI_R \quad (15)$$

$$I(x) = \frac{e^{\gamma x} - e^{-\gamma x}}{2} \frac{V_R}{z_c} + \frac{e^{\gamma x} + e^{-\gamma x}}{2} I_R \quad (16)$$

By setting

$\frac{e^{\gamma x} + e^{-\gamma x}}{2} = \cosh(\gamma x)$ *and* $\frac{e^{\gamma x} - e^{-\gamma x}}{2} = \sinh(\gamma x)$, the system becomes:

$$V(x) = \cosh(\gamma x)\, V_R + \sinh(\gamma x)\, z_c I_R \quad (17)$$

$$I(x) = \sinh(\gamma x) \frac{V_R}{z_c} + \cosh(\gamma x)\, I_R \quad (18)$$

By taking into account the limiting conditions of equations (17) and (18), we can assume that $V(l) = V_s$and $I(l) = I_s$, we obtain:

$$V_S = \cosh(\gamma x) V_R + \sinh(\gamma x) z_c I_R \quad (19)$$

$$I_S = \sinh(\gamma x) \frac{V_R}{z_c} + \cosh(\gamma x)\, I_R \quad (20)$$

As we examine the behavior of voltage and current along the line, we can assume that $V_R = V(x)$ and $V_R = I(x)$, so equations (19) and (20) become:

$$V_S = \cosh(\gamma x) V(x) + \sinh(\gamma x) z_c I(x) \quad (21)$$

$$I_S = \sinh(\gamma x) \frac{V(x)}{z_c} + \cosh(\gamma x) I(x) \quad (22)$$

Equations (21) and (22) are not compatible for examining the evolution of voltage and current along the line.These equations should be solved.Solving equations (21) and (22) with respect to V(x) and I(x), using the determinant method leads us to:

$$\Delta = \begin{pmatrix} \cosh(\gamma x) & \sinh(\gamma x) z_c \\ \sinh(\gamma x) \frac{1}{z_c} & \cosh(\gamma x) \end{pmatrix}$$

$$\Delta = cosh^2(\gamma x) - sinh^2(\gamma x) = 1$$

$$\Delta_{V(x)} = \begin{pmatrix} V_S & \sinh(\gamma x) z_c \\ I_S & \cosh(\gamma x) \end{pmatrix}$$

$$\Delta_{V(x)} = V_S \cosh(\gamma x) - I_S \sinh(\gamma x) z_c$$

$$\Delta_{I(x)} = \begin{pmatrix} \cosh(\gamma x) & V_S \\ \sinh(\gamma x) \frac{1}{z_c} & I_S \end{pmatrix}$$

$$\Delta_{I(x)} = I_S \cosh(\gamma x) - V_S \sinh(\gamma x) \frac{1}{z_c}$$

Expressions of$V(x)$ *and* $I(x)$are such that:

$$V(x) = \frac{\Delta_{V(x)}}{\Delta}$$

$$I(x) = \frac{\Delta_{I(x)}}{\Delta}$$

We finally get:

$$V(x) = \cosh(\gamma x) V_S - \sinh(\gamma x)\ Z_c I_S \quad (23)$$

$$I(x) = -\sinh(\gamma x) \frac{V_S}{Z_c} + \cosh(\gamma x) I_S \quad (24)$$

Line losses are made up of joule losses and crown losses:

$$\Delta P(x) = r_0 x I^2(x) + g_0 V^2(x) \quad (25)$$

Application: The application related to our study is made on the project of the construction of the Chollet-Oyo electric power transmission line in the Republic of Congo, in its northern part.Chollet is a hydroelectric power plant with an installed capacity of 600 MW of which300 MW for Congo and 300 MW for Cameroon since it is a joint project [Consulting Group, 2005; Direction Générale de l'Energie, 2006; Conseil Mondial de l'Energie, 2008].

Line presentation: The line is about 472 km long and is supposed to operate at a voltage of 400 KV.It must pass an active power less than or equal to 300 MW.This line is shown in Figure 2 below and the characteristics are shown in Table 1 below.

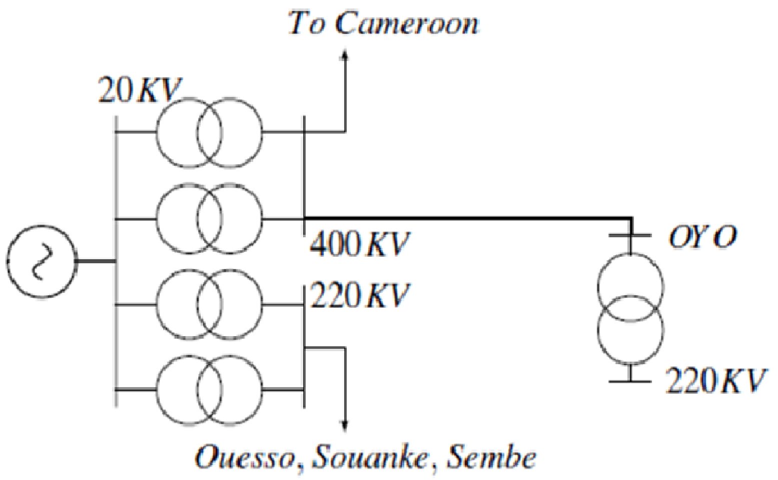

Fig. 2. Chollet-Oyo power transmission line

Tabl. 1. Line characteristics

r_0 (Ω/Km)	x_0(Ω/Km)	$g_0(\Omega^1/Km)$	$b_0(\Omega^1/Km)$	L (Km)	Us (KV)	Pg (MW)
0.03	0.33	$0.23\ 10^{-6}$	$3.5\ 10^{-6}$	620	400	300

Modelization : The Chollet-Oyo power transmission line is modeled according to the model in Figure 1 above.Equations (23), (24) and (25) describe how it works.This model takes into account the transverse and longitudinal parameters.The extract from Figure 2 to be modeled is shown in Figure 3 [Djida, 1994 ; Jean Pal Barret, 1997; Patrick, 1998; Guo, 2001; Jean-Marie Escane, 2021 ; Haddad, 2015].

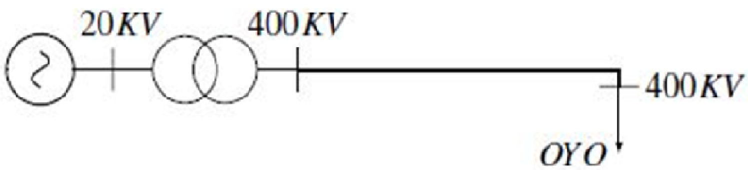

Fig. 3. Simplified Chollet-Oyo power transmission line

Simulations, results and discussion: We simulate the electric power transmission line on the basis of equations (23), (24) and (25) implemented in Matlab to understand the evolution of voltage, current and losses along the line in the absence of any form of regulation at the point of connection either to an existing network or to a load.

Simulations at empty: Simulations at empty consist in considering that the line is not connected to an existing electrical network or to a load.The assumptions used here are such that Is = 0, Vs = Vn and the length of the line is varied.

RESULTS

The simulation results obtained are shown in Figures 4, 5 and 6 below.These are curves of variations in voltage, current and joule losses as a function of the length of the no-load transport line of electrical power.

DISCUSSION

The increased voltage shown in Figure 4 is due to capacitive effects, and therefore the Ferranti effect which is very dangerous for transformers plugged into the end of this electrical power transport line.However, Figure 5 illustrates the evolution of the current injected into this line by the discrete capacitors that have formed.We notice that, for a length of 620 km and a voltage of 400 KV of the line, the current generated is of the order of 50 A. Finally, figure 6 shows how the joule losses vary according to the length of the line.These losses are due to the current generated by the discrete capacitors thus formed.

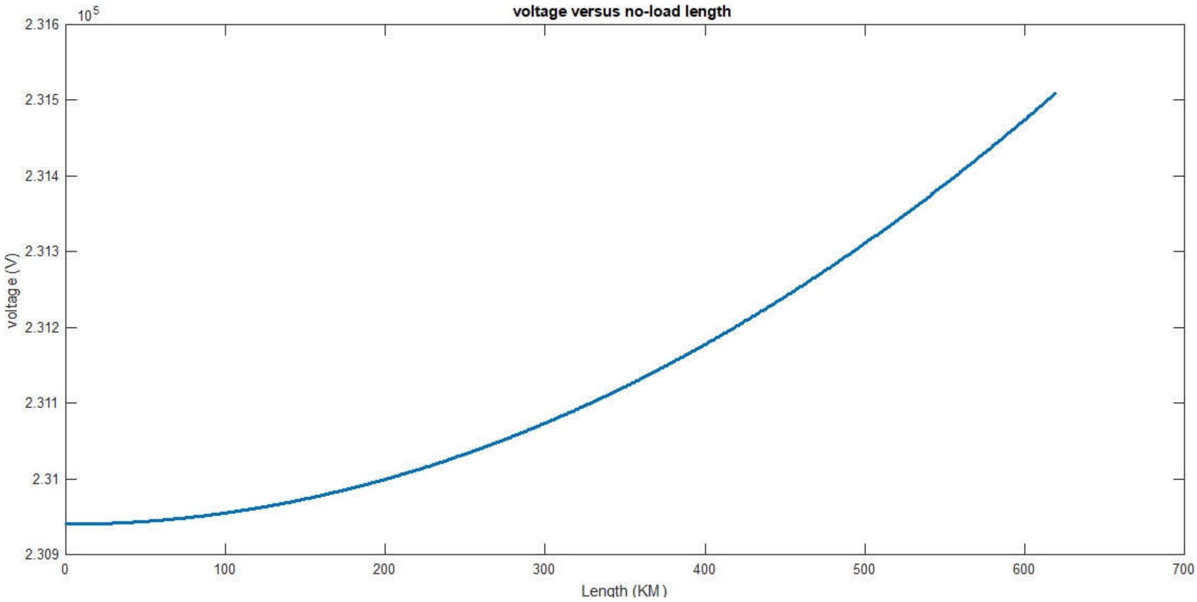

Fig. 4. Voltage evolution during no-load operation

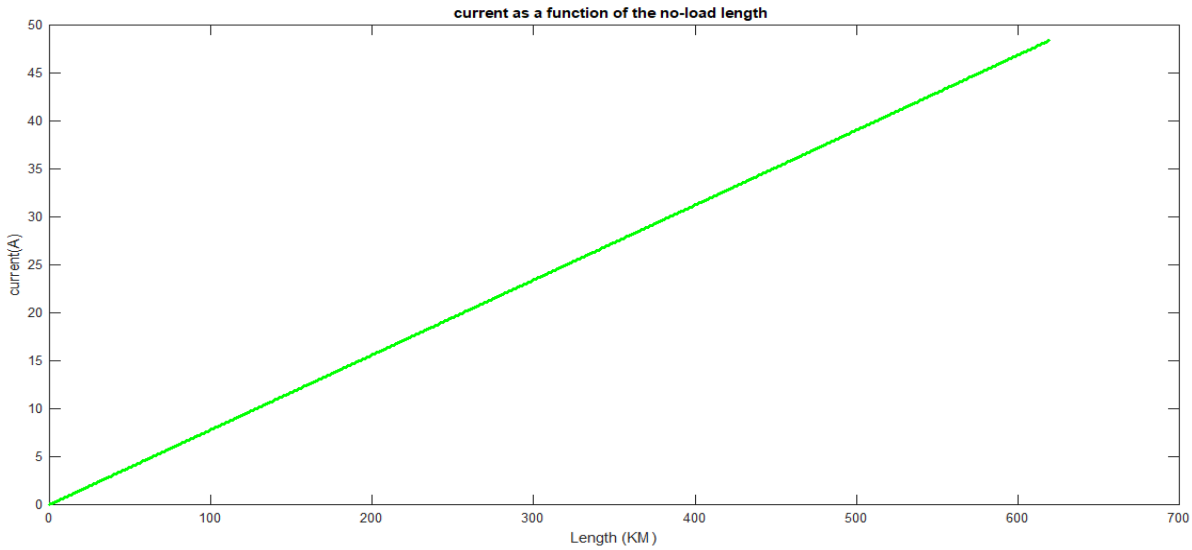

Fig. 5 . Evolution of the current during no-load operation

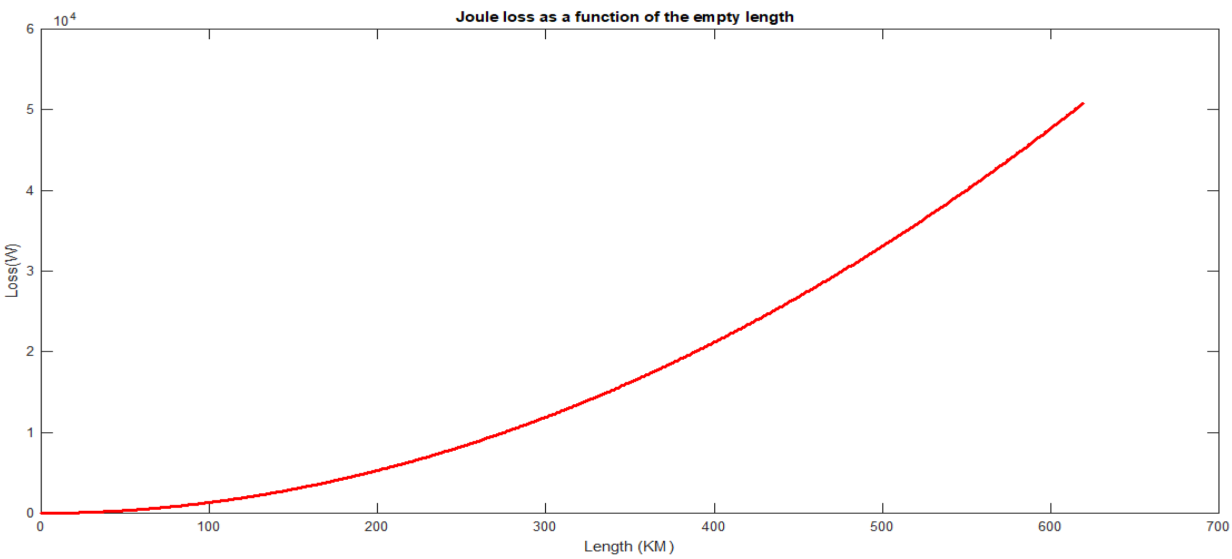

Fig. 6. Evolution of joule losses during no-load operation

Simulations in charge : The load or the existing electrical network being connected, the working hypotheses are such that $I_s = \frac{P_{Tl}}{\sqrt{3}U_s cos\varphi}$, $V_s = \frac{U_{Tl}}{\sqrt{3}}$ and X is a variable.

Results : The curves in Figures 7, 8 and 9 above illustrate the simulation results obtained during the load operation of the electric power transport line.These are the characteristics reflecting the evolution of voltage, current and joule losses.

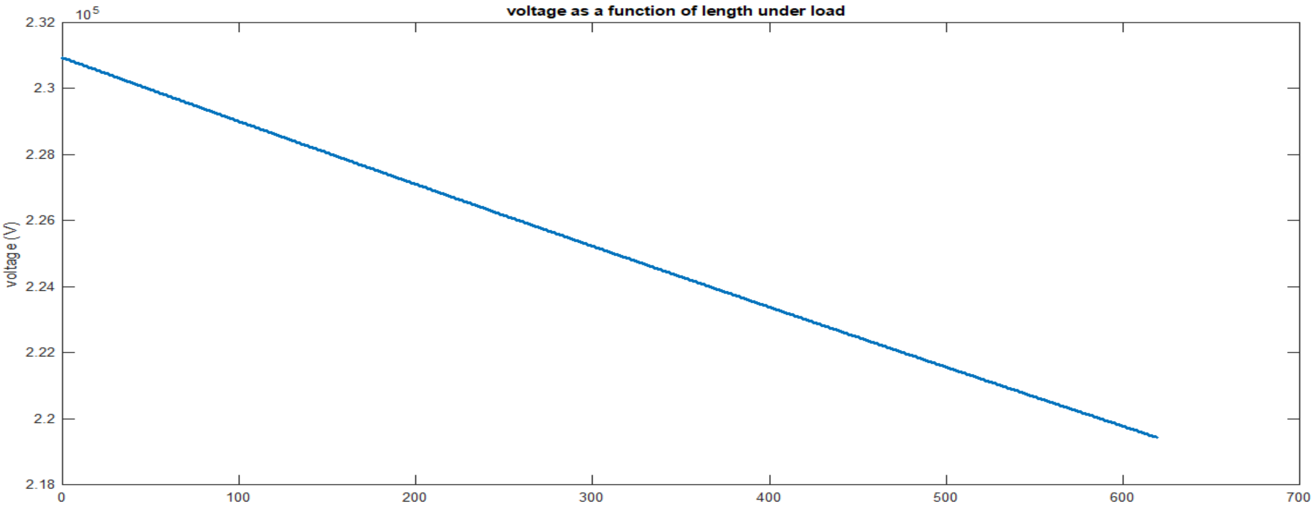

Fig. 7. Voltage evolution during functioning in charge

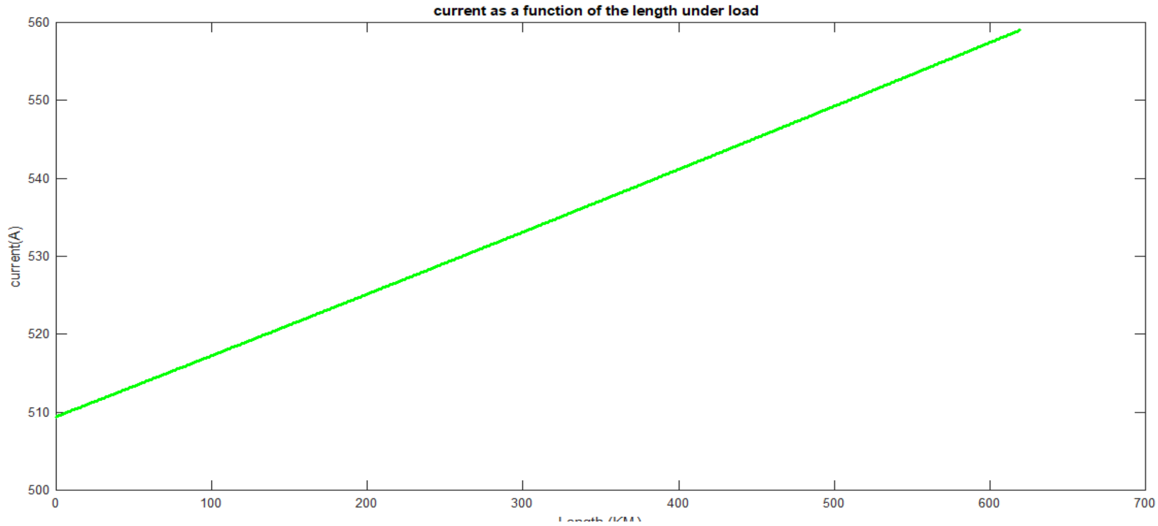

Fig. 8. Evolution of current during functioning in charge

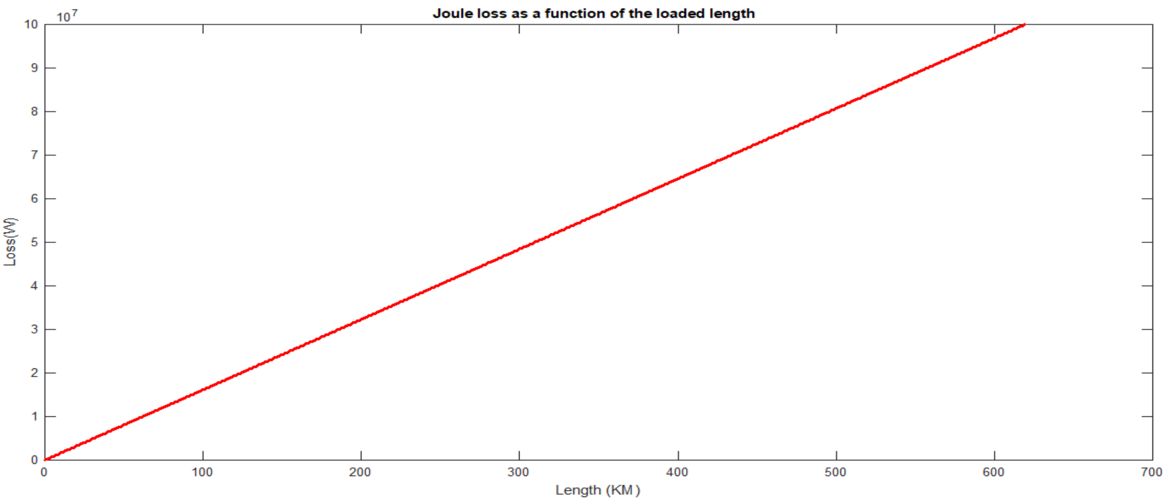

Fig. 9. Evolution of joule losses during functioning in charge

DISCUSSION

We notice that the impedance of the electrical energy transport line varies with its length causing the voltage drop to increase and therefore voltage drops.In addition, the current increases as a function of the length of the line.This increase compensates the power in view of very considerable voltage drops along the line.Joule losses also increase with the length of the line.The characteristics thus obtained are quasi linear.

Conclusion

The study that we have just carried out allowed us to understand how a long electrical energy transport line works when empty and under load.We have established that the voltage, current and joule losses characteristics during load operation vary almost linearly in the absence of end-of-line compensation.This study will make it possible to achieve an optimal compensation of the line by placing the compensators at a distance where the voltage service will be out of standard.

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