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# EHV Cable Line Compensation with P_Q Diagram

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***Abstract:*** *This paper deal with the transmission power in EHV cable lines. Because of high capacitive property of cables, its power transmission capability decreases due to its length increasing. Using compensators in different points of cable lines lead to increasing active power transmission ability and releasing capacity of this type of lines. Using P_Q diagram can be effective and helpful to optimum operation and determine compensation degree. Active power versus reactive power diagrams depicted by MATLAB software and compare with before compensated P_Q diagrams.*

***Keywords:*** *EHV Cables, Compensation, P_Q diagram.*

## INTRODUCTION

Deregulation of the electricity supply markets and growing environmental awareness stress the necessity of new transmission line solutions alternative to traditional overhead lines. So the transmission scenario is paying a great attention to the underground technologies. In particular, the use of XLPE AC cable lines seems very promising for new links. EHV cables can be used mainly for power transmission in large urban heavily populated agglomerations, as feeders in outdoor substations, and as generator bus-ducts. The first major (i.e. where a significant number of joints is required) XLPE cable systems have been in service since 1997 at 400 kV and 2000 at 500 kV. Since those dates, the importance and the interest on these applications are increased and deserve a very careful consideration (Benato and Paolucci, 2005).

EHV AC Cable Lines (CLs) produce a large reactive power surplus in every operating condition. For modern (XLPE-insulated) 400 kV-50 Hz underground cables this is over 10 Mvar/km, and can be over 20 Mvar/km for 500 kV-60 Hz cables. This reactive power reduces the power transmission capability of the cable and dictates the maximum feasible length of a cable line. Moreover, it may cause significant local voltage rises as well as under excitation of the nearest generators. In case of no-load energization and load rejection, high initial temporary overvoltages can occur (Stefano Lauria et al., 2007).

The present paper deals with the cable lines and power transmitted by them. Due to the great important of these lines, should be noted that the cable current does not exceed the rated current because it will led to serious damage to the insulation. The reminder of this paper is organized as follow: Section 2 described limits and the model used for cable lines. Then case study the line parameters are expressed. Section 3 examines the transmission power rates from cable lines and the circular curves of this type of lines. In this section the feature of cable lines without compensation will investigated and then effect of compensation on their will be studied.

**Operational Restrictions**

The main function of a cable in a EHV/HV network (as well as any transmission line) is to transmit active power P with a small amount of reactive power Q.
Moreover, it is well known that a long service life can be reached only with these constraints in any point along the cable: avoiding that the currents exceed the cable ampacity $I_c$, meant as the current carrying capacity (depending on the installation conditions) under stated thermal conditions without degradation: during operation.
The ampacity limits at both ends (S for Sending and R for Receiving end) and to assure a phase-to-earth voltage level in one of the two ends (in this paper S will be always selected):

$$|\bar{I}_{\mathrm{R}}| \leq I_{\mathrm{c}} \quad (1)$$

$$|\bar{I}_{\mathrm{S}}| \leq I_{\mathrm{c}} \quad (2)$$

Where $I_R$ and $I_S$ are receiving and sending ends current, respectively.
Moreover, other items are effective on cable lifetime such as allowable current in the two end of cable system, operating time, operating temperature and... (Benato and Paolucci, 2010).
For more analyses of cable lines feature, using the numerical values of these studies is the better. Therefore a XLPE insulation cable line is considered with a voltage level at 400kV. Cable line parameters in study are given in Table 1.

**Table 1:** Positive sequence parameters of cause study cable line (Benato and Paolucci, 2010)

| Parameters | Values |
|---|---|
| Line type | XLPE cable |
| Rated voltage | 400 kV |
| Length | km 70-100km |
| Cross section | 2500 mm2 |
| Apparent resistance | 13.3 mΩ/Km |
| Shunt leakance | nS/km 51.5 |
| Inductance | 0.576 mH/Km |
| Capacitance | 0.234uF/Km |
| Ampacity | 1788 A |

Two different lengths for cable is considered, 70 km and 100 km. by using classical line formula, implement two separated analysis. One time assume that the voltage and current at the sending end, i.e $V_S$ and $I_S$, is known, calculated the receiving end voltage and current ($V_R$ and $I_R$). Another time assume that the sending end voltage and receiving end current, i.e. $V_S$ and $I_R$, is known and calculated the receiving end voltage $V_R$ and sending end current $I_S$. in both analysis, current along the cable should not exceed from the nominal values of the line.

**Cable line modelling**

The simply model of transmission line can be used for this study because the length of the line is not very long but using distributed model lead to accuracy results (Benato, Di Mario, and Koch, 2007). Fig.1 show distributed model used in this paper.

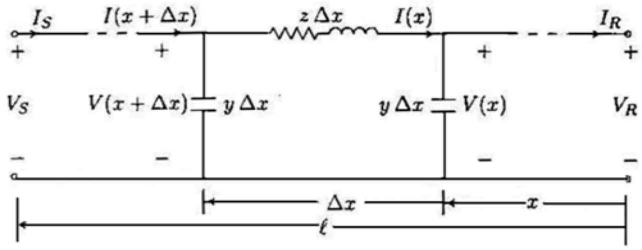


**Figure 1:** distributed model for cable line study (Hadi Saadat, 2010)

By using this model, A, B, C and D Coefficients are determined by following relations:

$$A=D=\cosh(kl) \quad (3)$$
$$B=Z_0.\sinh(kl) \quad (4)$$
$$C=\sinh(kl)/Z_0 \quad (5)$$

Where $Z_0$, $k$ and $l$ are surge impedance, propagation constant and length of cable line, respectively.

**Equation description**

The starting point is a rigorous application of the famous transmission formulae (solution of the telegraphs' equations) first written in 1876 by Oliver Heaviside and then used, rearranged and divulged by Steinmetz, Rossler, La Cour. Using the classic model line formula to be paid to the analysis of relationships:

$$V_S = A.V_R + B.I_R \quad (6)$$
$$I_S = C.V_R + A.I_R \quad (7)$$

At first, assume that the sending end voltage and current are known:

$$I_S = (I_c\angle 0) = (1.6\ \text{kA}\angle 0) \quad (8)$$
$$V_S = (V_o\angle\delta) = (230\text{kV}\angle\delta) \quad \delta = 0\_2\pi \quad (9)$$

It is worth noting that single phase circuit is considered, this means that the phase to ground voltage will be used in computations. Table 2 shows the main parameters calculated from distributed EHV cable line modelling.

**Table 2:** calculated parameters of EHV cable

| Parameters | L=70km | L=100km |
|---|---|---|
| A | 0.97 + 0.002i | 0.93 + 0.004i |
| B | 0.74 +12.419i | 1.03 +17.538i |
| C | 0.0052i | 0.0074i |
| Characteristic Impedance (Ω) | 48.7993 - 1.4505i | |
| Propagations Factor($km^{-1}$) | 0.0001 + 0.0037i | |
| Surge Impedance Loading(SIL) | 3276 MVA | |

So that the remaining quantities $V_R$ and $I_R$ can be determined:

$$V_R = A.V_S - B.I_S = A.(230kV\angle\delta) - B.(1.6kA\angle 0) \rightarrow V_R \quad (10)$$

$$I_R = -C.V_S + A.I_S = -C.(230kV\angle\delta) + A.(1.6kA\angle 0) \rightarrow I_R \qquad (11)$$

For numerical analysis values of voltage and current in sending point supposed to be equal at $V_S=230kV\angle\delta$ and $/I_S/=1.6\ kA$ respectively. $\delta$ can be changed between 0 to 2π.
In order to complete analysis, no load voltage is calculated. When receiving end current set in zero (i.e. $I_R=0$) no load voltage is:

$$(V_R)_{I_R=0} = \frac{1}{A}.V_S \qquad (12)$$

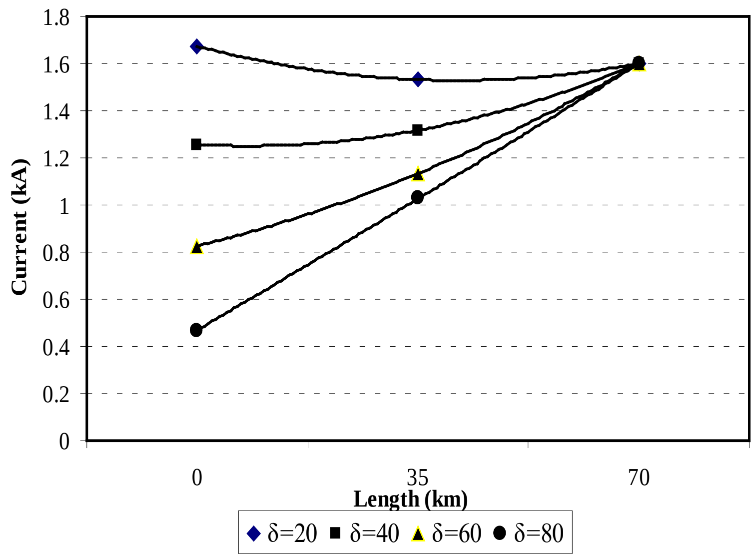


**Figure 2:** current profile along the cable line with different δ when $I_R$ is known

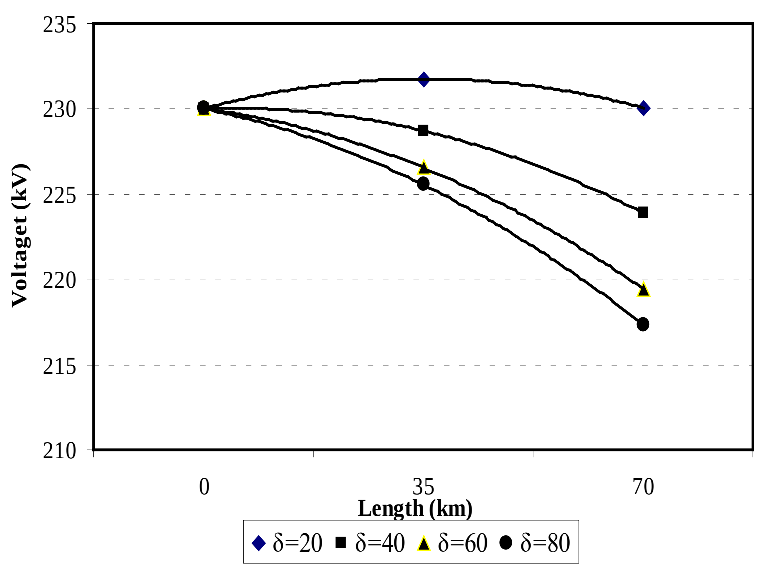


**Figure 3:** voltage profile along the cable line with different δ when $I_R$ is known

At next analysis, assume that the sending end voltage and receiving end current are known:

$$I_R = (I_c\angle 0) = (1.6\ kA\angle 0) \qquad (13)$$

$$V_S = (V_o\angle\delta) = (230\text{kV}\angle\delta) \quad \delta = 0\_2\pi \qquad (14)$$

Receiving end current set at nominal value, 1.6 kA. Note that in this states, current in sending end maybe exceeded from
Using relations (8) and (9), extract other two unknown parameters, $I_S$ and $V_R$:

$$V_R = V_S/A - B/A\,.\,I_S = (230kV\angle\delta)/A - B/A.(1.6kA\angle 0) \;\rightarrow\; V_R \quad (15)$$
$$I_S = C/A\,.\,V_S + I_S/A = C/A\,.(230kV\angle\delta) + (1.6kA\angle 0)/A \;\rightarrow\; I_S \quad (16)$$

In both analyses, once $I_S$ is known and second time $I_R$ is known, current along the cable not exceeded from their nominal values. Fig. 2 and Fig. 3 show current profile and voltage profile respectively, along the cable line with different load angle *δ,* when $I_R$ is known. In Fig. 2 We can see when *δ=20* current in sending side is more than rated ampacity of cable and maybe damaged the equipment of them. Also in this load angle, voltage at middling point of line exceeded from rated current.

## P_Q Diagrams

The locus of all points obtained by plotting $Q_R$*(3phase)* versus $P_R$*(3phase)*for fixed line voltages and varying load angle *δ* is a circle known as the receiving end power circle diagram. A family of such circles with fixed receiving end voltage and varying sending end voltage is extremely useful in assessing the performance characteristics of the transmission line. Here P_Q diagram (or circle diagram) are drawn for both sending end and receiving end power. (Colla et al., 2009)
For a given system operating at constant voltage, the power transferred is proportional to the sine of the power angle *δ*. As the load increases, *δ* increases. For a lossless line, the maximum power that can be transmitted under stable steadystate condition occurs for an angle of 90°. However, a transmission system with its connected synchronous machines must also be able to withstand, without loss of stability, sudden changes in generation, load, and faults. To assure an adequate margin of stability, the practical operating load angle is usually limited to 35° to 45° (Hadi Saadat, 2010).

## Cable line compensations

Large capacitive property of cable lines make problem duo to generate a large reactive Power. This large amount reactive power occupy useful capacity of line and reduce ability to transmit real power.
For releasing cable capacity and increasing ability to transfer active power, compensation reactors can be used throughout the line. In the best case, compensators distribute along the line uniformly, and will make the maximum yield. But this case will not applied practically (Colla et al., 2005). In one case the compensator can be installed in both ends of cable line. As shown in Fig. 2 compensator position in both ends of line is shown. In order to calculate the transmission line power capability in present of compensators, cable line coefficient combined with reactors coefficients. Fig. 2 shows this subject clearly.

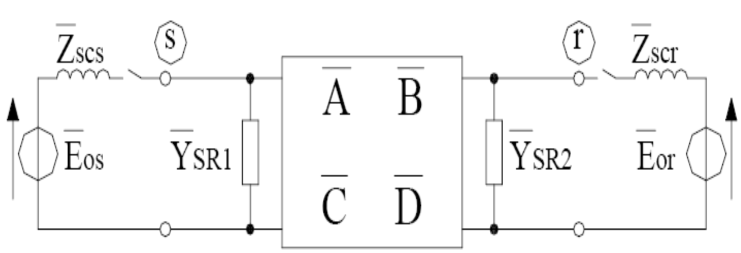


**Figure 2:** electrical circuit of cable line with compensators.

Coefficient of line after compensator placement will be changed. New equivalent coefficient calculated as following:

$$\begin{bmatrix} Aeq & Beq \\ Ceq & Deq \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_{SR1} & 1 \end{bmatrix} \cdot \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ Y_{SR2} & 1 \end{bmatrix} \quad (13)$$

Where $A_{eq}$, $B_{eq}$, $C_{eq}$ and $D_{eq}$ can be written as:

$$A_{eq} = (\mathrm{A} + \mathrm{B.Y_{SR2}}) \quad (14)$$

$$\mathrm{B_{eq}} = \mathrm{B} \quad (15)$$

$$\mathrm{C_{eq}} = (\mathrm{C} + \mathrm{A.Y_{SR1}} + \mathrm{B.Y_{SR1}.Y_{SR2}} + \mathrm{D.Y_{SR2}}) \quad (15)$$

$$\mathrm{D_{eq}} = (\mathrm{D} + \mathrm{B.Y_{SR1}}) \quad (16)$$

Determining the appropriate amount for compensators lead to change the amount of power passing from the line. Fig. 3 shows P_Q curves for cable line after and before compensation for two different length, 70 km and 100 km. As previously stated, assumed the current value at the sending end is constant. This means that with line compensation and release the amount of line capacity, reduced the losses and transmission power. This point is sensible in sending point reactive power curves, perfectly. Install of compensators lead to increase allowable and useable cable lines length.

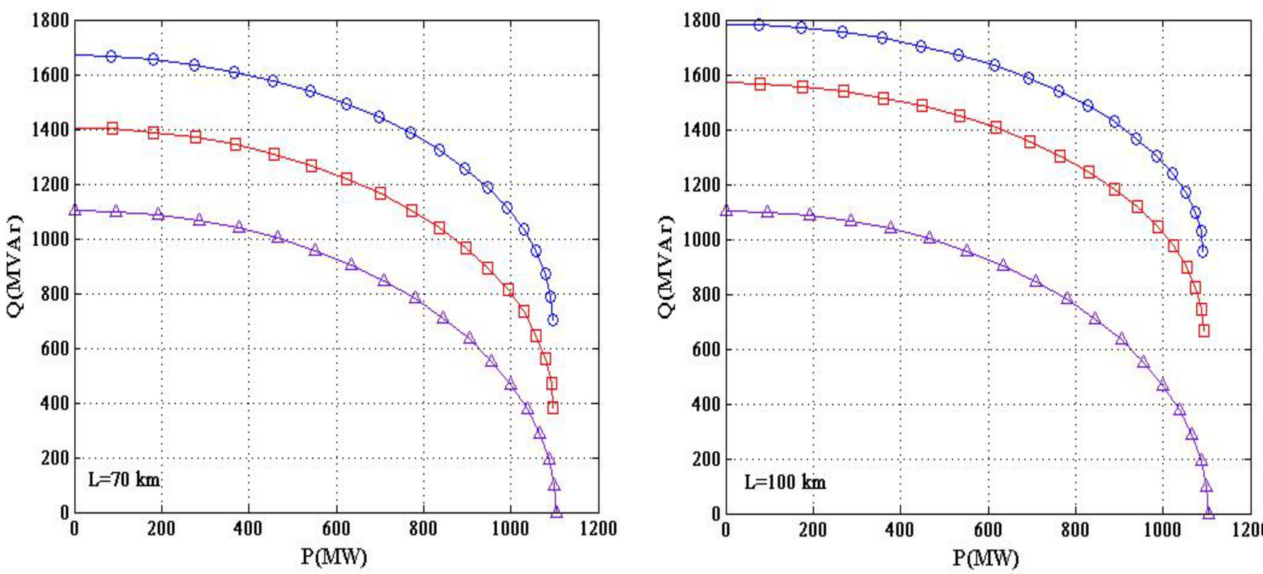


**Figure 3:** cable line P_Q diagram with two different lengths when $I_S$ is known (Δ Sending end power, □ Receiving end power of compensated line, ○ Receiving end power of uncompensated line)

In this case study, $Y_{SR1}$and $Y_{SR2}$ supposed to be equal to 1.1 $m\Omega^{-1}$. With this compensators, when $I_R$ is known, after and before line compensations Fig. 4 is depicted.

In this figure, using compensators help to control sending end current in allowable level.

Another effect of installing compensators, prevent the unallowable voltage increasing in no load or low load conditions.

Based on Ferranti phenomena, in no load condition at receiving end side load voltage increases and that voltage rise caused by damaged cable insulation. also reduces network life. using shunt reactors in two end of cable lines regulate this event (Judendorfer, Pack, and Muhr, 2008,).

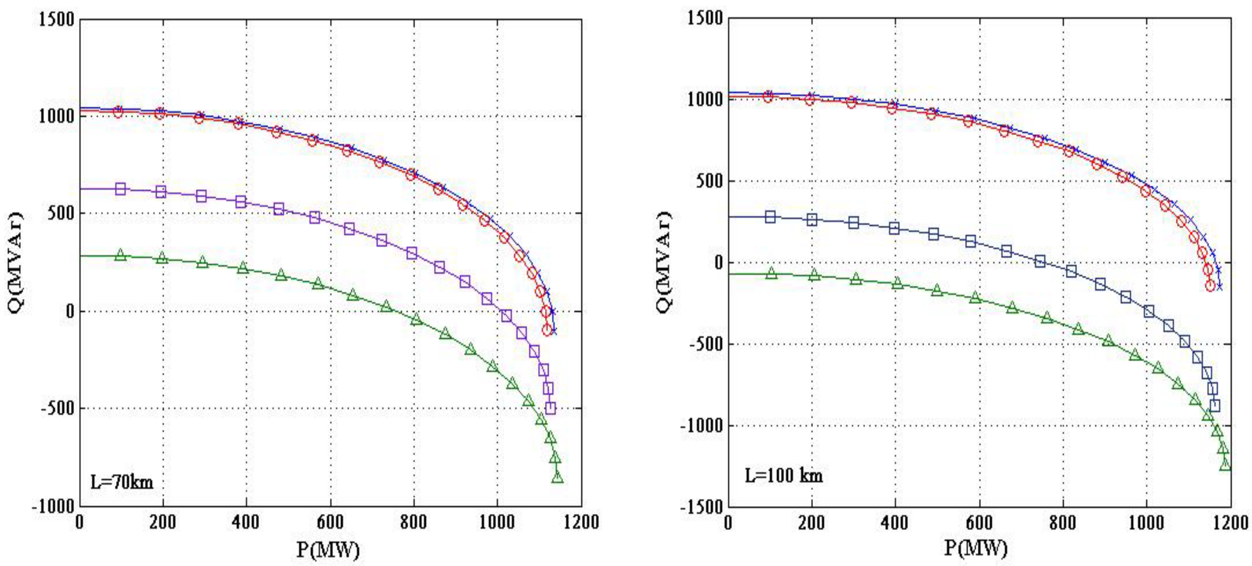


**Figure 4:** cable line P_Q diagram with two different length when $I_R$ is known (Δ Sending end power of uncompensated line, □ Sending end power of compensated line, ○ Receiving end power of compensated line, × Receiving end power of uncompensated line, )

## Conclusion

In this paper the high voltage transmission power cable lines are investigate. Based on the distributed model of a transmission line which take into account line loss and capacitances, some important characteristics governing the real power flows and voltage angle across the line have been derived and elaborated on. The result is then applied to the case of shunt reactive power compensation at both ends of cable line. Because of high capacitance of cable lines, reactive power is produced which they occupy useful cable capacity and limit maximum length of lines. The power capability chart represents an immediate and precise outlook on the possibilities of active and reactive power flows along the line. By using P_Q diagram amount of transmitted power in the cable lines studied. Two shunt reactors as compensator installed in both ends of line and release cable capacity in order to transfer more active power and increase the efficiency. Also using compensators help to overcome length limiting, loss reduction and increase ability of power transmission.

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