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Efficiency estimation method of three-wired AC to DC line transfer

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Abstract. The development of power semiconductor converters technology expands the scope of their application to medium voltage distribution networks (6-35 kV). Particularly rectifiers and inverters of appropriate power capacity complement the topology of such voltage level networks with the DC links and lines. The article presents a coefficient that allows taking into account the increase of transmission line capacity depending on the parameters of it. The application of the coefficient is presented by the example of transfer three-wired AC line to DC in various methods. Dependences of the change in the capacity from the load power factor of the line and the reactive component of the resistance of the transmission line are obtained. Conclusions are drawn about the most efficient ways of converting a three-wired AC line to direct current.

1. Introduction
Traditionally, DC transmission is associated with links which are connecting unsynchronized power systems, or with long-distant (thousands of kilometers) power transmission lines. The described cases assume the transmission of electricity at high voltage levels (hundreds of kilovolts). In the course of solving the described problems and developing the theory and practice of constructing a direct current transmission line, the concept of HVDC networks was formed [1–4]. Currently due to technological development of power electronics devices and methods of control of technological complexes, DC transmission is realized in medium voltage networks, which is reflected in the MVDC concept [5–7]. It is supposed to use technology in ship networks, to supply electric transport, to organize networks of coastal wind farms and to provide electricity for underground and open-cast mining.

Of special interest is the conversion of the AC transmission line to direct current to increase its capacity. The result is due to the fact that there is no reactive resistance of the line wires at the DC current, which reduces the voltage drop along the line. Moreover the transmission efficiency is increasing due to the lack of reactive power flow. The methods of transferring the power line to direct current are well described [3,8], it is possible to reconstruct a unipolar or bipolar DC line using one, two or three wires available or ground as a conductor, with line voltage boost or without. The initial stage of reconstruction is the evaluation of efficiency of such transfer or a calculation of the increase of transmission line capacity during the transfer to a DC.
2. Method

It is required to determine the meaning of the terms used in the presented article. Transmission line capacity $P_{\text{max}}$ is defined as the largest active power that can be transmitted over the line. This parameter can be limited by the conditions of permissible voltage drop in the line, the permissible current of the wires and the stability of the power system. If the parameter is determined by allowable voltage drop along the line, it is defined as $P_{\text{max},U}$, which should be read as the transmission line voltage capacity. If the parameter is determined on the basis of the permissible current of the wires, it is designated as $P_{\text{max},I}$ and is read as the transmission line current capacity. As networks with a voltage of 6-35 kV are considered, the voltage level is not determining in the stability of power systems so the capacity of the line for stability is not limited. Transmitted active power $P$ is the active power transmitted to the load through the power line. Transmission line current capacity margin coefficient $K_{\text{CM}}$ is defined as the ratio of the largest allowed current by heat limit to amount of current flowing through the line. Transmission line voltage capacity margin coefficient $K_{\text{VM}}$ is defined as the ratio of the transmission line voltage capacity of the power to the transmitted active power. The power transmission line margin coefficient is defined as the ratio of the transmission line capacity, determined with taking into account the current and voltage limits to the active power, which corresponds to a minimum of the current and voltage transmission line capacities:

$$K_{\text{PM}} = \frac{P_{\text{max}}}{P} = \min[K_{\text{CM}} ; K_{\text{VM}}].$$

To obtain the dependence, it is required to determine the voltage and current reserve factors for various line and load parameters. Figure 1 shows a vector diagram of the voltage and current of the line, used to determine the bandwidth of the voltage line. The voltages at the beginning and at the end of the line are denoted as $U_1$ and $U_2$, respectively, vector $\Delta U$ is the voltage drop along the line, vector $I$ denotes the current flowing through the wires, and $\varphi_{\text{line}}$ and $\varphi_{\text{load}}$ are the angles defining the ratio between the reactive and active power of the transmission line and the load, respectively. It should be noted that the diagram is constructed with the assumption that only the currents of the fundamental frequency, direct sequence, flow through the lines.

![Figure 1. Voltage along the transmission line](image-url)
Transmission line voltage capacity should be defined by formula 2:
\[ P_{\text{max,}U} = k_2 \frac{U_{\text{load}}^2}{z_\text{line}} \left( \sqrt{k_2^2 \cos^2(\varphi_{\text{line}}) + k_1^2 - k_2^2 - k_2 \cos(\varphi_{\text{line}})} \right), \] (2)

where \( z_\text{line} \) - transmission line impedance, \( U_{\text{load}} \) - transmission line nominal phase voltage, \( k_1 \) - ratio of module of voltage in the transmission line beginning to nominal voltage, \( k_2 \) - ratio of module of voltage in the transmission line end to nominal voltage.

It should be noted that \( \varphi_3 \) can also be defined as the arctangent of the ratio of the reactive resistance of the transmission line to its active resistance. Since there is no reactive voltage drop in the steady-state mode in the DC line, its line capacity is determined by formula 3:
\[ P_{\text{max,}U} = \frac{U_{\text{d}} - U_{\text{d}2}}{R_{\text{line}}} \] (3)

Index \( d \) indicates the parameters of the direct current line, as to the parameters of the AC line. In general, the AC resistance of the wires is greater than DC, which is due to the surface effect and proximity effect. However, at industrial frequencies (50-60 Hz), these effects are not pronounced, therefore \( R_{\text{line}} = R_{\text{d,line}} \). A comparison of the lines of direct and alternating current is possible, since their voltages are proportional [9]:
\[ U_{\text{d,load}} = \frac{3\sqrt{6}}{\pi} U_n. \] (4)

The change in the transmission line margin capacity is determined by the increase in the value of the direct current in comparison with the alternating current. To do this, it must be equated the active power transmitted by both transmission systems, which allows determining the ratio of the currents in them:
\[ 3 \cdot I_{\text{line}} \cdot U_{\text{phase}} \cdot \cos \varphi_{\text{load}} = \frac{3\sqrt{6}}{\pi} I_d \cdot U_{\text{phase}}. \] (5)

3. Modelling

Let us determine how many times the power reserve factor increases when a three-wire three-phase AC transmission line is transferred to a direct current in various ways without increasing the voltage. It was analyzed five different unipolar DC power lines and compared a two-wire line, a two-wire line with a wire interchange, a three-wire DC line, a three-wire DC line with a wire interchange and earth return three-wired line. Alternating wire switching allows power line works in a short-term overload mode, which increases the current capacity of the power line. Ground return involves the use of land as a conductor and ground electrodes, which ensure low transient resistance connection of the power system to the ground.

As an example, let us consider the simplest way to convert a three-phase three-wire AC transmission line to a direct current, a unipolar two-wire line. Assuming \( k_1 \) and \( k_2 \) for 1.1 and 0.9, respectively, let us determine how many times the safety factor for the voltage will increase:
\[ K_{d,gi} = K_{yi} \frac{0.2 \cdot \sqrt{1 + \tan \varphi_{line}^2}}{\sqrt{0.81 \cdot \cos \varphi_{line}^2 + 0.4 - 0.9 \cos \varphi_{line}}} \]  \hspace{1cm} (6)

From Equation 7 it can be seen that when transmitting the same active power, the current of a two-wire DC transmission line can exceed the current of a three-phase AC line up to 1.28 times depending on the power factor:

\[ K_{d,CM} = \frac{I_{max}}{I_d} = \frac{\sqrt{6} \cdot K_{CM}}{\pi \cdot \cos(\varphi_{load})} \approx \frac{0.78 \cdot K_{CM}}{\cos(\varphi_{load})} \]  \hspace{1cm} (7)

In Table 1, the considered method corresponds to column № 1, column № 2 corresponds to increase \( K_{CM} \) with \( \varphi_{load} = 0 \), column № 3 corresponds to increase \( K_{VM} \) with \( \varphi_{line} = 0 \), and column 4 corresponds to the scheme of the considered method. The lines indicated by Roman numerals correspond to the methods considered. Digit i corresponds to the method of electricity transmission by two wires, digit ii - the method of transmission over two wires with sequential interchange of wires, number iii corresponds to the method of transmission over three wires, number iv corresponds to the method of transmission over three wires with their sequential interchange, and digit v corresponds to the transmission method by three wires with a ground return.

**Table 1. Methods of DC transmission**

|   | 1   | 2    | 3    | 4 |
|---|-----|------|------|---|
| i | 0,78| 0,91 |      |   |
| ii| 0,95| 0,91 |      |   |
| iii| 0,78| 1,21 |      |   |
| iv| 1,11| 1,21 |      |   |
It should be noted that the increase of transmission line voltage capacity margin coefficient that involves a ground return is indicated from the assumption that the electrode-to-ground transition resistance is many times less than the resistance of the wires. It can be seen from the table that the most effective methods for converting a three-wire line to a direct current are iv and v methods. The use of the fifth method, involving the ground return, is not always possible, since the stray currents with this method of transmission cause corrosion of metal parts, partially or completely placed in the ground, for example pipelines or technological tanks [1]. Another undesirable phenomenon associated with stray currents is the disruption of the operation of signaling and control devices. Let us consider the fourth method of electricity transmission as an example. Dependence of the transmission line voltage capacity margin coefficient from the power factor of the load and the ratio of the reactive and active resistance of the power line wires when transferring it to a direct current through three wires with their sequential interchange is shown in Figure 2.

![Diagram](image)

**Figure 2.** Dependences of the power factor of power on the parameters of the transmission line and the load in the transmission of electricity by a current through three wires with their subsequent interchange

The dependence in Figure 2 is limited to two surfaces. The near-axis to the axis, this is the current limit of the power line, its level changes in accordance with the change in the power factor. The less power factor is the higher power capacity margin will be (formula 5). Physically, this is due to the exclusion of reactive currents from the line currents. The second plane reflects the change in the voltage margin of the line. The higher transmission line reactive resistance is the higher it will be. The physical meaning of the process is also understandable, in the transmission of electric power at a constant current in a steady state; there is no reactive voltage drop.
4. Conclusion

The article describes a method for determining the efficiency of the transfer of a three-phase, three-wire medium-voltage power transmission line to a direct current by the criterion of increasing the power capacity. Such analysis is possible due to the introduced power capacity factor, which takes into account the current and line voltage drop margin. The result of the analysis showed that the conversion of a three-wire line from AC to DC is not only an effective way to increase the transmission line capacity, but it can also offer various solutions. Comparison of the five ways of transferring the power line to direct current has shown that transmission line power capacity can be increased regardless of its parameters. With ground return, it is increased by 134%, and by 11% with the interchange of all three wires of line respectively. However, in spite of the enormous advantages of the method of DC transmission with return on the ground, which may seem the best solution, often its application may not be possible due to stray currents. The ways that involve switching wires require the installation of additional power devices in the system, which causes an increase in the cost of reconstruction of the power line, so this version of the transfer, too, cannot be considered as a universal solution.

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