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*Research Article*

# Techno-Economic Comparisons of HVAC and Simultaneous AC-DC Transmission

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Electric power consumption has been increasing rapidly across the globe; this increase specially accelerated in the last decade. Consequently, existing transmission lines are becoming overloaded beyond their power transfer capability. The inadequacy of the transmission lines has contributed to power interruptions and instability of the power system. Construction of new transmission lines can be a solution to mitigate these problems. However, to build the whole structure of a new transmission line, a huge investment is required. Besides this, environmental concerns would create further barriers that delay the accomplishment of the project. Therefore, the effective and quickest solution to tackle this problem is enhancing the power transfer capability and stability margin of existing transmission lines. This paper studied the techno-economic feasibility of converting an existing HVAC line into a simultaneous AC-DC power transmission system to enhance power transfer capability as well as to improve power system stability. Using the proposed method, the loadability of Tana Beles to Addis Ababa 400 kV, 476.2 km AC line has increased to more than double which is from 1091.66 MW to 2196.85 MW. The active power loss and corona loss evaluation of the two systems ensured that simultaneous AC-DC system is more efficient than HVAC system. It is also shown that the instability can be effectively improved by simultaneous AC-DC power transmission with fast DC power modulation. From the economic point of view, rather than constructing new HVAC line, converting existing HVAC line into simultaneous AC-DC transmission system has a price reduction of about 107,984,968.56 USD or 32.46% of the new HVAC line cost. Considering a 35-year project life cost analysis, it is observed that the life cycle cost of the simultaneous AC-DC transmission system is about 29.2% lower than the life cycle cost of a new 400 kV HVAC line. Thus, the designed simultaneous AC-DC power transmission system has better technical performance and also is less costly than constructing a new HVAC line.

## 1. Introduction

Ethiopia is a low-income country, with low electricity access and an inefficient power transmission network. Electricity access has increased by only 30% over the past 25 years and it reached 45% in 2018 [1]. There are over 350,000 registered customers who have been waiting for a connection for the past many years, of which about 50,000 have already paid the full-connection fee [2]. To respond to these demands, in parallel to increasing the generation capacity, Ethiopia Electric Power (EEP) has been undertaking expansion of transmission lines. The resultant cost of this transmission expansion over the 25-year period is estimated at 14.362 Billion US$ [3]. On the other hand, the existing long HVAC lines are not fully utilized to their thermal limits as a sufficient margin is kept against transient instability considerations. This situation demands the review of traditional power transmission theory and practices on the basis of new concepts that allow full utilization of existing transmission facilities without decreasing system availability and security. Reduction of such huge amount of expense for transmission expansion through full utilization of existing transmission facilities with improved power system stability forms the foundation of this study.

Tana Beles to Addis Ababa 400 kV transmission line is one of the transmission lines in Ethiopia that requires improvement in power transmission capacity and stability due to the fact that this transmission line connects the national grid to North-West region as well as to Tana Beles hydropower plant. In this region, in addition to regularly increasing power demand of the residents, huge industrial parks are under construction. These require a high uninterrupted power supply.

Simultaneous AC-DC transmission system provides the chance to load the transmission lines very close to their thermal limits. As a result of the additional DC power flow in the same HVAC lines, there is a substantial upgrade in the power transfer capability of the existing transmission line. Adding the DC power can result in a significance increment in the total power transfer due to the fact that the power transmitted by the DC link is independent of the angular difference between its AC terminals.

When DC is injected into AC and transmitted at the same time through the same transmission line, then the system is called simultaneous AC-DC transmission system. In operational point of view, this system is very much close to AC-DC parallel system and the difference is that simultaneous AC-DC has no separate DC line [4]. The advantage of adding the DC power can be taken of the fact that the power transmitted by the DC link is independent of the angular difference between its AC terminals and will essentially respond to what its control demands.

In the case of pure AC transmission system, the line reactance limits the power flowing capacity of the line and stability of the system. There are some other problems involved with the AC system such as switching surge causes severe transient overvoltage, high degree of corona loss, voltage rise at the receiving end due Ferranti effect, huge radio interference in communication system, and higher resistance due to skin effect [5].

To overcome these problems, existing high voltage long AC transmission line can be converted into HVDC transmission line. In this case of conversion, the line infrastructures are to be changed. The AC insulators must be replaced by DC insulators, and creep age distance and clearing distance must be increased. But, due to the geographical location of the existing line, in many cases, it becomes very difficult to change the line infrastructures.

In simultaneous AC-DC power transmission system, the conductors are allowed to carry DC current superimposed on AC current. AC and DC power flow independently and the added DC power flow does not cause any transient instability [6]. The DC power is obtained by converting a part of AC using line commutated 12-pulse rectifier bridge as used in conventional HVDC and injected to the neutral point of the zigzag connected secondary windings of sending end transformer. The converters are connected to AC buses by means of Y-Y and Y-D transformers. The same is reconverted to AC by the conventional line commutated 12-pulse inverter at the receiving end. The inverter bridge is connected to the neutral of zigzag connected winding of the receiving end transformer. The line conductors are connected between the zigzag secondary windings of the transformer at both ends.

This paper deals with the technical and economic comparisons between existing HVAC lines with the new simultaneous AC-DC transmission system. The technical comparison has been done by considering the power transfer capability and power system stability of the two systems. For economic comparison, the investment cost of the simultaneous AC-DC transmission system has been compared to the investment cost of a new HVAC transmission system that is capable to transfer the additional power obtained due to the conversion of existing HVAC transmission line into simultaneous AC-DC transmission. Besides the investment cost, life cycle cost of each of the transmission lines for 35 years is evaluated.

## 2. Literature Review

The interest to use the power transmission systems at their highest capacity with improved power system stability is mounting day by day. This is due to the dramatically increasing demand for electric power and the increasing cost of building new transmission lines along with the difficulties to obtain a new transmission corridor. Therefore, power system engineers and researchers are in continuous search for effective ways to exploit the full capacity of the existing transmission lines and to improve power system stability. The following are major studies conducted by different researchers on the issue of improving transmission capacity and power system stability using simultaneous AC-DC power transmission system.

Verma et al. [7] presented that one could transmit power through the installed high capacity AC voltage lines only up to a certain upper limit beyond which the system runs into transient instability. Consequently, the lines are never loaded up to their maximum thermal limit rather much less than that. This paper has also claimed that it is possible to load existing HVAC transmission lines to maximum values of their thermal limits by using simultaneous AC-DC Power transmission system.

Mohammad and Ahsan [4] proposed a mathematical model for simultaneous AC-DC power transmission system to analyze the behavior of a composite system in comparison with the original AC system. The load-carrying capability of an AC-DC composite system is compared with that of original AC system through numerical solution. In this paper, it is clearly observed that the loadability improvement increases with the increase in the value of DC voltage mix and obtained improvements for this system varies from 14.9% to 95.6% with the DC voltage mix variation from 10% to 50% respectively.

Rahman et al. [8] investigated the concept of simultaneous AC-DC power transmission system with a newly designed self-adaptive Voltage Dependent Control (VDC) procedure. With the model proposed in this paper, it is possible to load long AC transmission lines close to their thermal limits. The transmission lines and the conductors are allowed to carry the usual AC along with DC superimposed on it. The designed controller gives the feasibility of simultaneous AC-DC power transmission line to improve power transfer capability of transmission lines.

Venkatesh and Saraswathi [9] proposed a stability analysis model of simultaneous AC-DC power transmission system. The model presented in the paper has two independent components; one represents the loadability feature and the other represents the stability feature. The loadability model is based on the development of the correlation between the total power flow of simultaneous AC-DC system and that of pure AC system. The stability model is based on the equal area criterion principle. The model includes the SVPWM controller to generate PWM load line voltage which is equal to given load line voltage. The finding presented in this paper justifies that higher amount of transient stability (critical clearing time) is achieved in a simultaneous AC-DC system by exploiting the short-time overloading feature of converters after clearing the fault.

Alam et al. [10] studied maximum power flow analysis of simultaneous AC-DC power transmission system. The paper presented that, in simultaneous AC-DC system, power flow nature with respect to angle is a bit different from pure AC system. That is, initially power flow increases with the increase of transmission angle, and after a certain angle, the power flow decreases. It is seen that the maximum power flow occurs at an angle which is less than 90°. The impacts of line voltage, line reactance, and thermal limits of the conductor on the maximum power flow point are also clearly investigated in this paper. The analysis of the paper reveals that the angle at which the maximum power flow obtained depends on three parameters which are line voltage, line length, and thermal limit of the conductor.

Alam and Ahsan [11] presented an analytical expression for the objective function which is the function of two decision variables: power flowing capacity and critical clearing time. A mathematical model is developed for the optimal point of the objective function. It is observed that the loadability and stability improvements at the optimal points increase with the increase of DC voltage mix. The paper reveals that the rate of increase in loadability improvement is higher than that of stability improvement with the increase of DC voltage mix. At the highest point of DC voltage mix (49.5%), the optimal operation gives 61.87% and 49.71% of loadability and stability improvements, respectively.

As far as the author knowledge is concerned, the studies conducted on simultaneous AC-DC transmission line did not encompass detailed system power loss evaluation. Moreover, none of the studies that the authors come across on the internet provided a full-cost analysis of simultaneous AC-DC power transmission to show its economic feasibility. But this research forms a foundation to significantly improve both the power transfer capability and power system stability of Tana Beles to Addis Ababa 400 kV transmission using a detailed designed simultaneous AC-DC transmission system. The economic feasibility study of the model has been also conducted to evaluate its practicability and cost-effectiveness.

## 3. The Technical Aspect

*3.1. Power Transfer Capability of a Pure AC Line.* In this section, the loadability of Tana Beles to Sululta "ASTER 851," AAAC, twin bundle conductor, 400 kV, 50 Hz, 476.2 km double-circuit AC line has been evaluated. The transmission line parameters are provided as follows:

$$\begin{aligned} Z &= 0.0206 + j0.310127\ \Omega/\text{km/ph/ckt}, \\ Y &= 3.5386899 \times 10^{-6}\ \text{S/km/phase/ckt}, \\ I_{\text{Thermal}} &= 1.9381\ \text{kA}, \\ \text{Voltage} &= 400\ \text{kV}, \\ \text{Length} &= 472.6\ \text{km}. \end{aligned} \tag{1}$$

The reactance per phase of a single circuit = 0.310127 Ω/km/ph/ckt ×472.6 km = 146.5660 Ω/ph/ckt. However, the reactance per phase of double-circuit line is half of the reactance per phase of a single circuit. Therefore,

$$X = 73.2830\ \Omega/\text{Ph}. \tag{2}$$

The total power transfer through the double circuit line before conversion (i.e., original existing AC line) is [12]

$$P_{\text{total}} = \frac{E_S \times E_R \sin \delta_1}{X}. \tag{3}$$

$X$ is the transfer reactance per phase of the double circuit line and $\delta_1$ is the power angle between the voltages at the two ends. As mentioned above to keep sufficient stability margin, the angular difference at the two ends of a long transmission line does not often exceed 30° [7, 12–16].

For a long AC transmission line, a steady-state stability margin is generally taken as 50%, as the sufficient margin is kept against major disturbances like tripping of a major feeder, a three-phase fault, etc., and consequently in order to achieve transient stability [13]. The percent steady-state stability margin is [17]

$$\text{percent stability margin} = \frac{P_{\max} - P_{\text{limit}}}{P_{\max}} \times 100. \tag{4}$$

For 50% stability margin,

$$\begin{aligned} P_{\text{limit}} &= 0.5 P_{\max}, \\ \frac{E_S \times E_R \sin \delta_1}{X} &= 0.5 \frac{E_S \times E_R}{X}, \\ \delta_1 &= \sin^{-1} 0.5 = 30^\circ. \end{aligned} \tag{5}$$

As shown in Figure 1 [17], for a 50% stability margin, the load angle $\delta$ is 30°.

Thus the power angle of pure AC line has been taken as $\delta_1 = 30^\circ$. An approximate value of $\delta_1$ may also be computed from the loadability curve by knowing the values of Surge Impedance Loading (SIL) and transfer reactance $X$ of the line [12].

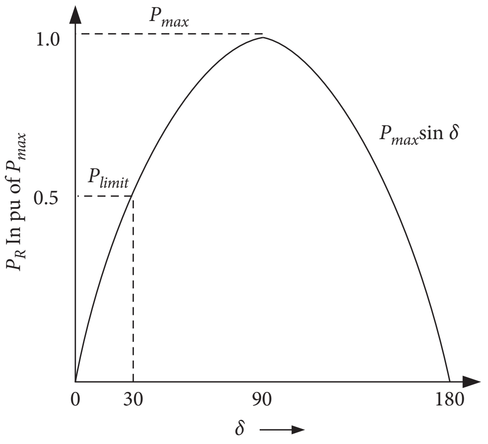

FIGURE 1: Power-angle curve.

$$P'_{\text{total}} = 2.M.\text{SIL}, \tag{6}$$

where $M$ is the multiplying factor and its magnitude decreases with the length of line. The value of $M$ can be obtained from the loadability curve.

As the sending end voltage of Tana Beles hydropower plant switchyard and receiving end voltage of Sululta substations are almost equal (≈400 kV), (3) can be rewritten as

$$\begin{aligned} P_{\text{total}} &= \frac{3V_{ph}^2 \sin\delta_1}{X} \\ \therefore P_{\text{total}} &= \frac{3 \times 230.94\,\text{kV}^2 \sin 30^\circ}{73.2830\,\Omega} \\ &= 1091.6573\,\text{MW}. \end{aligned} \tag{7}$$

The approximate value of AC current per phase per circuit of unconverted double circuit line can be computed as [12]

$$I_{ac} = \frac{V_{Ph}\sin\delta/2}{X} = \frac{230.94\text{kV}\sin 15}{73.2830\,\Omega} = 0.8156\,\text{kA}. \tag{8}$$

The conductor current 0.8156 kA is much below the current carrying capacity of twin bundle conductor $I_{\text{Thermal}} = 1.9381$ kA. So there is a huge current margin between the current carrying capacity of twin bundle "ASTER 851" AAAC and the current it carries at total power transfer through the double circuit line. This huge current margin will be covered by the DC current injected into the same conductor through zigzag transformer.

*3.2. Power Transfer Capability of Simultaneous AC-DC Power Transmission.* For this study, since there is no modification in the transmission line infrastructures, the peak phase voltage of the simultaneous AC-DC system should be equal to the peak phase voltage of the existing pure AC system. Therefore, the original AC voltage of the transmission line must be reduced as DC voltage is added such that peak voltage with respect to ground remains unchanged.

$$V_{\max} = V_d + \sqrt{2}V_a = \sqrt{2}V_{ph}. \tag{9}$$

To avoid the detrimental effect of unidirectional electric field, the simultaneous AC-DC voltage should be such that its produced electric field changes sign twice in a cycle and it can be ensured if $V_d/V_a < \sqrt{2}$ [14]. Under this condition, the higher creepage distance requirement for insulator discs as required for HVDC lines are not needed.

For Tana Beles to Addis Ababa, 400 kV AC transmission line, the new AC and DC transmission voltage level is determined as

$$\begin{aligned} V_a &= \frac{V_{ph}}{2} = \frac{230.94}{2} = 115.47\,\text{kV}, \\ V_d &= \frac{V_{ph}}{\sqrt{2}} = \frac{230.9\,\text{kV}}{\sqrt{2}} = 163.3\,\text{kV}, \end{aligned} \tag{10}$$

where $V_{LL}$ = line-to-line rms voltage of existing AC line and $V_{ph} = (V_{LL}/\sqrt{3})$ = per phase rms voltage of existing AC line.

The minimum AC voltage and maximum DC voltage for the new simultaneous AC-DC transmission line are found as 115.47 kV and 163.3 kV. The AC voltage $V_a$ has been increased from 115.473 kV to 120 kV and $V_d$ has been decreased from 163.3 kV to 160.0 kV to have two natural zero crossings in the voltage wave cycle. Thus for the conversion of existing Tana Beles to Addis Ababa 400 kV AC line into simultaneous AC-DC transmission line, per phase voltage of the AC component and the DC mix voltage level are selected as $V_a = 120$ kV and $V_d = 160$ kV, respectively.

The total power transfer through the simultaneous AC-DC transmission system is obtained by adding the AC power and DC power flow in the same conductor [12].

$$P_{\text{AC-DC}} = P_{\text{AC}} + P_{\text{DC}}, \tag{11}$$

where

$$\begin{aligned} P_{\text{AC}} &= \frac{3V_a^2 \sin\delta_2}{X}, \\ P_{\text{DC}} &= 2V_d I_d. \end{aligned} \tag{12}$$

The power angle $\delta_2$ between the AC voltages at the two ends of the simultaneous AC-DC transmission line can be increased to a high value. In pure AC system, the power transmission angle (from generator to infinite bus) cannot exceed 30° due to steady-state stability limitation, but by using simultaneous AC-DC transmission we can transmit AC power at a transmission angle around 70°–80° as transient stability is greatly enhanced by rapidly modulating DC power which is generally not possible for a pure AC line [16]. For a constant value of total power, $P_{\text{dc}}$ may be modulated by fast control of the current controller of DC power converters.

Taking a power angle which is similar to power angle of pure AC line $\delta_2 = 30^\circ$, the AC portion of the total power transfer through the simultaneous AC-DC transmission system is

$$P_{\mathrm{AC}} = \frac{3V_a^2 \sin \delta_2}{X} = \frac{3 \times 120\mathrm{kV}^2 \sin 30^\circ}{73.2830\,\Omega} = 294.75\,\mathrm{MW}. \tag{13}$$

Then AC current per phase per circuit of simultaneous AC-DC transmission system is

$$I_a = \frac{V_a \sin \delta/2}{X} = \frac{120\,\mathrm{kV} \sin 15}{73.2830\,\Omega} = 0.4238\,\mathrm{kA}. \tag{14}$$

The DC current superimposed on simultaneous AC-DC transmission conductor has been found using the following relation:

$$\begin{aligned} I_{\mathrm{dc-con}} &= \sqrt{I_{Th}^2 - I_a^2} = \sqrt{1.9381\,\mathrm{kA}^2 - 0.4238\,\mathrm{kA}^2} \\ &= 1.8912\,\mathrm{kA}. \end{aligned} \tag{15}$$

This current is below the DC current carrying capacity of "ASTER 851", All Aluminum Alloy (AAA) twin bundle conductor, and has been accepted. Each conductor of a line carries one-third of the total DC current along with AC current. Thus the total DC current $I_{\mathrm{dc}}$ is

$$I_{\mathrm{dc}} = 3 \times I_{\mathrm{dc-con}} = 3 \times 1.8912\,\mathrm{kA} = 5.6736\,\mathrm{kA}. \tag{16}$$

A master current controller (MCC) is used here to control the current order for converters online. It measures the conductor AC current, computes the permissible DC current in the conductor, and produces DC current order for inverters and rectifiers such that the conductor current never exceeds the thermal limit.

The DC part of the total power transfer through the simultaneous AC-DC transmission system is

$$P_{\mathrm{DC}} = 2V_d I_{\mathrm{dc}} = 2 \times 160\,\mathrm{kV} \times 5.6736\,\mathrm{kA} = 1815.55\,\mathrm{MW}. \tag{17}$$

And finally, the total power transfer through the simultaneous AC-DC transmission system is the summation of AC power and DC power flow in the same conductor.

$$\begin{aligned} P_{\mathrm{AC-DC}} &= P_{\mathrm{AC}} + P_{\mathrm{DC}} \\ &= 294.74\,\mathrm{MW} + 1815.55\,\mathrm{MW} = 2110.3\,\mathrm{MW}. \end{aligned} \tag{18}$$

Similarly, the power transfers of the converted simultaneous AC-DC line at various transmission angles have been computed and the result summaries are presented in Table 1.

It has been seen from the computation result that the maximum power transfer by simultaneous AC-DC line occurs at a power angle of 60°. The same amount of power transferred through the conventional double circuit HVAC line would require a power angle of 90°, which is beyond the safe limit for power angle. The corresponding conductor current (Iph/ckt) is 2.23 kA. This current value is also much beyond the current carrying capacity of "ASTER 851" AAAC twin bundle conductor.

## 4. Transmission System Losses

### *4.1. The Power Loss due to Corona for HVAC.*

According to Peek's formulas [18], the power loss due to corona under fair weather conditions can be expressed as

$$\begin{aligned} P_{ufwc} &= \frac{K}{\delta}\,(f + 25)\sqrt{\frac{R}{d}}\left(\frac{V_L}{\sqrt{3}} - E_{dcv}\right)^2 \\ &\quad \times 10^{-5}\ \mathrm{kW/km/phase}, \end{aligned} \tag{19}$$

where $K$ = fixed constant = 243, $p$ = atmospheric pressure, $t$ = temperature of the surroundings, $R$ = radius of conductor, $f$ = frequency, $V_L$ = line-to-line voltage, $E_{dcv}$ = disruptive critical voltage, and $\delta = 0.386P/(273 + t)$ = air density correction factor.

Based on Peek's sample table, the disruptive critical voltage can be mathematically expressed as [18]

$$E_{dcv} = E\delta m_o \mathrm{GMR}_{\mathrm{bundle}} \log \frac{\mathrm{GMD}}{\mathrm{GMR}_{\mathrm{bundle}}}, \tag{20}$$

where $E$ is the Conductor Surface Voltage Gradient and is mathematically expressed as [18]

$$E = \frac{V}{\sqrt{3}}\,\frac{\beta}{r\,\ln\left(\left(a/R_e\right)\left(2h/\sqrt{4h^2 + a^2}\right)\right)}, \tag{21}$$

where

$$\begin{aligned} \beta &= \frac{(1 + (n-1)(r/R))}{n}, \\ R_e &= Rn\sqrt{\frac{nr}{R}}, \\ R &= \frac{s}{2\,\sin(\pi/n)}. \end{aligned} \tag{22}$$

For the existing 400 kV HVAC transmission line, the following data have been considered as given in Table 2 to calculate the disruptive critical voltage and thereby the power loss due to corona.

For bundle conductor, the disruptive critical voltage can be found using (20).

$$\begin{aligned} E_{dcv} &= E\delta m_o \mathrm{GMR}_{\mathrm{bundle}} \log \frac{\mathrm{GMD}}{\mathrm{GMR}_{\mathrm{bundle}}} \\ &= 17.15 * 0.8965 * 0.85 * 7.7 * \log 131.3 = 213.21\,\mathrm{kV}. \end{aligned} \tag{23}$$

Thus, the power loss due to corona of existing 400 kV HVAC transmission line under fair weather condition is found as

Table 1: Computed results at various transmission angles.

| Transmission angle ($\delta_2$) | 30° | 45° | 60° | 75° | 80° |
|---|---|---|---|---|---|
| AC current $I_a$ (kA) | 0.4238 | 0.6266 | 0.8187 | 0.9968 | 1.0525 |
| Conductor DC current $I_{\text{dc-con}}$ (kA) | 1.8912 | 1.8340 | 1.7566 | 1.6621 | 1.6274 |
| DC current $I_d$ (kA) | 5.6763 | 5.5020 | 5.2698 | 4.9863 | 4.8822 |
| AC power $P_{\text{AC}}$ (MW) | 294.75 | 416.84 | 510.52 | 569.41 | 580.54 |
| DC power $P_{\text{DC}}$ (MW) | 1815.55 | 1760.64 | 1686.33 | 1595.616 | 1562.30 |
| Total power $P_{\text{AC-DC}}$ (MW) | 2110.03 | 2177.48 | 2196.85 | 2165.02 | 2142.84 |
| % power upgrade | 93 | 99 | 100 | 98 | 96 |

Table 2: HVAC corona loss calculation parameters.

| Symbol | Parameter | Value |
|---|---|---|
| $V$ | Rated voltage | 400 kV |
| $h$ | Height of conductor above ground | 3500 cm |
| $a$ | Phase spacing | 850 cm |
| $r$ | Radius of conductor | 1.9 cm |
| $\delta$ | Air density correction factor at $t = 40°$ and $P = 727$ torr | 0.8965 |
| $S$ | Distance between component conductor centers | 40 cm |
| $n$ | Number of component conductors in bundle | 2 |
| $\beta$ | Factor for multiple conductors | 0.5475 |
| $R$ | Outside radius of bundle | 20 cm |
| $R_e$ | Equivalent radius of bundle conductor | 17.43 cm |
| $E$ | Conductor surface voltage gradient | 17.15 kV/cm |
| $m_o$ | Irregularity factor for disruptive critical voltage [18] | 0.85 |
| GMD | Geometric mean distance for a three-phase line | 10.109 m |
| $\text{GMR}_{\text{bundle}}$ | Geometric mean radius of bundle conductors | 0.077 m |

$$\begin{aligned} P_{ufwc} &= \frac{K}{\delta}(f+25)\sqrt{\frac{R}{d}}\left(\frac{V_L}{\sqrt{3}} - E_{dcv}\right)^2 \times 10^{-5}\ \text{kW/km/phase} \\ &= \frac{243}{0.8965}(50+25)\sqrt{\frac{20}{850}}(230.9 - 213.21)^2 \times 10^{-5}\ \text{kW/km/phase} \\ &= 9.76\ \text{kW/km/phase}. \end{aligned} \tag{24}$$

For 3-phase line,

$$P_{ufwc} = 3 * 9.76\ \text{kW/km/phase} = 29.28\ \text{kW/km}. \tag{25}$$

For a total length of the line,

$$P_{ufwc} = 29.28\ \text{kW/km} * 476.2\ \text{km} = 13.943\ \text{MW}. \tag{26}$$

For double circuit three-phase transmission line, the total corona loss is

$$P_{ufwc} = 13.943\ \text{MW} * 2 = 27.866\ \text{MW}. \tag{27}$$

*4.2. The Power Loss due to Corona for Simultaneous AC-DC Transmission.* For simultaneous AC-DC transmission, the total coronal loss is the summation of the corona losses due to AC and DC voltage portion of the transmission line. Thus for the AC part, we can calculate corona loss using Peek's formulas.

Corona loss due to the AC component of the simultaneous AC-DC transmission system is computed by changing the line voltage of the transmission line to 208 kV and keeping similar the rest parameters of the existing transmission line. This is due to the fact that simultaneous AC-DC transmission system scheme demands no alterations of conductors, insulator strings, and towers of the original line.

$$\begin{aligned} E &= 120\ \text{kV} \times \frac{\beta}{r \ln\left((a/R_e)\left(2h/\sqrt{4h^2 + a^2}\right)\right)} \\ &= 8.9127318\ \text{kV}. \end{aligned} \tag{28}$$

The disruptive critical voltage can be found as

$$\begin{aligned} E_{dcv} &= E\delta m_o \text{GMR}_{\text{bundle}} \log \frac{\text{GMD}}{\text{GMR}_{\text{bundle}}}, \\ &= 8.91273 * 0.8965 * 0.85 * 7.7 * \ \log 131.3 \\ &= 110.804 kV. \end{aligned} \tag{29}$$

The power loss due to corona for the AC portion of simultaneous AC-DC transmission system under fair weather conditions can be found as

$$P_{ufwc} = \frac{K}{\delta}\,(f+25)\sqrt{\frac{R}{d}}\left(\frac{V_L}{\sqrt{3}} - E_{dcv}\right)^2 \times 10^{-5}\ \text{kW/km/phase}$$
$$= \frac{243}{0.8965}\,(50+25)\sqrt{\frac{20}{850}}(120-110.804)^2 \times 10^{-5}\ \text{kW/km/phase}$$
$$= 2.637\ \text{kW/km/phase}. \tag{30}$$

For 3-phase line,

$$P_{ufwc} = 3 * 2.637\ \text{kW/km/phase} = 7.911\ \text{kW/km}. \tag{31}$$

For a total length of the line,

$$P_{ufwc} = 7.911\ \text{kW/km} * 476.2\ \text{km} = 3.767\ \text{MW}. \tag{32}$$

For simultaneous AC-DC transmission, the total corona loss due to AC component in the double circuit is

$$P_{ufwc} = 3.767\ \text{MW} * 2 = 7.534\ \text{MW}. \tag{33}$$

The approximate calculation of corona losses in DC bipolar lines can be expressed as [19]

$$P_{\text{loss}} = 2V\left(1 + \frac{2}{\pi}\tan^{-1}\frac{2H}{S}\right) \times 0.2 \times n \times r \times 2^{0.25\,(g-g_o)} \times 10^{-3}\ \text{kW/circuit/km}, \tag{34}$$

where $V =$ the pole to ground voltage in kV, $n =$ the number of subconductors, $r =$ the radius of each subconductor in cm, $g =$ maximum conductor surface gradient at operating voltage (in kV/cm), $g_o = 22\ \delta$ kV/cm where $\delta =$ relative air density, $H =$ mean height of conductor, and $S =$ pole spacing.

The maximum gradient $g$ is given by [20]

$$g = \frac{[1+(n-1)(r/R)]V}{nr * \ \ln\left(2H/\left(nrR^{n-1}\right)^{1/n}\left[(2H/S)^2+1\right]^{1/2}\right)}, \tag{35}$$

where $R =$ radius of the bundle in cm.

Using (34), the corona loss of simultaneous AC-DC line due to DC portion of the transmission is

$$P_{\text{loss}} = 2 \times 160\left(1 + \frac{2}{\pi}\tan^{-1}\frac{2\times 43.5}{8.1}\right) \times 0.2 \times 2 \times 1.9 \times 2^{0.25\,(19.76-19.72)} \times 10^{-3}\ \text{kW/pole/km}$$
$$= 0.4753\ \text{kW/pole/km}, \tag{36}$$

where $g$ = 19.7565 kV/cm, $g_o$ = 19.723 kV/cm, $H$ = 43.5 m, $S$ = 8.1 m, and $V$ = 160 kV.

For a total length of the simultaneous AC-DC transmission line, the corona loss due to DC is

$$P_{\text{loss}} = 0.4753\ \text{kW/pole/km} \times 472.6\ \text{km} = 224.63\ \text{kw/pole}. \tag{37}$$

Since the simultaneous AC-DC transmission line consists of 3 lines per pole, the total corona loss of the three bipolar lines (i.e., 6 poles) is

$$P_{\text{loss}} = 224.63\ \text{kW/pole} \times 6\ \text{pole} = 1.35\ \text{MW}. \tag{38}$$

Therefore, the total corona loss of simultaneous AC-DC transmission line is

$$P_{\text{total-loss}} = P_{ufwc} + P_{\text{loss}} = 7.534\ \text{MW} + 1.35\ \text{MW}$$
$$= 8.884\ \text{MW}. \tag{39}$$

*4.3. Active Power Loss of HVAC.* The existing 400 kV HVAC transmission system has a line rating of 1341 MVA. Thus, the line current per phase is 1.9355 kA. The AC resistance of "ASTER 851" AAAC is 0.0419 Ω/km. Since it is bundled with 2 subconductors, its effective resistance amount is reduced to 0.02095 Ω/km. The active power loss of each circuit will be

$$P = I^2 \times R \times L = 3 \times 1.9355^2 \times 0.02095 \times 476.2$$
$$= 112.12\ \text{MW}, \tag{40}$$

where $I =$ line current, $R =$ AC resistance of the conductor, and $L =$ length of the transmission line.

*4.4. Active Power Loss of the Simultaneous AC-DC Line.* For simultaneous AC-DC transmission, the total active power loss is the summation of AC power loss and DC power loss because the conductor AC and DC resistances are different. To calculate AC active power loss of each circuit, AC resistance of the twin bundle conductor 0.02095 Ω/km is considered.

$$P_{\text{ac-loss}} = I^2 \times R \times L = 3 \times 0.8187^2 \times 0.02095 \times 476.2$$
$$= 20\ \text{MW}, \tag{41}$$

whereas the DC resistance of the "ASTER 851" AAAC is 0.039 Ω/km; thus, DC resistance of the bundle conductor is reduced to 0.0195 Ω/km.

$$P_{\text{dc-loss}} = I^2 \times R \times L = 3 \times 1.7566^2 \times 0.0195 \times 476.2 = 85.95\,\text{MW}. \tag{42}$$

The total active power loss of each circuit of the designed simultaneous AC-DC transmission line is

$$P_{\text{total-loss}} = P_{\text{ac-loss}} + P_{\text{dc-loss}} = 20\,\text{MW} + 85.95\,\text{MW} = 105.95\,\text{MW}. \tag{43}$$

The total power losses due to corona and $I^2R$ are calculated above. The corona loss for simultaneous AC-DC system is the summation of corona loss due to AC and DC. It is obvious that the corona losses are significantly lower in the case of DC. Also, the corona loss due to AC is minimized since the AC voltage level of the simultaneous AC-DC transmission line is reduced from 400 kV to 207.8 kV. Thus, the overall corona loss of the proposed system has been lower than the existing system. The total corona loss of the HVAC transmission line is 27.66 MW, and for the simultaneous AC-DC transmission line, the total corona loss is 8.844 MW. So that the corona effects such as radio interference, television interference, and audible noise become more severe in the HVAC line than the simultaneous AC-DC line, and thus the HVAC transmission line has an impact on the environment.

The simultaneous AC-DC transmission line has an advantage over HVAC regarding $I^2R$ loss. The active power loss of each circuit of the HVAC transmission line is 112.12 MW and, for the simultaneous AC-DC transmission line, it is 105.68 MW.

## 5. Transient Stability Improvement

The transient stability criteria include the ability of the system to withstand a three-phase fault at critical locations such as near the heavily loaded generator bus at the line carrying large amount of power in case of AC transmission and near the inverter in case of HVDC [4].

During the fault condition, the transmission line does not transmit any power. That is, the electrical power consumption is zero. However, during this period, the mechanical system continues to produce energy, and due to this excess mechanical energy, the whole system may be unstable. To attain stable conditions, after clearing the fault, the electrical system must consume an additional amount of energy which is equal to the excess mechanical energy generation. That is, for the stability of the system after the occurrence of the fault,

$$\begin{aligned}&\text{excess mechanical energy generation during the existence of the fault}\\&\quad= \text{excess electrical energy consumption right after clearing the fault.}\end{aligned} \tag{44}$$

During the transient period after the clearance of the fault in simultaneous AC-DC system, AC power supply is kept off and the DC power flow is increased to produce a retarding torque to bring back the generator to its normal speed. HVDC current regulator having a very fast control facility is employed for this purpose. AC circuit breakers are then switched on and the AC power flow is resumed at its prefault value without any oscillation. The power swing is low and the system is optimally damped almost at the end of the first swing. If the augmentation facility of HVDC power controller is limited, proper governor control of remote generators may be used to reduce the total power flow and to maintain the DC power flow only. After the system becomes stable, the AC power supply is switched on and the power oscillation is minimized with HVDC power controller.

The main advantage of simultaneous AC-DC system is that in case of emergency, after clearing a transient fault, power transmission can be increased by increasing the DC power flow through converter control for a shorter period of time. Note that, converters can be overloaded up to 50% of their rated capacity for a shorter duration [4].

## 6. Economic Aspect

The cost of a transmission line includes the investment and operational costs. The investment cost includes costs of Right of Way (RoW), transmission tower, conductors, insulators, labor, and terminal equipment's. The operational costs include mainly the cost of losses.

The simultaneous AC-DC transmission system is designed to transfer 2196.85 MW power by injecting DC power in the existing HVAC circuit. The power upgrading factor is 2.0 times of the existing capacity and 1105 MW extra power is supplied through the simultaneous AC-DC transmission system. Thus the economic comparison lays between the costs converting existing HVAC line into simultaneous AC-DC transmission system with the costs of new double-circuit 400 kV HVAC transmission line which is able to transmit the additional 1105 MW power attained by the conversion.

*6.1. HVAC Investment Cost.* For the HVAC transmission line project, the investment cost includes the capital investment required for the actual infrastructure (i.e., Right of Way (RoW), towers, conductors, insulators, and terminal equipment), substation upgrading, and costs incurred electrical power losses.

Tana Beles to Addis Ababa 400 kV power transmission line connects Tana Beles hydropower plant to Sululta substation (national grid) through Bahir Dar and Debre Markos substations. The power transmission has a length of about 67 km from Tana Beles hydropower plant switchyard to Bahir Dar II substation, about 193.77 km from Bahir Dar II substation to Debre Markos substation, and about 215.43 km from Debre Markos substation to Sululta substation.

The investment costs of substation upgrade and double circuit 400 kV AC line are provided below. The cost includes supply, transportation, insurance and erection, and test and commission costs. During calculation of transmission and substation extension investment cost, the price schedules of different local and international project have been taken. Table 3 shows the investment cost of Tana Beles to Sululta new 400 kV transmission line and the corresponding substation upgrade cost.

Table 4 shows the total budget required for the compensation payment. The total budget required for the compensation payment, i.e., for loss of crops, trees, and residential houses due to RoW, tower foundation, access roads, etc., has been calculated by taking the EEP (Ethiopia Electric Power) compensation payment data of existing Tana Beles-Sululta 400 kV transmission line. For adaption of the EEP compensation payment data, the necessary economic assumptions such as inflations are considered.

Therefore, the investment cost for constructing the new 400 kV HVAC line is the summation of the project cost and compensation cost, which is 332,620,351.37 USD.

*6.2. Simultaneous AC-DC Investment Cost.* For the proposed simultaneous AC-DC transmission system, since existing transmission infrastructures are used, the investment costs of converter stations and zigzag transformers have been calculated. During cost calculation, different assumption from local and international HVDC converter station project has been taken. The inflation as well as the countries experience to estimate the cost is also taken into account. Table 5 shows the details of simultaneous AC-DC investment cost.

Figure 2 shows the project cost comparisons of new HVAC and simultaneous AC-DC transmission. Thus, from the investment point of view, rather than constructing new HVAC line, converting 476.2 km 400 km transmission line into and simultaneous AC-DC transmission has price reduction of 107,984,968.56 USD.

Table 3: 400 kV double circuit HVAC investment cost

| Item | Total cost (USD) |
|---|---|
| Transmission line cost from Tana Beles to Sululta | 255,065,116.51 |
| Tana Beles switchyard upgrading | 6,238,633.51 |
| Sululta substation upgrading | 13,439,557.28 |
| Total cost | 274,743,307.30 |
| Engineering and administration (5% of the total cost) | 13,737,165.37 |
| Total project cost | 288,480,472.67 |
| Physical contingency (5% of the total cost) | 14,424,023.63 |
| Price contingency (10% of the total project cost) | 28,848,047.27 |
| Grand total | 331,752,543.56 |

Table 4: Compensation cost required.

| S/n | Compensation payment route | Total cost (Birr) |
|---|---|---|
| 1 | Tana Beles-Bahir Dar | 7,014,625.58 |
| 2 | Bahir Dar-Debre Markos | 12,058,020.3 |
| 3 | Debre Markos-Sululta | 15,724,711.8 |
| Total cost (Birr) | | 34,797,357.68 |
| Total cost (USD) (1$ = 40.098 (detailing 180 days of USD to ETB historical data from 19/11/2020 to 16/05/2021)) | | 867,807.81 |

Table 5: Simultaneous AC-DC transmission system investment cost.

| Item | Total cost (USD) |
|---|---|
| Converter station and zigzag transformer cost | 186,033,443.32 |
| Engineering and administration (5% of the total cost) | 9,301,672.17 |
| Total project cost | 195,335,115.49 |
| Physical contingency (5% of the total cost) | 9,766,755.774 |
| Price contingency (10% of the total project cost) | 19,533,511.55 |
| Grand total | 224,635,382.81 |

## 7. Transmission Line Life Cycle Cost

When costs are considered while building a transmission line, the initial investment costs based on equipment selection, procurement, and installation are not the only criteria that should be considered. Overall life cycle costs of electrical infrastructure also need to be considered such as operation, maintenance, losses, and environmental impact.

Life cycle costs are the total cost of ownership of an asset or facility from inception to the end of its useful life. Life cycle costs provide the information to compare project alternatives from the perspective of the list cost of ownership over the life of the project.

Money has a time value because of the existence of interest. If an investment is made, the principal will compound each year as interest is paid again and again on the principal plus the interest earned. The result is that the future value of an investment is worth more than its present value. One widely accepted approach of comparing options over their life cycles is to bring all costs to a single point in time the present. This can be done by applying present value (PV) factors to all costs to provide an overall PV or NPV (Net Present Value).

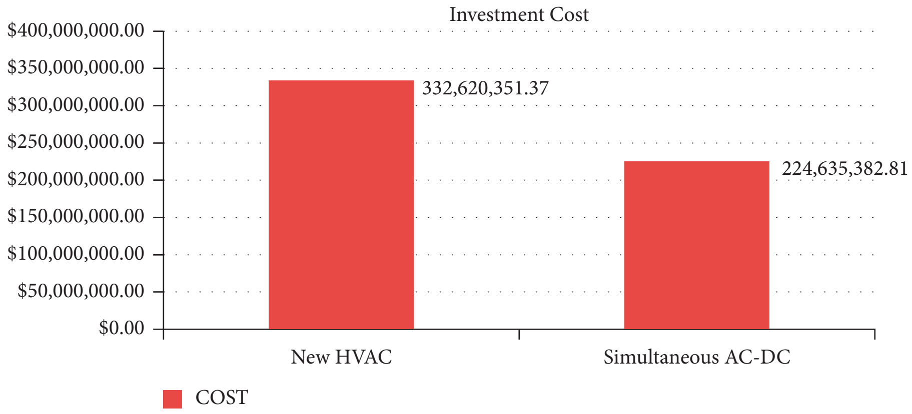

Figure 2: Investment cost comparisons.

Table 6: Data used for life cycle cost calculation.

| Item | Value |
|---|---|
| Discount rate-base | 10% |
| Discount rate-low, high | 8%, 12% |
| Economic lifetime | 35 year |
| Operation and maintenance cost | 2% of investment cost |
| Operation and maintenance cost escalation factor | 4.0% |
| Capital recovery factor | 14.1% |
| Energy cost escalation factor | 1.2% |
| Insurance and interim replacement | 0.5% of investment cost |
| Demand growth from 2017 up to 2030 | 14% |
| Demand growth from 2031 up to 2039 | 7% |
| Energy cost | 0.03973 $/kwh |
| Energy generation cost | 0.05 $/kwh |
| Load factor | 0.57 |
| Loss factor | 0.38 |

Table 6 shows the economic assumptions used in the life cycle cost calculation of both transmission lines [20–23].

*7.1. Annual Cost of Losses.* In a transmission line, electrical losses are unavoidable phenomenon; the loss is always there whereever the line is energized with any load. The economical assessment of the power losses plays a significant role in the overall cost evaluation during the operational life of a transmission line. The cost of losses depends on the resistance of the conductors, current levels, and dollar value of power and energy. The annual loss cost is determined by (45) [20, 22]. The loss calculations are based on peak load current for a given line and a system loss factor.

$$L_C = \frac{3RI^2 \times 8760}{1000} L_D^2 \left(L_o E_C + \mathrm{EGC}\right), \qquad (45)$$

where $L_O$ = cost of losses ($/km/year), $R$ = conductor resistance (ohms/phase/km), $I$ = peak load current on the line (amps), $L_D$ = annual load factor, $L_O$ = annual loss factor, $E_C$ = annual average cost of energy ($/kWh), and EGC = annual average cost of generation ($/kWh).

Load factor (electrical) is the average power divided by the peak power over a period of time. In the electricity industry, load factor is a measure of the output of a power plant compared to the maximum output it could produce.

Loss factor is the ratio of average and peak losses during a designated time period. This factor represents the level of uniformity of the loss over the given period of time, usually one year. Since the loss varies with the square of the load, as the load increases, the loss factor increases by the square of the load increase, and the loss cost increases accordingly.

The discount rate: the interest rate is used in discounted cash flow analysis to determine the present value of future cash flows. The discount rate takes into account the time value of money (the idea that money available now is worth more than the same amount of money available in the future because it could be earning interest).

*7.2. Present Value of an Annually Recurring Loss Cost.* The formula used for finding the present value (PV) of an annually recurring loss cost (LC) is as follows [20]:

$$\mathrm{PV} = L_C\left(\frac{(1+d)^N - 1}{d(1+d)^N}\right), \qquad (46)$$

Table 7: Annual loss cost.

| | Loss cost (USD/km/year) | PV (USD/km) |
|---|---|---|
| Simultaneous AC-DC line | 40,745.92 | 392,960.13 |
| New HVAC line | 43,532.25 | 419,831.94 |

where PV = is the present value of an annually recurring loss cost, $L_C$ = loss cost, $d$ = discount rate, and $N$ = economic life time of the transmission line.

Taking the data given on Table 6 and considering the peak load current of the two systems, the annual loss of cost for HVAC and simultaneous AC-DC line has been calculated. The results found from the calculation are provided in Table 7.

From the loss cost analysis, the unit loss cost over a 35-year period for simultaneous AC-DC is 392,960.13 USD/km and for HVAC is 419,831.94 USD/km. Over a 35-year period, the loss cost of simultaneous AC-DC is around 187,127,613.91 USD and for HVAC 199,923,969.83 USD. Therefore, 12,796,355.92 USD can be saved over the life cycle of the transmission lines.

Considering a 35-year project, life cost analysis calculation is performed for both new 400 kV HVAC line and simultaneous AC-DC line. It is observed that the life cycle cost of new 400 KV HVAC is 4,378,521.47 USD/km and 3,038,309.25 USD/km for simultaneous AC-DC line.

The life cycle cost of the new 400 kV HVAC line is about 41.14% higher than that of the simultaneous AC-DC. When we compare the loss cost, still the new HVAC line is 6.84% higher than the simultaneous AC-DC line. By considering all economic cost comparison, a simultaneous AC-DC investment is more advantageous.

## 8. Conclusion

This paper demonstrates the technical and economic feasibility of simultaneous AC-DC power transmission. It has been shown that for the simultaneous AC-DC line length of 476.2 km, there is a substantial increase in the loadability of the line. The loadability of the line is increased from 1091.66 MW to 2196.85 MW which is about 100% power upgrade.

The total corona loss of the HVAC transmission line is 27.66 MW, and for the simultaneous AC-DC transmission line, the total corona loss is 8.844 MW. So the corona effects such as radio interference, television interference, and audible noise become more severe in the HVAC line than the simultaneous AC-DC line, and thus the HVAC transmission line has an impact on the environment. The simultaneous AC-DC transmission line has also an advantage over HVAC regarding to $I^2R$ loss. The active power loss of each circuit of the HVAC transmission line is 112.12 MW, and for the simultaneous AC-DC transmission line, it is 105.68 MW.

From the economic point of view, since there is no alternation in conductors, insulator strings, and towers of the original transmission line, the investment cost of simultaneous AC-DC system has been significantly reduced. The investment cost for constructing new double-circuit 400 kV AC line to transmit the additional 1105 MW power is about 332,620,351.37 USD. The simultaneous AC-DC system costs 224,635,382.81 USD. The price reduction is about 107,984,968.56 USD. Thus, from the investment point of view, the total reduction of cost is about 32.46%.

Considering a 35-year project life cost analysis, it is observed that the life cycle cost of new 400 kV HVAC is 3,676,031.92 USD/km and 2,604,581.43 USD/km for simultaneous AC-DC line. The life cycle cost of the simultaneous AC-DC transmission system is about 29.2% lower than the life cycle cost of the new 400 kV HVAC transmission line.

From the loss cost analysis, the unit loss cost over a 35-year period for simultaneous AC-DC is 392,960.13 USD/km and for HVAC is 419,831.94 USD/km. Over a 35-year period, the loss cost of simultaneous AC-DC is around 187,127,613.91 USD and for HVAC 199,923,969.83 USD. Therefore, 12,796,355.92 USD can be saved over the life cycle of the transmission lines. The loss cost of the new HVAC line is 6.84% higher than the simultaneous AC-DC line.

Considering both technical and economic aspects, simultaneous AC-DC power transmission system is more economical and efficient for upgrading transmission line capacity and improves power system stability.

## Data Availability

All data are included within this manuscript.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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