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Technical and Economic Assessment of VSC-HVDC Transmission Model: A Case Study of South-Western Region in Pakistan

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Abstract: The southwestern part of Pakistan is still not connected to the national grid, despite its abundance in renewable energy resources. However, this area becomes more important for energy projects due to the development of the deep-sea Gwadar port and the China Pakistan Economic Corridor (CPEC). In this paper, a voltage source converter (VSC) based high voltage DC (HVDC) transmission model is proposed to link this area to the national gird. A two-terminal VSC-HVDC model is used as a case study, in which a two-level converter with standard double-loop control is employed. The proposed model has a capacity of transferring bulk power of 3500 MW at 350 kV from Gwadar to Matiari. Furthermore, the discounted cash flow analysis of VSC-HVDC against the HVAC system shows that the proposed system is economically sustainable. The outcomes of this study reveal that the implementation of this project can bring economic stability and energy security in the southwestern region.

Keywords: technical assessment; voltage source converter; power transmission; discounted cash flow; energy security

1. Introduction

The demand for power supply in Pakistan is growing exponentially in domestic and industrial sectors [1], and thus, the country has faced severe energy crises in recent times. The two primary sources for electricity production in Pakistan, i.e., hydropower and fossil fuels, have been adopted for long, but cannot meet the increasing demands of the country. Currently, Pakistan has been taking initiatives to utilize renewable energy to bridge the gap between demand and supply effectively. However, the weak, old transmission system is still a significant hindrance to uphold the rapidity with growing energy production supply [2,3].

Pakistan has five provinces, namely, Gilgit Baltistan, Khyber Pakhtunkhwa (KPK), Sindh, Balochistan, and Punjab. Among these, Balochistan province with 347,190 km^2 area is the largest one, consisting of approximately 45% land of the country. Additionally, the tremendous renewable energy resources, like wind and solar, are available to their vast extent and potential in the southwestern area of Balochistan province. Monthly mean solar radiations ranged from 153.61–281.94 W/m^2 throughout the year, while the total wind power generation capacity in this area is about to 146 GW [4,5].

In this region, the population density is comparatively low due to the scarcity of natural resources, and only 6% of the population is residing in this region. Possibly, the one most haunting reason for neglecting this high potential energy-producing area is its unstable and uncertain bordered geographical location that is far away from the main grid. Keeping in view the power production potential of this area along with the rapidly increasing energy crisis in Pakistan, it is indispensable to discover cheap and high potential renewable energy sources like wind power. Whereas Punjab and Sindh provinces are the most populated areas of the country, approximately holding 76% of the total population [6].

Moreover, to date, there is no available transmission line from these areas to the main national grid. Figure 1 shows the existing transmission network in different regions of the country [7]. Despite substantial available power potential, still, Pakistan is depended on importing the power from Iran to provide electricity in southwestern areas. Due to the lack of power generation projects and no available transmission network, these areas are still not connected with the main national gird.

On the other hand, China Pakistan Economic Corridor (CPEC) projects and Saudi Arabia investment in the oil sector this area becomes more important for the development of new power projects and the setup of a new transmission line. Exploiting these energy resources not only helps the CPEC and other future projects, but also fulfills the power demand of the country. Renewable energy department authority and Pakistan national transmission and dispatch company have evaluated that the transmission network of the country is overloaded. Therefore, new transmission lines are required to meet the power supply demand across the country.

Generally, power is transmitted from the generation side to the main grid. There are two possible ways to transmit the power to the national grid, i.e., high voltage alternating current (HVAC) and high voltage direct current (HVDC). HVDC is proposed to be suitable for transmitting bulk power over long distances in comparison to HVAC. HVDC transmission lines based on voltage source converters (VSC) or line commutated converters (LCC) both are considered as a viable alternative than HVAC [8–10]. Furthermore, due to the advancement of technologies and cost comparison over a long distance, the HVDC systems are considered economically sustainable. Detailed analysis includes the technical and economic comparison of HVDC and HVAC systems that are elaborated in [8].

Additionally, the recent development in DC circuit breaker technologies and reliable protection schemes makes the VSC-HVDC transmission links more promising [11,12]. The concept of a hybrid DC circuit breaker with fault limiting capacity for VSC-HVDC transmission network is proposed in [12], which can rapidly isolate the fault within permissible limits of fault current. Likewise, a novel multi-terminal HVDC protection scheme based on artificial neural network (ANN) and high-frequency components from fault current signals is utilized to detect, classify, and locate overhead line faults accurately. This includes high impedance faults without compromising the accuracy of fault location [13,14]. Based on the consecutive data window method (CDWM), another protection scheme is introduced for the VSC-HVDC transmission system, which is capable of prompt fault detection and isolation [15,16]. Furthermore, a new theory for locating line fault in the transmission system is presented in [17], which has thoroughly presented the theoretical aspects, and simulations for the line faults. With ongoing improvements in protection technology, the authors believe this will be sufficiently supportive of the proposed transmission line.

There are various factors, such as technical considerations, economic aspects, and legal requirements, that are critical in the planning of new transmission lines. A technical consideration transmission line based on VSC-HVDC and economic aspects are presented in this paper. It is hoped that the outcomes of this study can help to understand the importance of the new proposed VSC-HVDC based transmission line in this area and provide a base for the further academic research in this field.

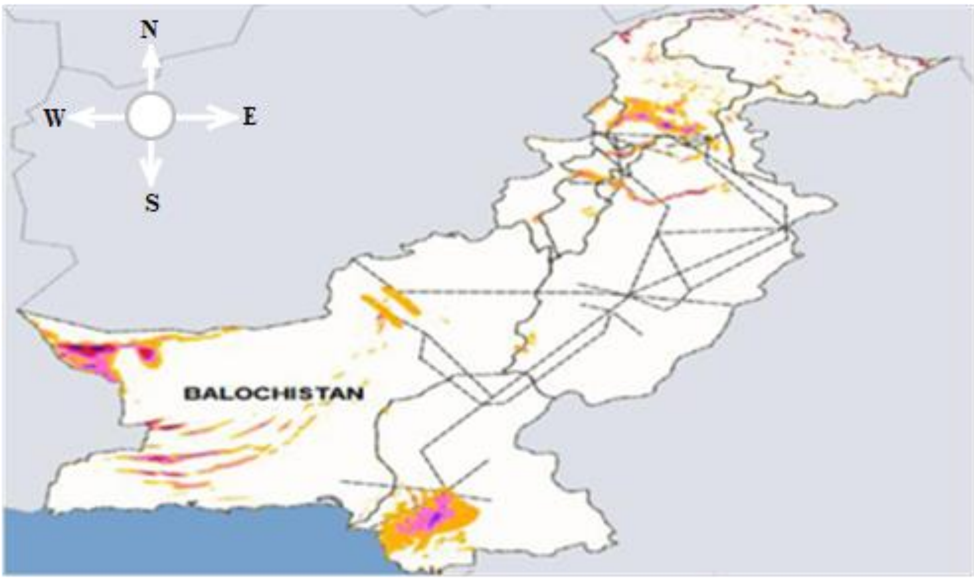

Figure 1. Transmission network in Pakistan (dotted lines indicate the existing networks).

2. Overview of HVDC Systems

AC-based transmission networks were commonly used in the earlier era of power system development, while DC networks were rarely practiced due to lack of technologies at that time. Nevertheless, after 1945, the solid-state power electronics components penetrated into the power sector, and HVDC got researchers' attention and made a comeback. HVDC transmission network consists of two types of technologies, depending upon the control of converters, i.e., voltage source converter (VSCs) or line commutated converters (LCCs). In the initial stages, LCC-HVDC networks were commonly used, but with time, HVDC transmission-related technologies became more efficient and mature, which also provided a window for the development and implementation of VSC-HVDC based transmission networks [10,18–20]. Some HVDC transmission networks based on both technologies were installed in different regions of the world and are summarized in Table 1, and other projects are discussed in [21–24].

Table 1. List of HVDC projects in different countries.

Project Name	Year	Voltage (kV)	Power (MW)	Distance (km)	Type	Supplier
Three Gorges–Shanghai (China)	2006	500	3000	1060	Thy	ABB
Estlink (Estonia–Finland)	2006	150	350	105	IGB	ABB
NorNed (Netherland–Norway)	2008	450	700	580	Thy	ABB
Yunnan–Guangdong (China)	2010	800	5000	1418	Thy	Siemens
SAPEI (Italy)	2011	500	1000	435	Thy	ABB
BorWin1 (Germany)	2012	150	400	200	IGB	ABB
Mundra–Haryana (India)	2012	500	2500	960	Thy	Siemens
Zhoushan (China)	2014	200	400	134	IGB	NA
AL-link (Aland–Finland)	2015	80	10	158	IGB	ABB
Western Alberta Transmission Line (Canada)	2015	500	1000	350	Thy	NA
NordBalt (Sweden–Lithuania)	2015	300	700	450	IGB	ABB
Skagerrak 4 (Denmark Norway)	2015	500	700	244	IGB	Nexans, ABB
Jinsha River II–East China (China)	2016	800	6400	NA	Thy	NA
DolWin2 (Germany)	2016	320	900	135	IGB	ABB
SydVastlanken (Sweden)	2016	300	720	260	IGB	Alstom
Western HVDC Link (UK)	2017	600	2200	422	Thy	Prysmain Group, Siemens
Xinjiang–Anhui (China)	2017	1100	10,000	3333	Thy	NA

After many years of research and development process, the VSC based HVDC transmission systems became an attractive option for bulk power transmitting over long distance. Recently, VSC-HVDC is being preferred to LCC-HVDC, because VSCs offer the independent control of both reactive and active power. Also, VSCs do not need external sources to push off the switches, while LCCs needed the external mechanical switches. VSC-HVDC based networks offer many advantages over LCC-HVDC, and some of them are summarized in Table 2 [25,26].

Table 2. Comparison of VSC-HVDC and LCC-HVDC.

Operation/Function	VSC-HVDC	LCC-HVDC
Direction reversal	No external mechanical switches needed, current direction change is possible in the converter	Cannot change the current direction, need external switches
AC influences	Offer fault ride-through capability, No AC disturbances, a less loss of active power transfer	Possibly commutation failure; short circuit of the HVDC grid
AC Voltage Control	Allows active and reactive power control	Consumes 50 percent of reactive power (VAR), needed AC filters for VAR compensation
AC connections	Electrically can be connected to weak or black AC circuits	Connection limited to medium and high capacity circuits.
Multi-Terminals Options	No limitations	Limited to 3-terminals
Delivery period	2 years	3 years

3. Deployment of Proposed Transmission Line

The proposed transmission line is based on VSC-HVDC, which can stretch approximately 815 km from Gwadar, Balochistan, to Matiari, Sindh. A major part of the line will be in Balochistan province for up to about 600 km, and the remaining portion will be in Sindh province. The Pakistan first-ever LCC-HVDC transmission line project (under the vision of CPEC) from Matiari to Lahore is under construction and can be operational at the start of 2021. This HVDC line is 878 km long, will be capable of bulk power transmission of about 4000 MW at 660 kV, generated from various power projects in the south part to the most populated area of Punjab province [27].

Gwadar is one of the busiest sea routes in between Southwest and South Asia on the Arabian Sea shore due to its geographical, commercial, and strategically significant deep-sea port. It covers the 35% of global sea-trade, including 45% of China's oil trade. It is being bordered with Iran, which has broadened the opportunities to reach the overland business activities. With this recent development of Gwadar Sea Port under CPEC projects, it has become the hub of global economic activities. Recently, the memorandum of agreement [MOU] between Saudi Arabia and Pakistan has been signed to set up a joint working group for the petrochemical complex and the state-of-the-art oil refinery in Gwadar city. Moreover, Iran has made an agreement with Pakistan to build an oil refinery, whereas Qatar also has shown its interest in establishing a food storage system at Gwadar port. This initiative would help boost the economic and energy development of the region [28–30].

Owing to substantial renewable energy resources, development of port and oil refinery, and other economic activities, the southwestern region should be connected to the national grid, which can provide the power security and demolish the power shortages of the country. The proposed VSC-HVDC transmission line is capable of dispatching bulk power approximately 3500 MW at 350 kV from Gwadar to Matiari. The location of the proposed bipolar HVDC transmission line is shown in Figure 2. The whole area is easily accessible for all types of vehicles through Makran coastal high way in Balochistan and the national high way in the Sindh part. Most of the line will pass through the rural areas and have a negligible effect on the social instability.

It is worth mentioning here that this kind of research is hardly carried out before for this area. It is hoped that the implementation of this project can be a game-changer in the region, provides employment opportunities, infrastructure development, increases land revenue, and uplifts the socio-economic. Besides, the access amount of electricity that can be available in the national grid ensures the energy security, which can also result in industrial development and expansion of industry in the country.

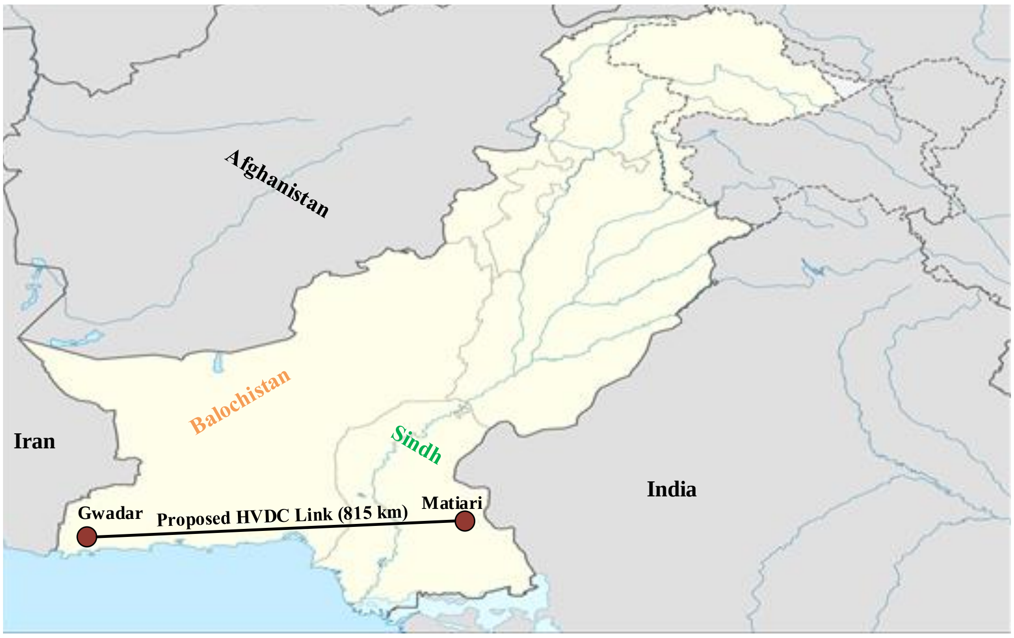

Figure 2. Proposed HVDC transmission line for the South-western part of Pakistan.

4. VSC-HVDC System Theory and Simulation

Different types of voltage source converters are used for HVDC transmission; the most commonly used in this regard are a two-level converter, three-level neutral-point clamped (NPC) converter, and modular multilevel converter (MMC) [31]. In this paper, a case study with results is incorporated using MATLAB simulation to understand the significate of the VSC-HVDC system. In this context, a two-terminal VSC-HVDC model is used, in which a two-level converter with standard double-loop control is employed. Where terminal-I is controlling DC-voltage and active power, while terminal-II is controlling active and reactive power.

4.1. Converter Control

There are several approaches to control the converter; out of many, vector control and direct power control are commonly used ones. In vector control, voltage and current vectors in reference (rotating) frame are transformed into a two-dimensional stationary frame using Clark's transformation [32]. The AC side voltage vectors are represented by Equations (1)–(3), whereas the application of Clark's transformations is given in Equation (4).

$$v_a(t) = V_m cos(\theta) \tag{1}$$

$$v_b(t) = V_m cos\left(\theta - \frac{2\pi}{3}\right) \tag{2}$$

$$v_c(t) = V_m cos\left(\theta - \frac{4\pi}{3}\right) \tag{3}$$

The details of variables attached to Equations (1), (2), and (3) are as follows. v_a, v_b, and v_c are the respective phase voltages in the balanced AC grid, V_m represents the amplitude of phase voltage, $\theta = \omega t$ represents the phase angle measured in radians. The design of any control method in the original/natural three-dimensional frame (or ABC frame) is complicated because of three independent vectors concerning different state variables, e.g., voltage or current, etc. Therefore, the variables in the original/natural three-dimensional frame are converted to a two-dimensional frame, either static frame (or αβ-frame) using Clark's Transformation, or a rotating frame (or dq-frame) using Park's

Transformation, depending on the design of the control. In this way, control schemes can be designed based on the control of two independent vectors, simpler in design and easier to implement.

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \\ v_o(t) \end{bmatrix} = Tv_{abc}(t) = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} \tag{4}$$

In Equation (4), "T" is the transformation matrix, $\begin{bmatrix} v_\alpha(t) & v_\beta(t) & v_o(t) \end{bmatrix}'$ represents the voltage vector in the αβ-frame, while $\begin{bmatrix} v_a(t) & v_b(t) & v_c(t) \end{bmatrix}'$ denotes the voltage vector in ABC-frame. Using similar approaches, current in the two-dimensional stationary frame can also be obtained. Once the values in the two-dimensional stationary frame are obtained, then these transformed into two-dimensional rotating frame or dq-frame, by the application of Park's t transformations, which is given in Equation (5).

$$\begin{bmatrix} v_d(t) \\ v_q(t) \\ v_o(t) \end{bmatrix} = T_o v_{\alpha\beta o}(t) = \begin{bmatrix} cos(\theta) & sin(\theta) & 0 \\ -sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \\ v_o(t) \end{bmatrix} \tag{5}$$

In Equation (5), $\begin{bmatrix} v_d(t) & v_q(t) & v_o(t) \end{bmatrix}'$ represents the voltage vector in dq-frame, "T_o" is the transformation matrix, and $\begin{bmatrix} v_\alpha(t) & v_\beta(t) & v_o(t) \end{bmatrix}'$ indicates the voltage vector in αβ-frame. It should be noted that if the d-axis of the rotating frame (dq-frame) is aligned to the AC voltage vectors, such that $v_q = 0$, consequently, the instantaneous active and reactive power is given in Equations (6) and (7), respectively, which are based on the instantaneous power theory of Akagi [33].

$$P = \frac{3}{2}v_d i_d \tag{6}$$

$$Q = -\frac{3}{2}v_d i_q \tag{7}$$

From the mathematical relationships, it is evident that the control of active and reactive power is directly linked with controlling current and voltage in the dq-frame. Figure 3 explains the working of conventional double-loop control for two-level voltage source inverter (VSI) [34]. An outer control loop produces the reference currents I_d^* and I_q^*, and these reference values serve as input for the inner control loop. The inner control loop controls the actual values of V_d and V_q to produce desired reference current, and ultimately V_d^* and V_q^* are transformed into *abc* frame and then sent to the pulse width modular PWM controller to directly control the firing angle of IBGTs to achieve the desired results. Where L_E is the line inductance and V_{dc}^*, P^*, Q^* are the reference values of DC voltage, active power, and reactive power, respectively.

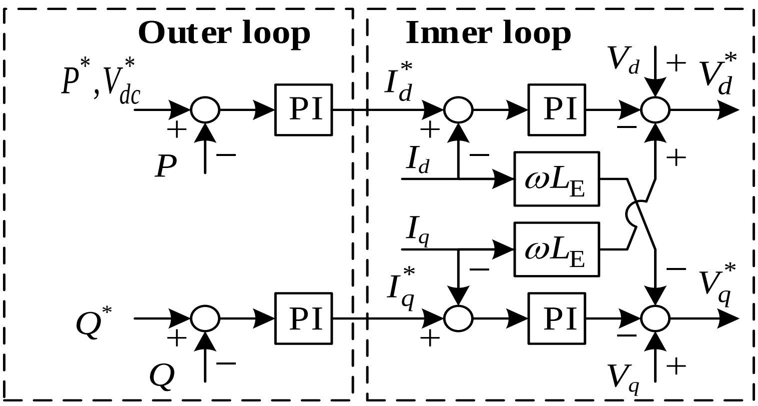

Figure 3. Double loop-control for the converter.

4.2. Two-Terminal Model Simulation

The schematic layout used for simulation is shown in Figure 4, whereas the double-loop control structure explaining the control aspects of VSI is given in Figure 3. For simulation, a two-terminal system is developed with conventional 2-level VSI and double loop control.

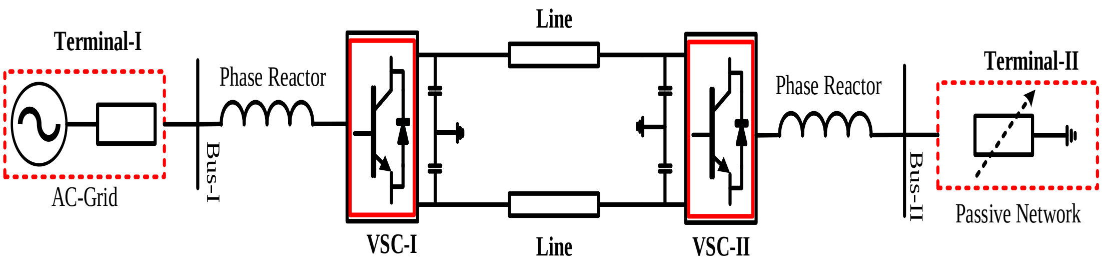

Figure 4. VSC-HVDC system with the passive network.

The terminal-I used to regulate the DC-voltage and reactive power, whereas for terminal-II active and reactive power is regulated. Between two terminals, an 800 km long transmission line model is also used. The essential parameters for the system are given in the Appendix Table A1; the simulation model is also built under these parameters.

The Figure 5a contains the AC grid voltage concerning terminal-I, likewise, Figure 5b shows the terminal DC-voltage at VSC-I, and it can be seen that the regulation of terminal DC voltage is achieved convincingly, and terminal DC voltage is kept at the desired level of 400 kV.

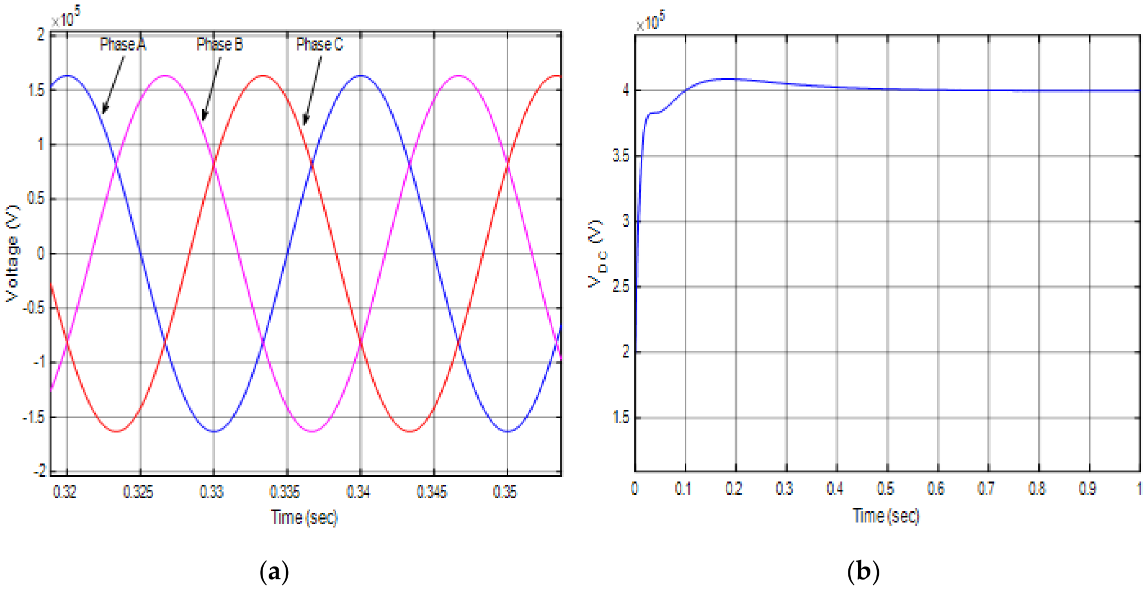

Figure 5. VSC terminal-I voltages; (**a**) AC grid voltage, (**b**) DC-voltage.

The receiving voltage at DC-link capacitors of terminal-II is depicted in Figure 6a. It can be observed that DC-voltage is slightly less than the rated value; this is obvious because line parameters can influence the value of DC-voltage at the receiving station. The remaining results concerning terminal-II includes AC voltage and current in Figure 6b.

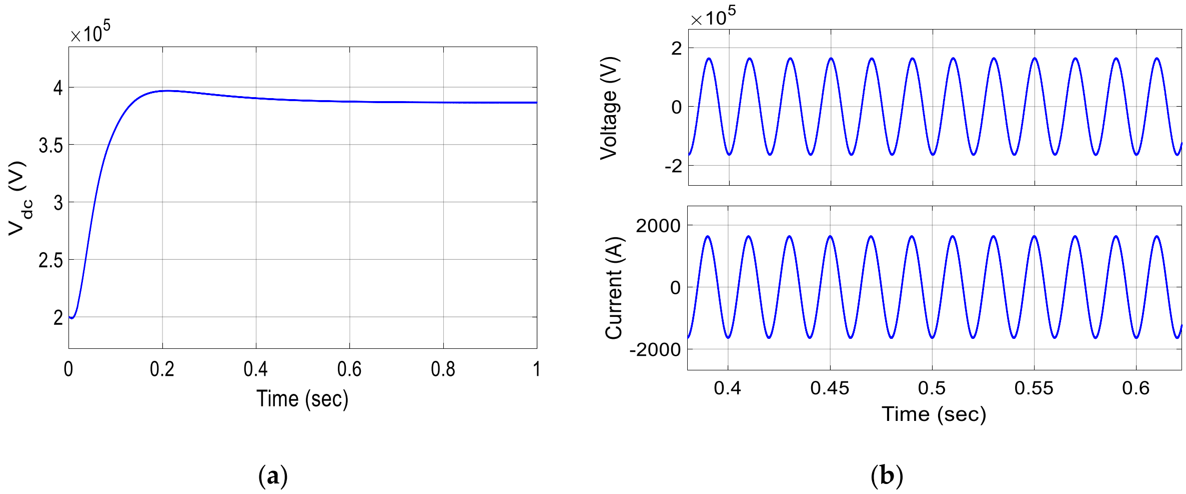

Figure 6. VSC terminal-II voltages and current; (**a**) DC-voltage, (**b**) Voltage and current waveforms.

Lastly, Figure 7 shows the active power transmitted to terminal-II, where it is apparent that the active power is regulated successfully at terminal one, which is kept at the level of 400 MW following the designed criteria.

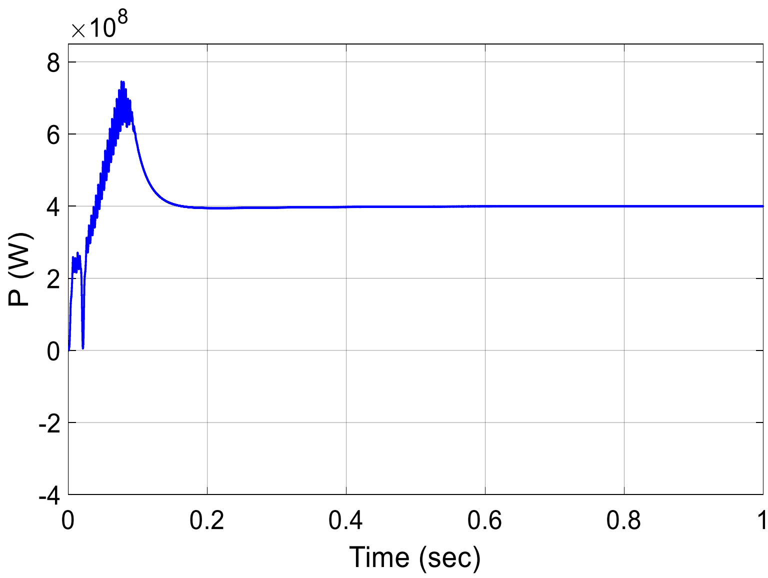

Figure 7. Active power transmission at terminal-II.

5. Cost Assessment

Economic comparisons can usually be made by various methods, as depicted in Figure 8. However, the discounted cash flow method (DCF) is the commonly used method due to its time value of money. In this context, all imminent cash flows are computed and discounted to get the net present values (NPV) [8].

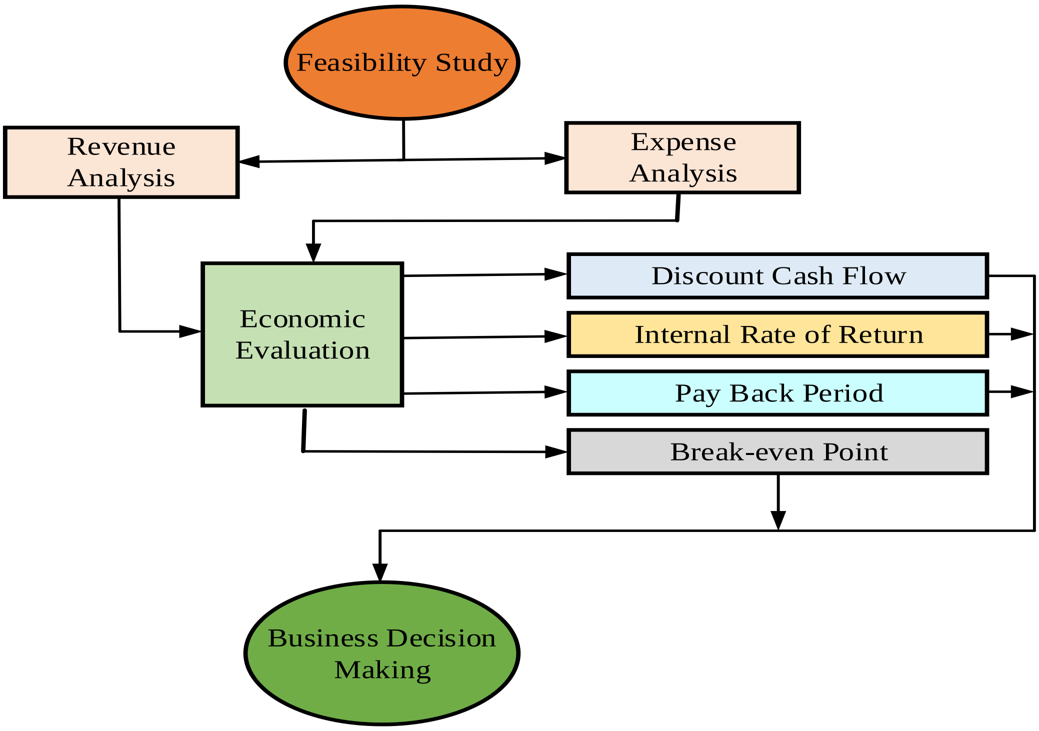

Figure 8. The general procedure of business decision making.

5.1. Methodology

The discount cash flow (DCF) analysis method is applied for the economic comparison of HVAC and VSC-HVDC transmission systems. This method uses the difference in the investment costs and annual costs of the systems for economic comparison. The maintenance costs and costs of transmission losses are accounted for the annual cost; here, reliability and insurance factors are neglected. DCF analysis result is the difference of NPVs of mentioned transmission line-technologies, which also comprises the discounted annual cost (C*da*) and initial investment cost (C_i) for each transmission system. The mathematical expressions for the DCF method are given as [8,35];

$$Total\ investement\ cost_{HVAC} = S_c + L_c + OT_c + Q_c \quad (8)$$

$$Total\ investement\ cost_{HVDC} = S_c + L_c + OT_c \quad (9)$$

where, S_c, L_c, OT_c, and Q_c are the cost of substation, land, overhead transmission line, and cost of reactive power compensations, respectively. The annual cost (Ç), NPV, Annuity factor (Ⱥ), C_{da}, are expressed as;

$$\text{Ç} = M_c + Ls_c \quad (10)$$

$$NPV = Total\ investement\ cost\ _{HVAC/DC} + C_{da} \quad (11)$$

$$\text{Ⱥ} = \frac{\left[1 - (\text{Đ} + 1)^{-t}\right]}{\text{Đ}} \quad (12)$$

$$C_{da} = \text{ᵽȺ} + \left[\text{Ç} * (1 - \text{ɍ}) - (\text{ɗ} * \text{ɍ})\right] \quad (13)$$

where, M_c stands for maintenance cost, Ls_c denotes the cost of losses, Đ is the discount factor, t shows system lifetime, ᵽȺ is the present cost for Ⱥ, Ƴ represents annual costs, ɍ and ɗ are taxation rate and depreciation value, respectively. To get a more representative reflection, the lifetime (t) of the transmission system is assumed to be 30 years, whereas the discount factor (Đ) and the tax rate of 13.25% and 17%, respectively, are set for this study [36,37].

5.2. Investment Cost Analysis

VSC-HVDC system is based on a relatively new technology, which makes it better than other DC or AC options. However, this choice may also depend on the economic aspects of the two systems. In this regard, a cost analysis is drawn to compare the HVDC and HVAC systems to determine the better option for a 3500 MW generation over 815 km overhead transmission line. The DC system considered in this work is comprised of bipolar ground-return transmission lines at 350 kV having the cable cross-section of 4×125 mm^2. A substation with voltage-rating 350 kV is to be installed at each of the proposed locations, i.e., Gwadar and Matiari.

Nevertheless, the HVAC systems are proposed to be 500 kV grid at both ends. The cost is analyzed based on the transmission system components. These components are the substations, transmission lines conductors, installation, and land expenses, as illustrated in Table 3 (cost/component is calculated in a million US dollars "$M"). STATCOM expenses are also included in the case of HVAC. It can be seen that despite the higher price of HVDC substations, the total price is kept low due to the cheaper overhead transmission line equipment and absence of STATCOM. The total cost required for an 815 km AC transmission line is 1201 $M, with a cost of 1.47 $M/km, which is 1.35 times of HVDC line cost.

Table 3. HVAC and HVDC systems investment cost comparison [8,9,38].

Components	Transmission Systems	
	HVAC Cost ($M)	**HVDC Cost ($M)**
Substation	343	490
Land use	65	65
STATCOM	189	Nil
Overhead system	1201	889
Total price	1798	1445

5.3. Annual Cost

The system maintenance costs and losses each year will account for the annual cost of the system. The annual maintenance cost is considered to be 0.5% of the total components cost. These components are the substations costs, cable installment costs, and STATCOM costs in case of the HVAC system. The annual maintenance costs of the HVDC and HVAC systems are found to be 4.45 $M and 3.37 $M, respectively. The VSC based HVDC systems have comparatively higher losses, with a percentage of 1.8% for each station. In the case of two stations, 3.6% of the total power flow is considered, which is found to be 52.02 $M. In the case of HVAC systems, 5% of total power flow is considered to be the loss. Hence, 89.92 $M is computed to be the loss's cost for HVAC systems. As a result, the annual costs for HVDC and HVAC systems are calculated to be 56.48 $M and 94.3 $M, respectively.

5.4. Discounted Cash Flow (DCF) Analysis

From the perspective of transmission systems, the DCF analysis results presented in Figure 9, are of great significance. It shall be noted that on a lifetime basis, the HVDC system is cheaper than the HVAC system. As compared to the investment costs, the higher difference in NPV is due to the significant difference in the annual costs. It must be stated that the VSC based HVDC systems are still evolving and are expected to be more feasible in the future.

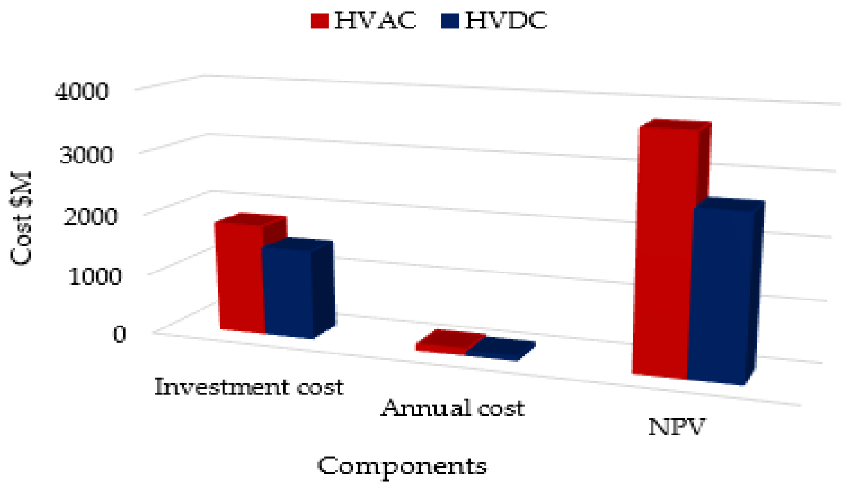

Figure 9. DCF analysis comparison of HVAC and HVDC.

5.5. HVDC Systems' Economics Comparison

It is difficult to determine the exact cost of an HVDC system because each project has different features and circumstances, such as rated power, line distance, terrain, and used technology. However, an overall estimate can be obtained based on the knowledge from previous projects. In particular, the Chongqing-Hubei back-to-back DC grid interconnection project in China was the first distinct VSC-HVDC line with the highest voltage capacity of 420 kV and the largest power transmission capacity of 5000 MW, covering the total distance of 1711 km [39,40]. The project cost was 1498.36 $M, which is roughly 0.9 $M/km. Accordingly, the cost of 1.3 $M/km was calculated for South Australia to Queensland 400 kV HVDC line in Australia with a length of 1450 km [41]. The Southern Hami-Zhengzhou (SHZ) HVDC line is one of China's large-scale HVDC projects (800 kV, 8000 MW), which is stretched from Xinjiang province in the northwest down to Henan province in central China. The project cost reached 3500 $M and about 1.8 $M/km. Whereas a slight decrease in the cost of 1.7 $M/km was incurred for the Lingzhou-Shaoxing HVDC line (with the same ratings of SHZ line) due to its shorter line coverage of 1722 km as compared to SHZ line distance, which is 2200 km [42,43].

Furthermore, Pakistan's first-ever HVDC Line Matiari to Lahore with a rated power of 4000 MW and voltage of 660 kV, spanning 878 km, is in progress by the cooperation of State Grid Corporation of China (SGCC) and Ministry of Water and Power Pakistan under the vision of CPEC. The project estimated cost is 1658.34 $M (approximately 1.9 $M/km) [44]. Similarly, this study provides an estimated cost of 1.7 $M/km for the proposed HVDC line, which is reasonably comparable to the cost of previously selected HVDC projects. Hence, the proposed HVDC model is economically sustainable and a better choice for the future transmission projects in Pakistan.

6. Conclusions

The southwestern region of the country is expected to become a hub for economic and industrial development due to CPEC projects. Conversely, power shortage and energy security are critical factors in this area and should be solved promptly to enhance the CPEC projects and other economic activities. In this context, a study of technical and economic aspects of a proposed two-terminal VSC-HVDC transmission line is carried out. The simulation results for the power, voltage, and current waveforms are found stable and reliable at the receiving end. The DCF analysis shows that the net present value of the HVDC system is lower as compared to the HVAC system. The NPV for HVAC is found to be 3725 $M, while the HVDC NPV was 2599 $M. Moreover, the cost/km of the proposed model is relatively analogous to selected existing HVDC projects. Therefore, HVDC proves to be a realistic and feasible transmission system.

Further research should be carried out by considering the socio-economic impact of such projects. Similarly, comprehensive studies comprising of further technical considerations and legal requirements of HVDC systems can be carried out for the real-time implementation of the project.

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Nomenclature

P	Active power
Q	Reactive power
Ç	Annual cost
Ⱥ	Annuity factor
Đ	Discount factor
ꞧ	Taxation rate
ɗ	Depreciation value

Abbreviations

CPEC	China Pakistan Economic Corridor
VSC	Voltage source converter
MMC	Modular multilevel converter
HVDC	High voltage direct current
HVAC	High voltage alternate current
LCC	Line commutated converter
DCF	Discounted cash flow method
NPV	Net present value
Cda	Discounted annual cost
C_i	Initial investment cost
S_c	Cost of substation
L_c	Cost of land
OT_c	Cost of overhead transmission line
Q_c	Cost of reactive power compensations

Appendix A

The following parameters are used to build the simulation model.

Table A1. System's parameters used for simulation.

System Capacity	400 MVA
Line Current	1 kA
Line Voltage	400 kV
Active Power	400 MW
Distance	800 Km
R_L	0.0256 Ω/Km
L_L	468 µH/Km
C_L	0.0124 µF/Km

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