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Saudi Arabia Central-West HVDC Project: 3500 MW ±600 kV LCC 770km High Performance Embedded Link Crossing a Desert Area

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1

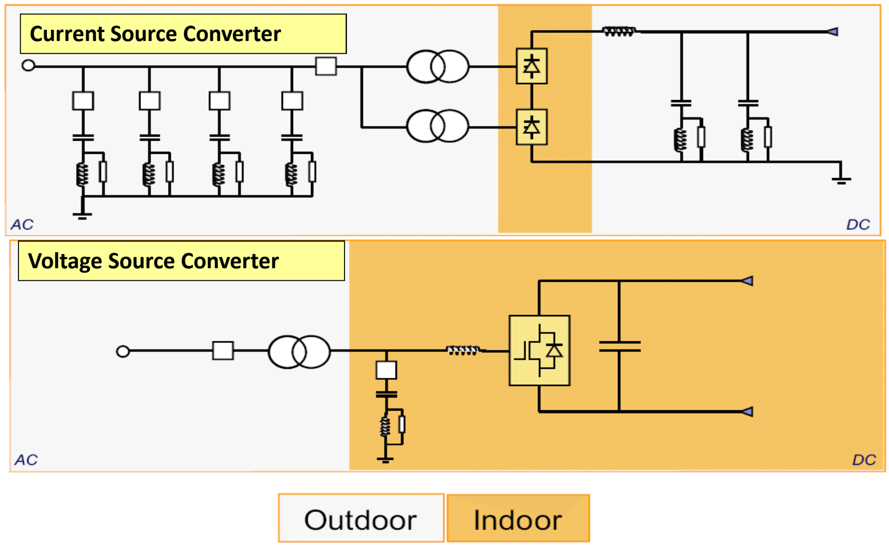
- A long distance HVDC transmission link between Central Operating Area and Western Operating Area in the Kingdom of Saudi Arabia was planned and designed.
- It **is currently under development**.
- This 770 km long point-to-point link consists of **two LCC type converter stations.**
- It is embedded in a powerful AC network.
- Both converter stations are connected to **380 kV existing substations**, each one part of a meshed network.

2

Power converters currently available on the market can be classified in two major categories:

- Line Commutated Converter (LCC) or Current Sourced Converter (CSC) and Voltage Sourced Converter (VSC).
- Both technologies have the same ultimate function and both can provide all benefits related to HVDC transmission.
- They perform in a different way because of the intrinsic differences of power electronic components.

Converter Stations between AC and DC Networks



- **Current Source Converters (CSC)** are traditional method of connecting networks – requires strong AC network [HVDC – Classic]- Thyristor controlled
- **Voltage Source Converters (VSC).** [HVDC – Light]-IGBT controlled (Insulated Gate Bipolar Transistors)

The HVDC scheme is **bipolar with neutral dedicated metallic return**, and the possible operating configurations are:

- **normal bipolar with metallic return**,
- rigid bipolar (without neutral return) and
- monopolar with different possible connections of pole lines and metallic return.

7

- Due to environmental constraints, mainly pipelines, **no return through ground is allowed.**
- The nominal voltage is ±600 kV and the nominal power is 3500 MW with a considerable overload capability, both in short term and in continuous overload.
- These nominal values and the size of conductors of the overhead line were selected on the basis of **a least cost criterion**.

8

- The line is fully overhead in desert area: it is a standard HVDC tower design up to 600 kV nominal voltage.
- The insulation withstand capability of the transmission line and of the DC open air part of the converter stations were selected considering the **pollution conditions**, close to coastal area and in inland area.
- The link **requires a huge AC filter banks.**

9

SAUDI ELECTRICITY COMPANY (SEC)

PLANNED TRANSMISSION INTERCONNECTION PROJECTS (*380 KV)*

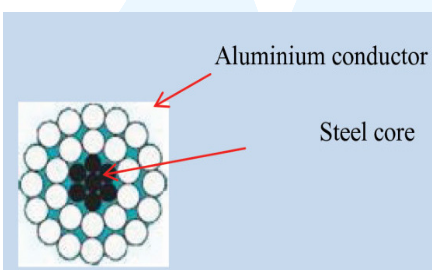
Networks Interconnection Projects	Commissioning Year
Hail – Al Jouf	2013
Qassim – Madinah Stage 2	2013
Interconnection of Qaisumah	2013
Tabouk – Dhibah	2014
Tabarjal – Qurayyat	2013
Jizan – Najran	2013
Eastern – Central 5th Interconnection	2017
Southern region - Wadi Aldawasir	2015
Madinah – Hail	2017
Central - Western regions HVDC Link	2018
Tabouk – Madinah HVDC Link	2018
Western – Southern 2nd interconnection	2016
Debha – Wajh / Ula	2015
Yanboa - Umlaj	2014
Boosting Connection of the western- Southern Region	2016
Tabouk – Eygpt HVDC Link	2016
Tabouk – Tabarjal	2016
Al Jouf – Tabarjal	2016
Boosting Interconnection of Madinah - Hail	2019
Al Kharj – Al Aflaj - Wadi Aldawasir	2019

2. Selection of Nominal Power and Voltage

- The losses of the converter stations versus the transmitted power and the losses in the conductors versus the transmitted power for a reference 35°C ambient temperature were considered.
- The corona losses were considered as per Table 1.
- ACSR Joree (aluminum conductor steel reinforced)

11

ACSR (Aluminum Conductor Steel Reinforced) - Conventional Conductors With Steel Core



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12

$$L_{Corona} = L_{Fair} \cdot 0.8 + L_{Foul} \cdot 0.2$$

	Conductor	Corona losses		
		Fair Weather [kW/km]	Foul Weather [kW/km]	Total [MW]
600 kV	Joree	0,7915	3,995	1,14576

Table 1: Corona losses along the whole HVDC line (for a preliminary line length of 800 km) per pole

3. Characteristics of the AC Networks and Connection to Existing 380 kV Substations

Nominal System voltage		380 kV
Maximum continuous voltage in normal condition		400 kV
Minimum continuous voltage in normal condition		360 kV
Maximum continuous voltage for 30 min		420 kV
Minimum continuous voltage for 30 min		340 kV
Nominal system frequency		60.00 Hz
Maximum frequency in normal condition		60.50 Hz
Minimum frequency in normal condition		58.80 Hz
Maximum frequency in exceptional condition for 30 min		61.50 Hz
Minimum frequency in exceptional condition for 30 min		57.50 Hz
Maximum frequency in exceptional condition *lasting no more than 30 s*		62.50 Hz
Minimum frequency in exceptional condition *lasting no more than 30 s*		57.00 Hz
AC negative sequence voltage for performance		1%
AC negative sequence voltage for equipment rating		2%
	HHR1 (PCC for Bahra)	PP11 (PCC for Dhuruma)
Maximum short circuit level in normal condition (year 2016)	24 GVA (36 kA)	36 GVA (55 kA)
Minimum short circuit level in normal condition (year 2016)	13 GVA (20 kA)	16 GVA (24 kA)
Minimum short circuit level in exceptional condition (year 2016)	9 GVA (14 kA)	14 GVA (21 kA)

Table 2: Main characteristics of 380 kV interconnected system.

- All equipment at 380 kV are rated to withstand a **short circuit current of 63 kArms for 1s.**
- The **pre-existing AC voltage harmonics** for performance evaluation have been assessed in some existing 380 kV busses close to the 380 kV busses where the HVDC converter stations will be connected.
- The **AC voltage harmonics** to be applied for equipment rating corresponds to the planning levels of IEC/TR 61000-3-6, with **THD = 3%,** in both Bahra and Dhuruma converter stations.
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14 /

4. Environmental Conditions in the Sites of the Converter Stations

The environmental conditions in the sites of the two converter stations are:

- Altitude above mean sea level: 120 m for Bahra & 655 m for Dhuruma
- Ambient air temperature (outdoor)

➢ minimum = -5°C

➢ maximum = 55°C

➢ monthly average of the hottest month = 45°C

➢ monthly average of the coldest month = -5°C

➢ yearly average = 35°C

15

- Maximum relative humidity = 80 ÷ 100%
- Design wind velocity = 170km/h
- Approximate highest density solar radiation = 1.10kW/m^2
- Maximum earthquake severity = 0.2g
- Average rainfall per year : 330 mm
- Keraunic level: 50 storm days/year

16

5. Main Characteristics of the HVDC Line

- Bahra and Dhuruma converter stations, are connected through a 770 km long overhead HVDC line.
- Each pole line conductor (suited to withstand 600kV to ground) consists of a bundle of four sub-conductors, **ACSR Joree** type.
- **The metallic return consists of two parallel bundles of two sub-conductors each** (i.e. a total of four parallel sub-conductors), **ACSR Falcon** type.
- The maximum allowed permanent temperature of all conductors for all continuous operating conditions is 84°C.

17

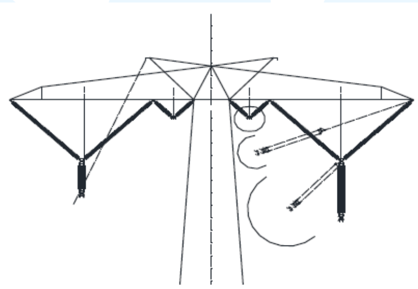
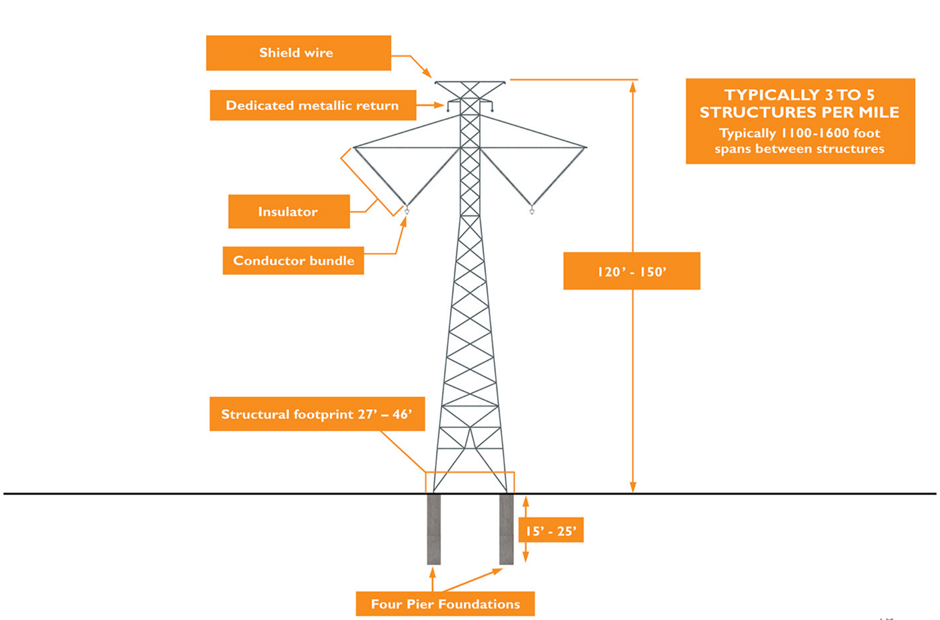


Figure 2: HVDC tower head: long insulator string shown on right side, short one on left side.

18

TYPICAL LATTICE STRUCTURE: 120 - 150 FEET



19

6. Main Constructional Characteristics of the Converter Stations

- The footprint for the ±600 kV, 3500 MW HVDC converter station, is of the order of 500 m x 450 m for the Western site and 850 m x 380 m for the Central site.
- Each HVDC converter station is equipped with its own **internal 380 kV AC GIS substation**, housed in a dedicated building, which is connected to the nearby **existing 380 kV AC GIS substation** through four 380 kV AC links;
- Bahra is connected to HHR1 by **four aerial links** while
- Dhuruma is connected to PP11 through **four cable links.**

20

- The **converter transformers consist of single-phase units and they can be either two windings or three windings type.**
- This choice **has no impact on the functional performance of the link**, but **on maintenance and spare units.**
- The minimum Unified Specific Creepage distances (USCD) for all DC equipment of both converter stations are shown in Table 3, as a function of the insulator average diameter.

21

DC Minimum Unified Specific Creepage Distance					
Insulator	INDOOR	OUTDOOR			
Average diameter		Dhuruma Station (totally inland, >100 km from the sea)		Bahra Station (marginally coastal, 20÷50 km from the sea)	
		ceramic	composite	ceramic	composite
D	USCD	USCD	USCD	USCD	USCD
mm	mm/kV	mm/kV	mm/kV	mm/kV	mm/kV
300	20	75	65	100	80
400	20	78	65	105	80
500	20	82	65	110	80
600	20	85	65	115	80

Table 3: DC Minimum creepage distance.

The insulation levels for the 380 kV AC equipment are specified in *Table **4*** and *Table **5***.

380 kV System Nominal Voltage 420 kV Highest Voltage for Equipment			Phase-to-earth and Between phases				Across Open Switching Device and for Isolating Distance	
			G	T	O	OB	G	O
External Insulation	Outdoors	LIWV (kVpeak)	1425	1425	1425	1425	1425(+240)	1425(+315)
		PFWV (kVrms)	650	695	620	630	815	800
	Indoors	LIWV (kVpeak)	1425	1300	1300	1300	1425(+240)	1300(+240)
		PFWV (kVrms)	650	625	520	570	815	610
Internal Insulation	LIWV (kVpeak)		NA	1300	1300	NA	NA	NA
	PFWV (kVrms)		NA	520	520	NA	NA	NA

G – applicable for GIS;
T – applicable for transformer bushing only (Outdoor and Indoor)
OB – applicable for Other Bushings (Other than transformer and GIS bushings)
O - applicable for Other Equipment

Table 4: Lightning Impulse Withstand Voltage (LIWV) and Power Frequency (PFWV) Withstand Voltages for 380 kV AC equipment.

380 kV System Nominal Voltage 420 kV Highest Voltage for Equipment		Phase-to-earth and Across Open Switching Device		Between phases		Across Isolating Distance	
		G	O	G	O	G	O
Outdoor	SIWV (kVpeak)	1050	1050	1575	1680	900(+345)	900(+450)
Indoor/Internal	SIWV (kVpeak)	1050	950	NA	1425	900(+345)	900(+345)

G – applicable for GIS;
O - applicable for Other Equipment

Table 5: Switching Impulse Withstand Voltage (SIWV) for 380 kV AC equipment.

7. Main Characteristics and Performances of the HVDC Link

- The nominal capacity of the link, in both directions, is 3500 MW in bipolar configuration with a nominal DC voltage of ±600 kV and a consequent nominal DC current of 2917 A.
- The nominal power is delivered on the DC side of the rectifier converter station; however the link is rated to get 3500 MW at inverter AC side.
- The valve arrangement consists of one 12-pulse converter per pole.

23

- **A dedicated metallic return is provided without earth electrodes.**
- The DC link is operated with the **neutral grounded in one converter station only, namely in Bahra.**
- The insulation withstand and the rating of all equipment and the layout of both converter stations are suited to allow **a possible future change of the grounded converter station**.
- The main operating configuration is **bipolar with neutral metallic return.**

24

- The HVDC link will be **operated for limited time in monopolar configuration** with consequent transmission capacity reduction, due to:
  - Scheduled maintenance
  - Forced outages following a fault in one pole of the converter stations or of the HVDC line
- All functional performances are referred to the connection with the existing AC substations (point of common coupling):
  - HHR1 for Bahra converter station and
  - PP11 for Dhuruma converter station.

25

- In normal bipolar operating mode **the neutral is connected to the metallic return** and **each converter pole is connected to its respective pole conductor of HVDC line** (operating mode A).
- In case of outage of the metallic return, the link is capable of operating in bipolar rigid operation with the metallic return disconnected (operating mode D).

26

- In case of any outage in one pole of either converter station or one pole conductor of the HVDC line, **the link is capable of operating in monopolar configuration** through a suitable DC yard configuration.
- In case of an outage of one converter station pole, the link can exploit both pole conductors and the metallic return; therefore different monopolar operations are allowed.

27

7.2 Functional performances

- Table 8 summarizes the nominal power values (at DC side of the rectifier) and the overload capability (at AC side of the inverter, namely at existing 380 kV AC substation).
- The link has the same transmission capability in both directions.
- Table 9 shows the DC operating voltage values of the link.

28

Rated power	where	MW
Nominal power in bipolar configuration	DC side of rectifier	3500
Nominal power in monopolar configuration	DC side of rectifier	1750
Minimum power in bipolar configuration	DC side of rectifier	350
Minimum power in monopolar configuration	DC side of rectifier	175
Overload in bipolar configuration – continuous at 55°C (#2)	AC side of inverter	3500
Overload in monopolar configuration – continuous at 55°C (#2)	AC side of inverter	1750
Overload in monopolar configuration – three hours at 55°C (#3)	AC side of inverter	2000

Table 8: Nominal power and overload capability.

29

Nominal DC voltage	± 600 kV
Maximum continuous DC voltage (pole to ground)	± 620 kV
Reduced DC voltage at nominal current	± 480 kV
Reduced DC voltage with reduced performances	± 420 kV

Table 9: DC operating voltage.

Reactive power exchanges limits	Bahra (MVAr)	Dhuruma (MVAr)
Supplied to AC (converter station as a capacitor):		
- normal DC voltage	≤ 100	≤ 100
- reduced DC voltage (80% ≤ DC voltage < 100%)	≤ 300	≤ 300
Absorbed from AC (converter station as a reactor):		
- normal DC voltage	≤ 150	≤ 150
- reduced DC voltage (80% ≤ DC voltage < 100%)	≤ 300	≤ 300

Table 10: Reactive power exchange limits.

30

- Table 10 shows the **limits of reactive power exchanged** between the converter stations and the AC system.
- These limits are applicable with the normal operating conditions of the AC network (as for Table 2) and with the transmitted power ranging from technical minimum to overloads.
- At reduced DC voltage (80% ≤ DC voltage < 100%), the reactive power exchange is relaxed within ±300MVAr; all other performances are guaranteed with the DC current that can reach its nominal value.

31

Reactive power exchanges limits	Bahra (MVAr)	Dhuruma (MVAr)
Supplied to AC (converter station as a capacitor): - normal DC voltage - reduced DC voltage (80% ≤ DC voltage < 100%)	 ≤ 100 ≤ 300	 ≤ 100 ≤ 300
Absorbed from AC (converter station as a reactor): - normal DC voltage - reduced DC voltage (80% ≤ DC voltage < 100%)	 ≤ 150 ≤ 300	 ≤ 150 ≤ 300

Table 10: Reactive power exchange limits.

32

- As regards **harmonic voltage distortion** at the point of common coupling, the limit for **THD is 1.5%,** while the individual voltage harmonic limits (VL HVDC) are defined according to the following formula, which considers the pre-existing distortion on AC busbars (from IEEE Std 519-1992):

$$V_{L\,HVDC} = \begin{cases} 0.5 \cdot \sqrt{IEEE_{LIM}^2 - V_{BCK}^2} & if\ V_{L\,HVDC} > 0.4\% \\ 0.4 & if\ V_{L\,HVDC} \leq 0.4\% \end{cases}$$

where:

- V_{LHVDC}: individual voltage harmonic limit for each harmonic order;
- $IEEE_{LIM}$: correspond to the figures in Table 11.1 of IEEE Std 519-1992;
- V_{BCK}: pre-existing individual harmonic voltage.

33

- As regards **DC harmonic distortion**, the values of the "equivalent disturbing current" I_{eq} at all points along the route of the DC line in all the operating modes is not greater than 1.5 A in bipolar operation and 2.0 A in monopolar operation.
- In order to meet this requirement, **DC harmonic filters are provided in both poles of both converter stations.**

34

Total losses per pole per station (at 45°C):	
- bipolar operation at nominal power and nominal DC voltage	0.7%
- monopolar operation at nominal power and nominal DC voltage	0.7%
- bipolar operation at the power corresponding to the overload #2 and nominal DC voltage	0.75%
- no-load operation	0.15%

Table 11: Converter station losses (in % of nominal power of a single pole).

Converter stations reliability and unavailability	unit	Required value
Number of forced outage per monopole	faults/year	≤ 4
Number of forced outage per bipole	faults/year	≤ 0.2
Forced energy unavailability	%	≤ 0.8

Table 12: Converter station reliability and unavailability.

35

- The total losses of the link (converter station losses plus HVDC line losses) at nominal power and nominal DC voltage and at 45°C ambient temperature are expected:
- « bipolar 138 MW (3.9% of the nominal power)
- « monopolar 140 MW (8% of the nominal power).

36

- The power frequency component of the induced current in the HVDC pole lines due to interaction with parallel AC lines is kept within a tolerable value for the converter transformer by applying suitable DC blocking filters on the neutral side of each converter pole.
- The whole HVDC link, both converters stations and the overhead line, is in line with the international and Saudi Arabia requirements for all other performance: **electric and magnetic field, audible noise, electromagnetic interference**.

THANK YOU

Comparison between:

Voltage Source Converters (VSC)

and

Current Source Converter (CSC) or LCC Technology

LCC Technology

LCC Converter Station, Courtesy Siemens

Background

- Also called Current Source Converter (CSC)
- in existence since early 1950
- requires connection of two active power networks at either side of link
- typically based on use of power electronic components, so called thyristors

VSC Technology

VSC Converter Station, Courtesy Siemens

Background

- In commercial use since 1999
- Contrary to LCC, it can also be applied for linking isolated networks to the grid, e.g. supply power from generation sources like wind farms or to remote islands.
- Recently developed, compact VSC Multilevel Converters have lower transmission losses and are likely to be the converter type of the future

Key characteristics of LCC

- more powerful
- lower losses
- requires robust networks in operation on both sides and therefore is currently the preferred technology for subsea interconnections
- LCC converter stations require more space than VSC depending on the power and therefore are likely to be located on land
- LCC induces more severe working conditions on cables, for such reasons a cable design approved for LCC can also be used with VSC, but not vice versa.

Key characteristics of VSC

- younger technology
- able of “black start” (i.e. able to start without additional power at one of the two ends)
- currently limited in power (in the order of 1.000 MW) and voltage (up to 500 kV)
- more flexible, smaller and lighter and therefore more suitable for offshore platform installations.

Comparison between HVDC Classic and HVDC Light

HVDC Classic	HVDC Light
• Requires strong AC networks at connection points to control reactive power issues.	• Does not require strong AC connection
• Difficult to connect to weak Island /offshore generation grids.	• Relatively easy to connect to weak Island /offshore generation grids.
• Most suited to single node links	• Ideal for Multi-mode connection
• Much experience of operation	• Less operational experience
• Higher power transmission compared to HVDC (Light) experimentation with higher voltages ~ 800 kV.	• Power transmission restricted to around 1000 MW per cable pair @ 300 kV.

Weak electric grid:

- low short circuit capacity
- low x/r ratio for the feeders
- distribution networks with low voltage are weak grid

Current Source Converters (CSC) and Voltage Source Converters (VSC)

- The main requirement in a power transmission system is the precise control of active and reactive power flow to maintain the system voltage stability.
- This is achieved through an electronic converter and its ability of converting electrical energy from AC to DC or vice versa.
- There are basically two configuration types of three-phase converters possible for this conversion process, Current Source Converters (CSC) and Voltage Source Converters (VSC).
- Modern HVDC transmission systems can utilize either traditional CSC or VSC as the basic conversion workhorse.

Voltage Source Converters (VSC)

- Voltage Source Converters operating with the specified vector control strategy can perform independent control of active/reactive power at both ends.
- This ability of VSC makes it suitable for connection to weak AC networks, i.e. without local voltage sources.
- For power reversal, the DC voltage polarity remains the same for VSC based transmission system and the power transfer depends only on the direction of the DC current.

45

Current Source Converter (CSC)

- In a Current Source Converter, the DC current is kept constant with a small ripple using a large inductor, thus forming a current source on the DC side.
- The direction of power flow through a CSC is determined by the polarity of the DC voltage while the direction of current flow remains the same.

Self-commutated Voltage Source Converters are more flexible than the more conventional Current Source Converter since they allow controlling active and reactive power independently.

46