Líneas de transmisión en corriente directa

ANAJUM

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10 de febrero de 2025, Monterrey, NL

Beneficios de los sistemas HVDC

1. Menores pérdidas (en la línea).
2. La línea de CD requiere menor derecho de vía para la misma potencia.
3. En grandes distancias son más económicos que la transmisión en corriente alterna. El conjunto equipo en terminales y línea de CD puede tener mayores pérdidas; pero éstas pueden ser menores que las de CA al aumentar la distancia para una potencia dada.
4. Permiten el intercambio de potencia entre dos sistemas de frecuencia distinta o cuando la interconexión entre los sistemas trae problemas de estabilidad. Para ello se puede usar un sistema HVDC sin línea de transmisión (back to back), solo con los convertidores en ambas terminales.
5. Los cables submarinos tienen que ser de CD a partir de cierta distancia. La capacitancia paralelo aumenta con la longitud y en cables es mucho más grande que en aéreas. Con CD el efecto capacitivo solo se presenta al inicio, cuando la línea adquiere voltaje (se carga), en estado estable el efecto capacitivo es muy pequeño.
6. Los sistemas de CD permiten mayor control en el flujo potencia.

Ned Mohan, Electric Power Systems a First Course, Wiley, 2012
https://www.energy.siemens.com/mx/en/power-transmission/hvdc/applications-benefits/hvdc-benefits.htm#content=Benefits

Resistencia en CA y en CD: Efecto piel

The general formula for the skin depth is:[3][4]

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\ \sqrt{\sqrt{1+(\rho\omega\epsilon)^2}+\rho\omega\epsilon}$$

where

ρ = resistivity of the conductor

ω = angular frequency of current = 2π × frequency

$\mu = \mu_r \mu_0$

μ_r = relative magnetic permeability of the conductor

μ_0 = the permeability of free space

$\epsilon = \epsilon_r \epsilon_0$

ϵ_r = relative permittivity of the material

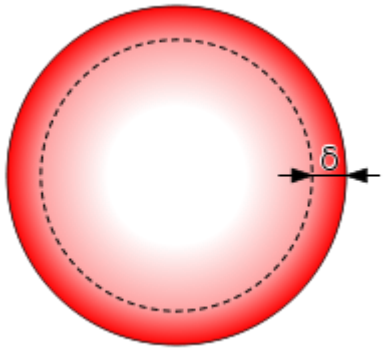
ϵ_0 = the permittivity of free space

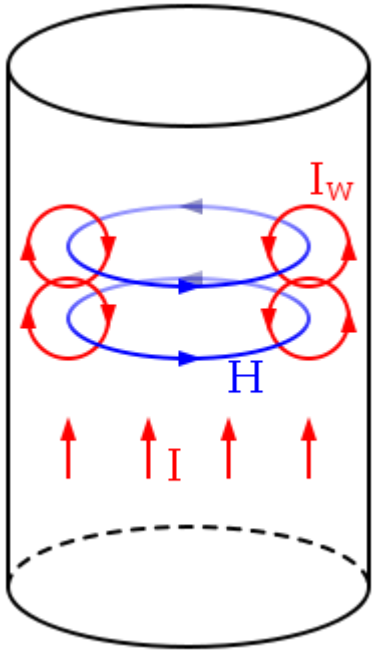
At frequencies much below $1/\rho\epsilon$ the quantity inside the large radical is close to unity and the formula is more usually given as:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}.$$

ACSR 477 MCM
Rcd = 0.1874 Ω/mi
Rca= 0.1919 Ω /mi

650 A
79 kW/mi
81 kW/mi





En CA la corriente tiene mayor densidad en la parte exterior del conductor que en el interior, efecto piel, en CD no hay efecto piel.

https://en.wikipedia.org/wiki/Skin_effect

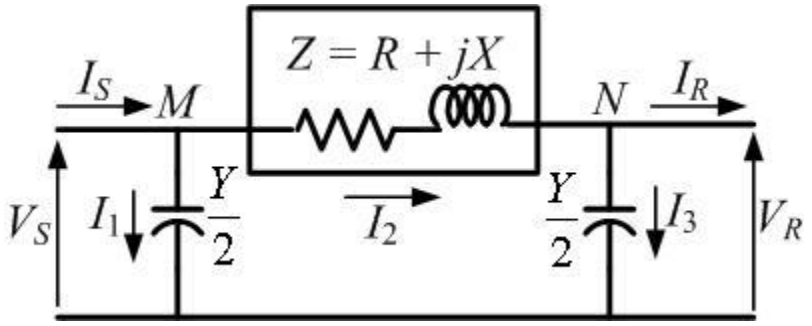
Inductancia y capacitancia distribuida de las líneas y cables

Sin importar si es de CD o de CA, una línea (cable) tiene capacitancia e inductancia distribuidas, esto es, cada unidad de longitud agrega inductancia serie y capacitancia paralelo.

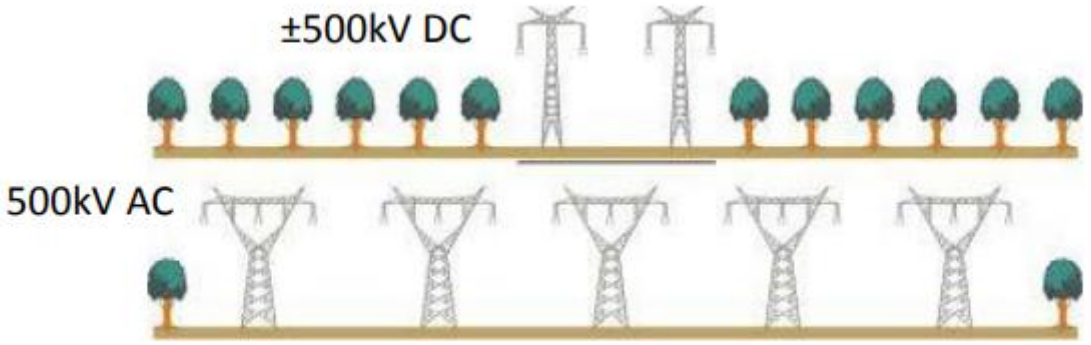
Al operar en corriente alterna, la reactancia serie, da lugar a que con el paso de la corriente haya caída de voltaje y consumo de potencia reactiva. El voltaje y la admitancia paralelo dan lugar a que haya corriente de carga capacitiva y generación de potencia reactiva.

Una línea en vacío o con muy poca carga se comporta como un capacitor, al aumentar la carga aumenta el consumo de potencia reactiva. Por ello, a partir de cierta longitud, las líneas de 400 kV CA requieren un reactor paralelo en los extremos. Este reactor se conecta con poca carga y se desconecta al aumentar la carga por arriba de cierto nivel.

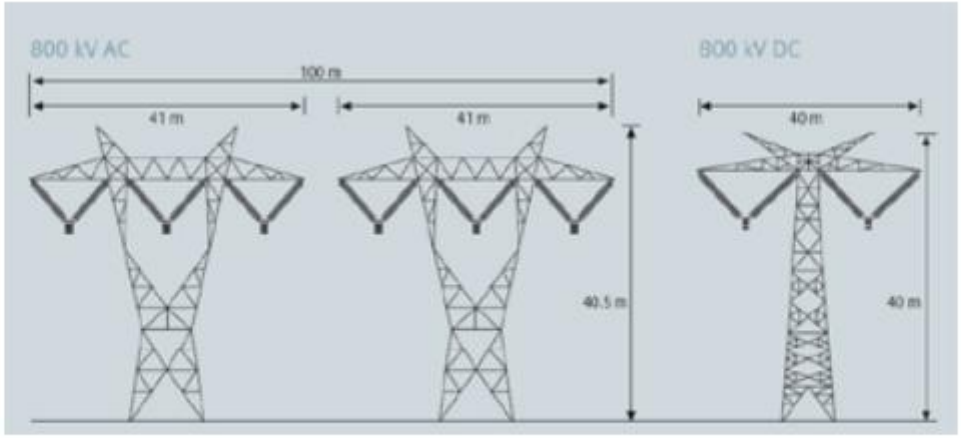
Al operar en CD, el efecto de la inductancia serie y la capacitancia paralelo solo es relevante durante la energización de la línea o el cable. En estado estable el efecto es casi nulo.



Derecho de vía para 6000 MW



±500kV vs. 500kV AC

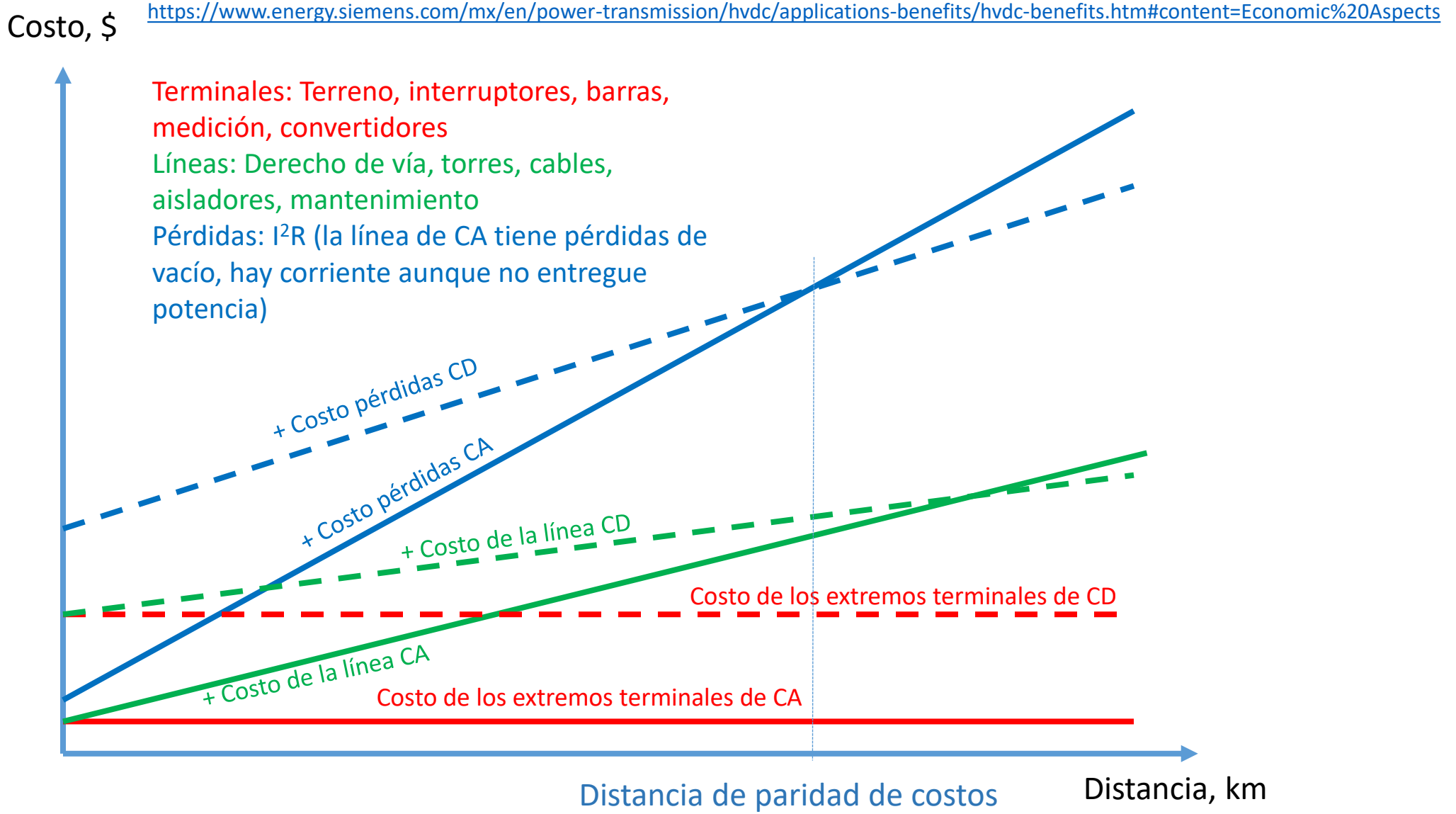


±800kV vs. 800kV AC

http://www.cleanlineenergy.com/sites/cleanline/media/resources/Electrical-Considerations-for-HVDC-Transmission-Lines.pdf

Costos de transmisión contra distancia

https://www.energy.siemens.com/mx/en/power-transmission/hvdc/applications-benefits/hvdc-benefits.htm#content=Economic%20Aspects

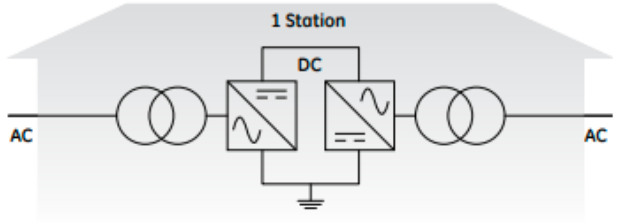


Esquemas HVDC

HVDC Schemes

Back to Back Scheme

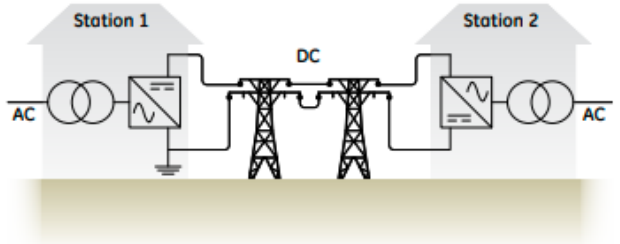
Suitable for frequency changing and asynchronous connections. This scheme provides fast accurate power flow, limiting the spread of cascading faults and provides increased system flexibility relative to new generation requirements. Once interconnected, the two systems' daily and seasonal cost differences can also be optimized.



Back to back scheme is suitable for frequency changing and asynchronous connection

Point to Point Scheme

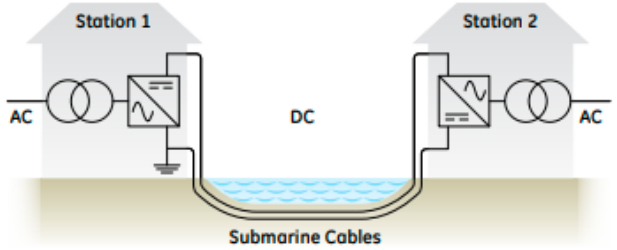
Commonly used for bulk transfer of power applications utilizing overhead lines over long distances providing low cost, fully functional, reliable and environmentally friendly way to transmit power.



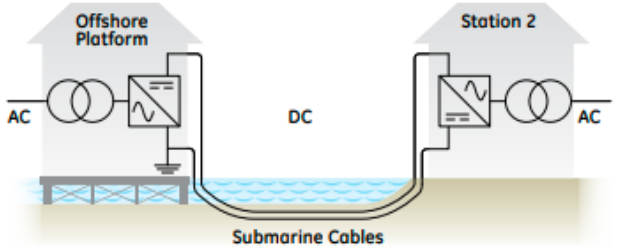
Point to point overhead line is suitable for bulk transmission overland

Submarine/Land Cable Scheme

Where the power exchange or transmission crosses water, or an environmentally sensitive region, cables may be the favored method of interconnection between the HVDC Converter Stations. HVDC transmission is particularly attractive and may be the only technically feasible method of transmitting power using cables.



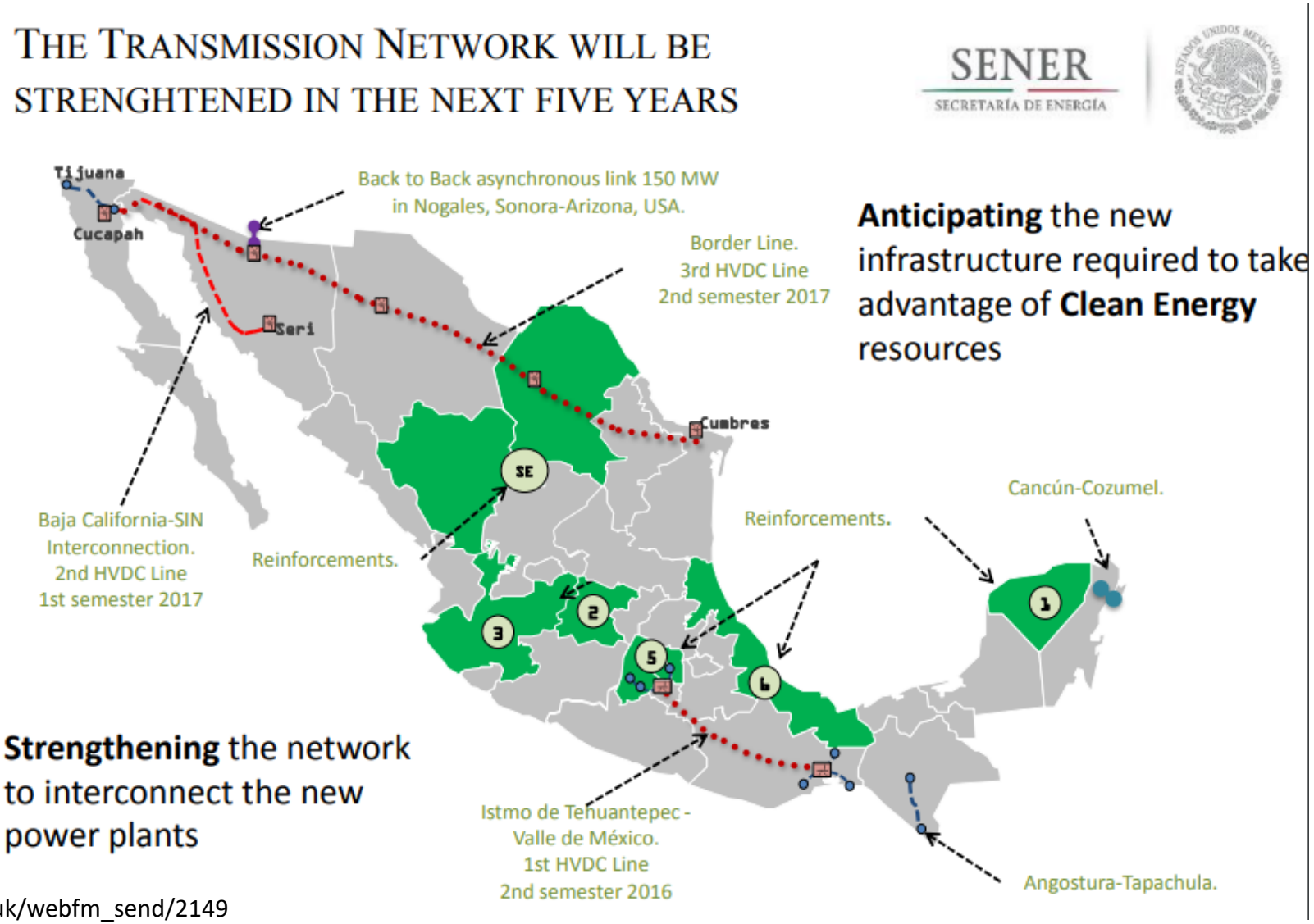
Point to point submarine cable bulk transmission underwater or underground



Submarine scheme provides bulk transmission from offshore platform to shore

https://www.gegridsolutions.com/products/brochures/powerd_vtf/hvdc_systems_gea-31971_lr.pdf

HVDC en la Planeación



http://www.energynet.co.uk/webfm_send/2149

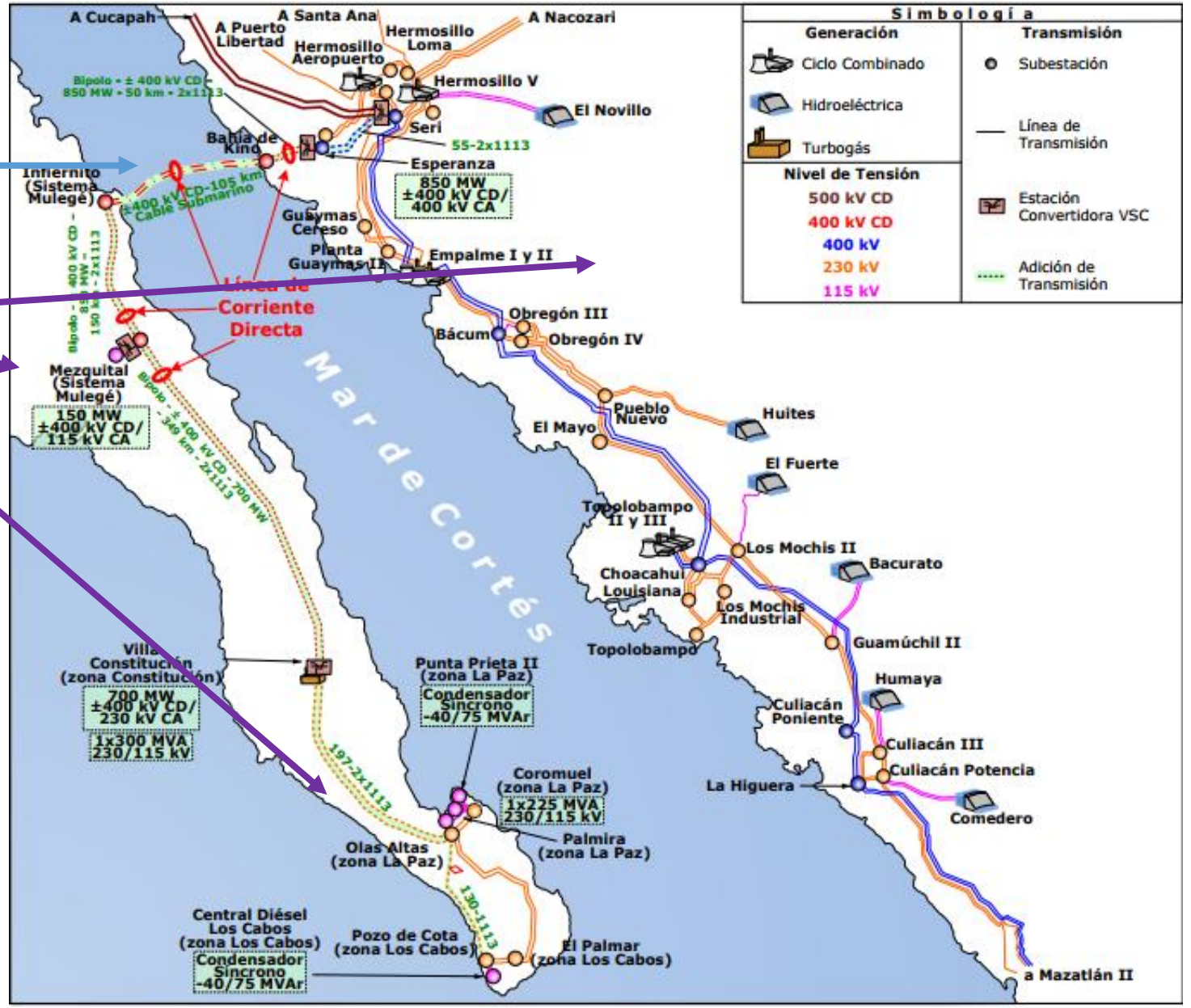
Aplicaciones de HVDC

1. Transmisión por cable, submarino o subterráneo
2. Enlace asíncrono entre sistemas de corriente alterna
3. Transmisión de gran potencia en grandes distancias usando líneas aéreas (casi 550 km aérea y 100 km cable)

VSC

1. Línea aérea: 50 km
2. Cable submarino: 105 km
3. Línea aérea: 150 km
4. Línea aérea: 349 km

Diagrama con el proyecto Interconexión BCS-SIN (multiterminales)



http://b4.cigre.org/content/download/1971/25259/version/1/file/What+is+HVDCID10VER33.pdf

http://www.cenace.gob.mx/Docs/Planeacion/ProgramaRNT/Programa%20de%20Ampliaci%C3%B3n%20y%20Modernizaci%C3%B3n%20de%20la%20RNT%20y%20RGD%202017-2031.pdf

SIN + Mulegé + BCS ➔ Instruido

PROYECTOS Y OBRAS EN LA RED NACIONAL DE TRANSMISIÓN BAJO ESQUEMAS DE ASOCIACIÓN O CONTRATO

Transmisión

SENER

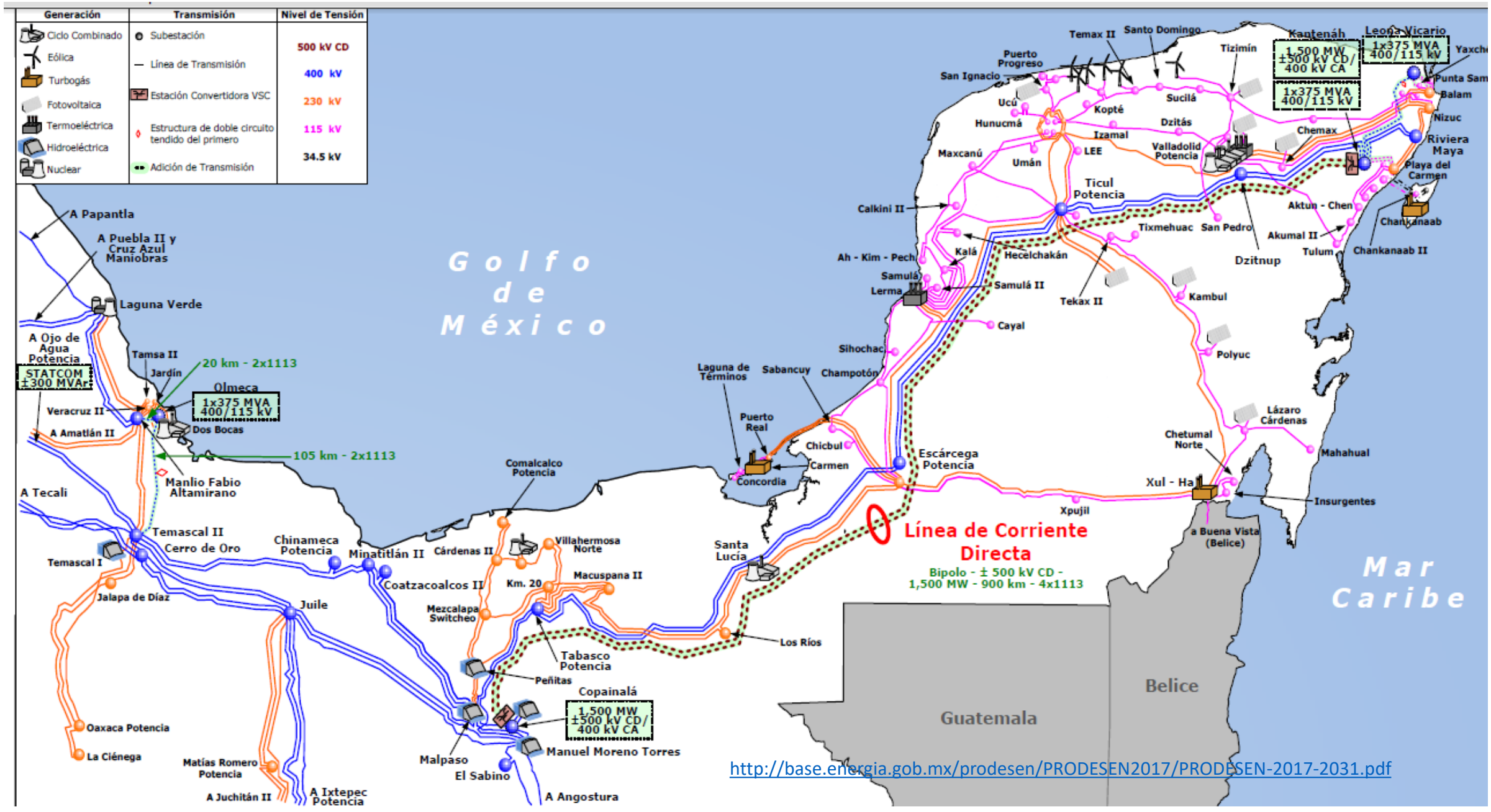
Interconexión Sistema Interconectado Nacional-Baja California Sur

FEOF: Abr-2022

Obras	Gerencia de Control Regional	Tensión kV	Equipo	Transmisión		Transformación		Compensación
				Circuitos	km-c	MVA	Relación	MVAr
Coromuel entronque Punta Prieta II - Palmira	Baja California Sur	115	1 CA	2	4.0			
Villa Constitución - Olas Altas		230	1 CA	2	394.0			
Olas Altas - Pozo de Cota [1/]		230	1 CA	2	130.0			
Coromuel Banco 1			4 AT			133.0	230/115	
Villa Constitución Banco 1			4 AT			300.0	230/115	
Villa Constitución Estación Convertidora VSC			1 EC			840.0	±400/230	
Olas Altas MVAr		115	1 CAP					15.0
Villa Constitución MVAr		115	1 CAP					12.5
Central Diésel Los Cabos Condensador Síncrono		115	1 CON					40 Ind./75 Cap.
Punta Prieta II Condensador Síncrono		115	1 CON					40 Ind./75 Cap.
El Infiernito - Mezquital [2/]	Mulegé	±400	1 CD	Bipolo	300.0			
El Infiernito - Bahía de Kino [2/, 3/]		±400	1 CD	Bipolo	210.0			
Mezquital - Villa Constitución [2/]		±400	1 CD	Bipolo	698.0			
Mezquital Estación Convertidora VSC			1 EC			180.0	±400/115	
Bahía de Kino - Esperanza [2/]	Noroeste	±400	1 CD	Bipolo	100.0			
Esperanza - Seri		400	1 CA	2	110.0			
Esperanza Estación Convertidora VSC			1 EC			1,020.0	±400/400	

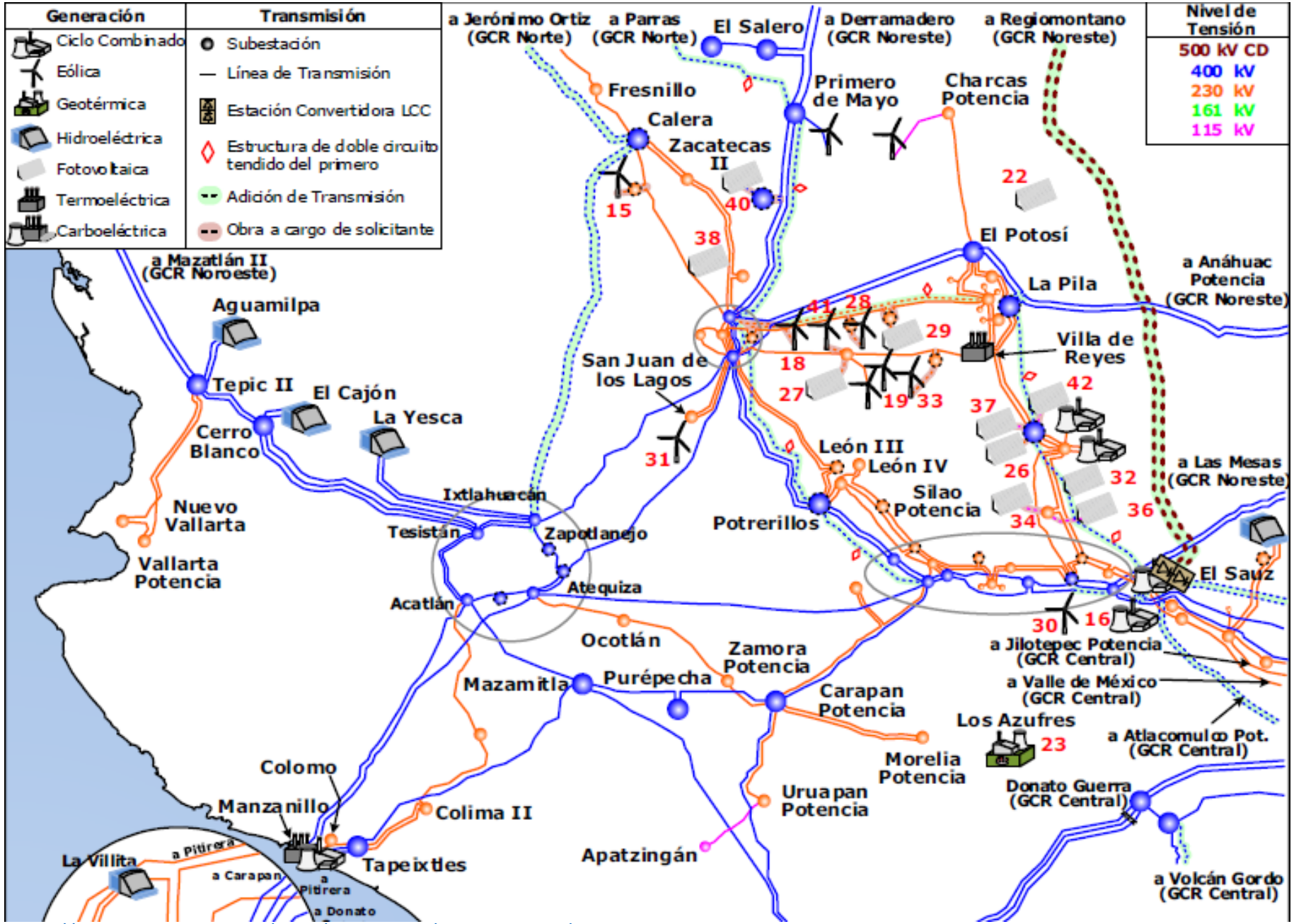
https://www.gob.mx/cms/uploads/attachment/file/252148/Proyectosyobrasinstruidos.pdf

Sureste Peninsular ±500 kV CD, 1500 MW, 900 km, VSC



http://base.energia.gob.mx/prodesen/PRODESEN2017/PRODESEN-2017-2031.pdf

http://www.cenace.gob.mx/Docs/Planeacion/ProgramaRNT/Programa%20de%20Ampliaci%C3%B3n%20y%20Modernizaci%C3%B3n%20de%20la%20RNT%20y%20RGD%202017-2031.pdf



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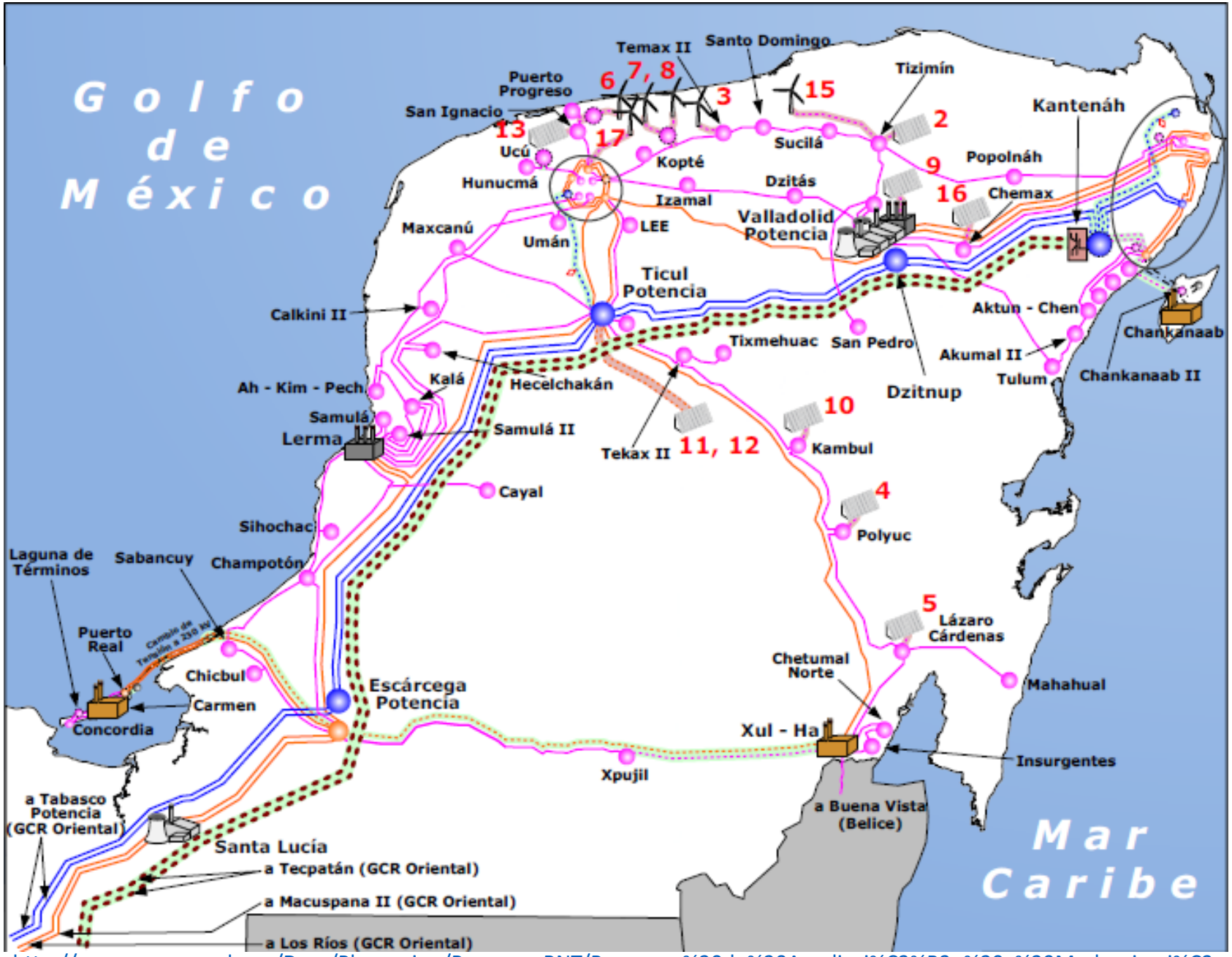

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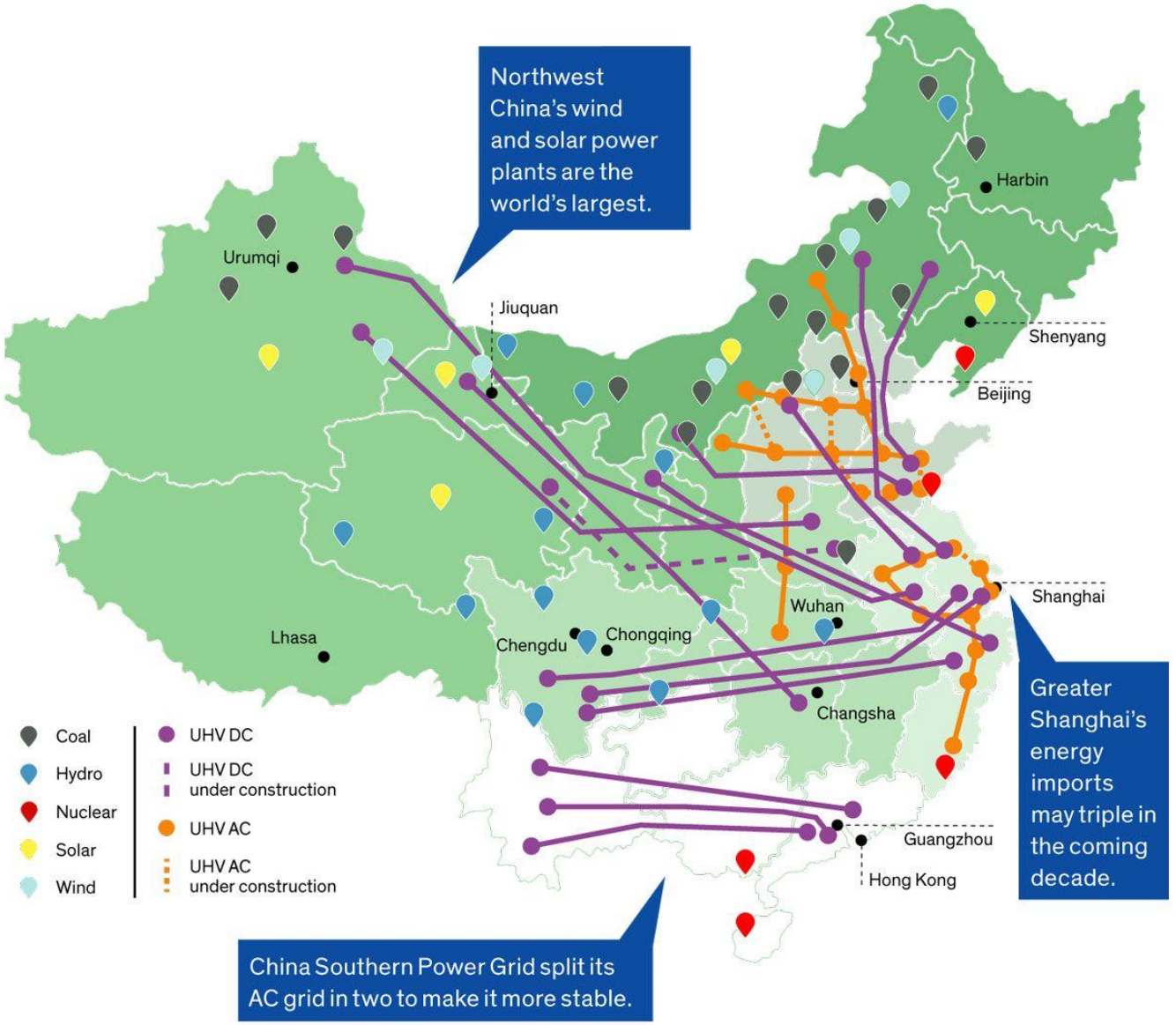


https://spectrum.ieee.org/chinas-ambitious-plan-to-build-the-worlds-biggest-supergrid

HVDC en China al 2013

China Power Southern Grid = CSG

State Grid Corporation of China = SGCC

Los que están en azul son **U**HVDC

El que está en rojo es VSC

http://www.dsius.com/cet/HVDCinChina_EPRI2013_HVDC.pdf

国家电网 STATE GRID
国网智能电网研究院 STATE GRID SMART GRID RESEARCH INSTITUTE

C-EPRI

HVDC Projects In Operation (1987~2013)

A young but booming market

No.	Commercial operation	Project name	Voltage (kV)	Capacity (MW)	Distance (km)	EPC/User
1	1987	Zhoushan	-100	50	54	SGCC
2	1990	Gezhouba-Nanqiao	±500	1200	1045	SGCC
3	2001	Tianshengqiao-Guangzhou	±500	1800	980	CSG
4	2002	Shengsi	±50	60	66.2	SGCC
5	2003	Three Gorges-Changzhou	±500	3000	860	SGCC
6	2004	Guizhou-Guangdong I	±500	3000	882	CSG
7	2004	Three Gorges-Guangdong	±500	3000	940	SGCC
8	2005	Lingbao Back-to-Back I	120	360	-	SGCC
9	2006	Three Gorges-Shanghai I	±500	3000	1040	SGCC
10	2007	Guizhou-Guangdong II	±500	3000	1194	CSG
11	2008	Gaoling Back-to-Back I	±125	2x750	-	SGCC
12	2009	Lingbao Back-to-Back II	166.7	750	-	SGCC
13	2010	Deyang-Baoji	±500	3000	534	SGCC
14	2010	Hulunbuir-Liaoning	±500	3000	908	SGCC
15	2010	Xiangjiaba-Shanghai	±800	6400	1907	SGCC
16	2010	Yunnan-Guangdong	±800	5000	1418	CSG
17	2011	Ningdong-Shandong	±660	4000	1335	SGCC
18	2011	Three Gorges-Shanghai II	±500	3000	970	SGCC
• 19	2011	Nanhui wind farm integration	±30	18	8.4	SGCC
20	2012	Sino-Russia Back-to-Back	±125	750	-	SGCC
21	2012	Qinghai-Tibet (Above 10K ft)	±400	600	1038	SGCC
22	2012	Jinping-Sunan	±800	7200	2093	SGCC
23	2012	Gaoling Back-to-Back II	±125	2x750	-	SGCC

! • represents the VSC-HVDC projects

SGCC y CSG

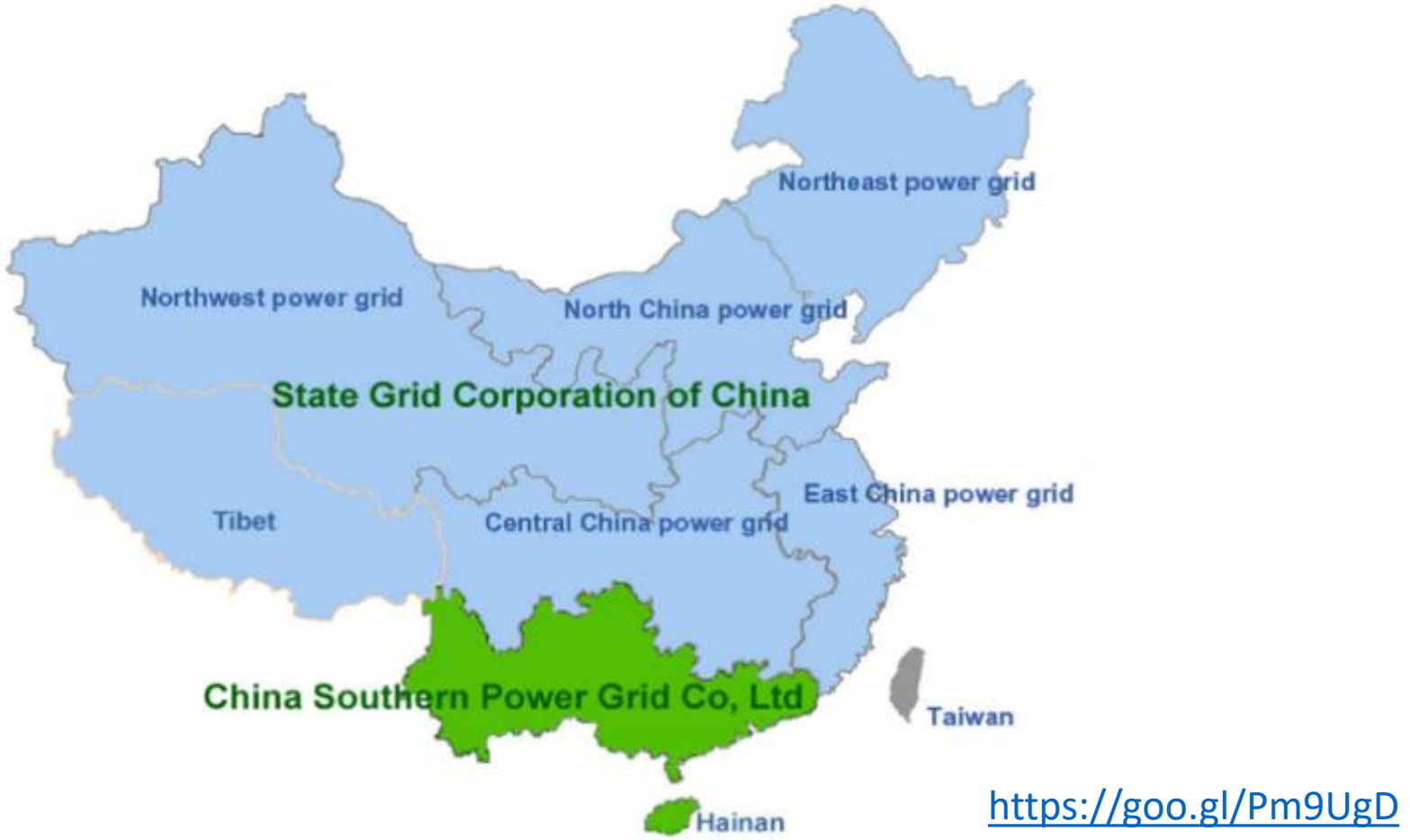
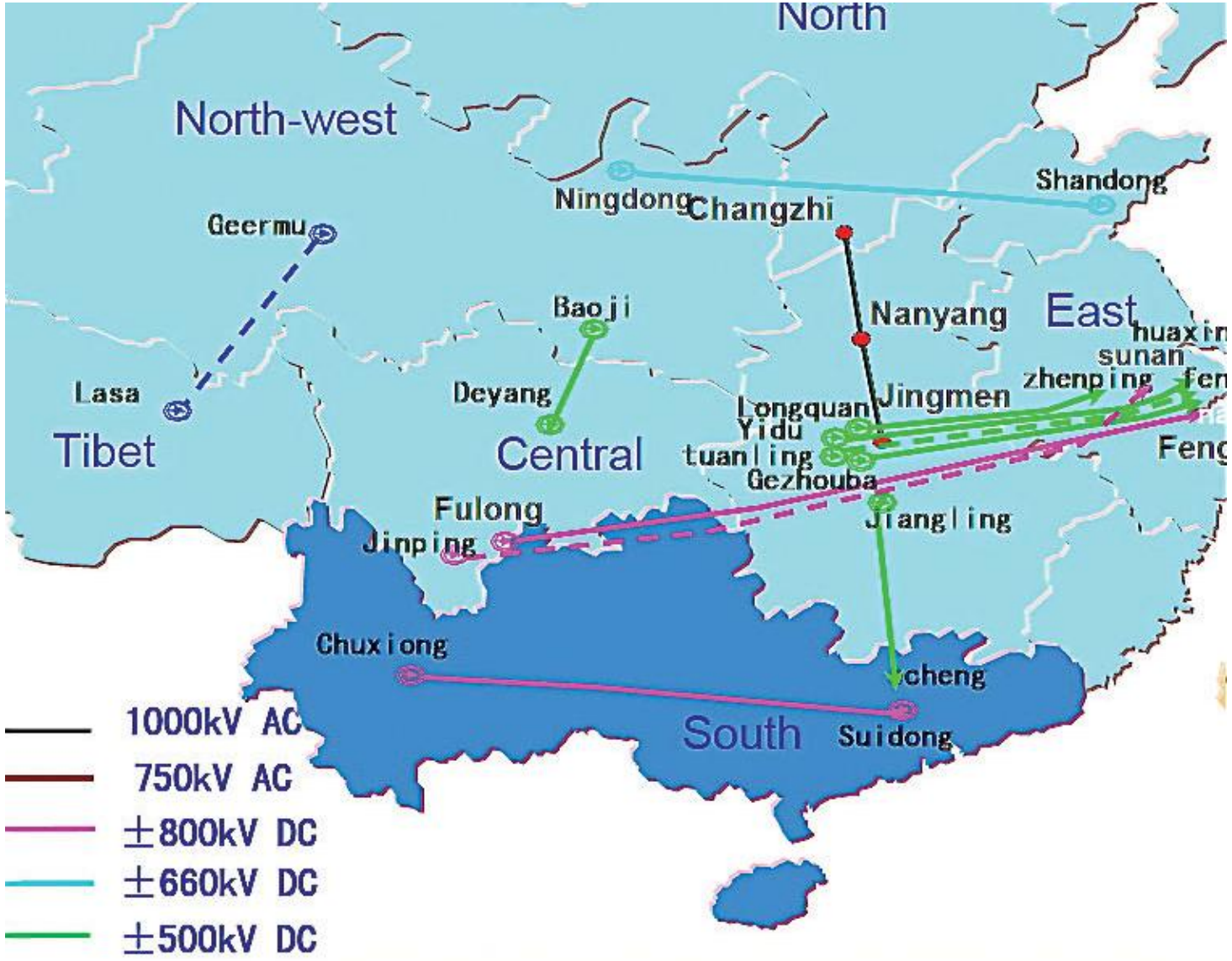


Fig. 1. The geographical coverage of SGCC and CSG.
(Source: St. John, 2014)

https://goo.gl/Pm9UgD

UHVDC

- La transmisión en corriente directa a voltajes mayores a ±800 kV ha sido una tendencia creciente en China, donde la mayoría del recurso hidroeléctrico se encuentra en el oeste, el carbón en el noroeste y los centros de carga se ubican en el este y el sur.



UHVDC en China (State Grid Corporation of China)

http://www.sgcc.com.cn/images/ywlm/socialresponsiility/brief/2017/06/07/ADB6A512CC8CA2C5D5864D2E064D6D3F.pdf

Inicia construcción proyecto HVDC mayor longitud del mundo

Construction begins in the World's longest power transmission project, the ±1100KV Changji-Guquan UHVDC

On the 4th January 2017, the assembly of the first transmission tower in the ±1100KV UHVDC Changji-Guquan project was completed. The tower will support the 3324km UHVDC transmission line as it crosses the Qinling Mountains, the west-east range that crosses the Shaanxi province, in the NorthWest of China.

Figure 1. UHVDC Transmission Tower (Source: Xinhua WANG)

https://hvdcnewschina.blogspot.mx/2017/01/world-longest-power-transmission.html

UHVDC en ±1,100 kV; 12,000 MW

This project is the one of most advanced Ultra High Voltage DC transmission projects globally, an the first at 1100kV transmission voltage, also breaking the records for largest transmission capacity, and longest transmission distance. The project is part of the Chinese Government's strategy for 'transmitting power from the West to the East of China'. It has ability to transmit 66 billion KWh annually, which equal reducing coal transport around 30.24 million tones, declining 59.4 million tones CO2, above all it reducing the dependence of fossil-fuel based power plants in Eastern China.

Changji - Guquan

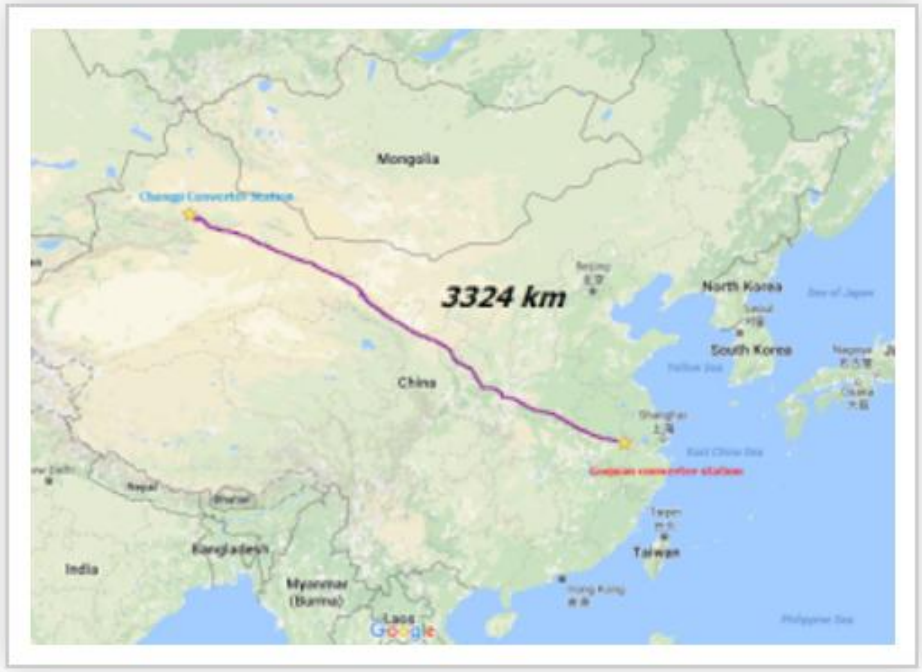


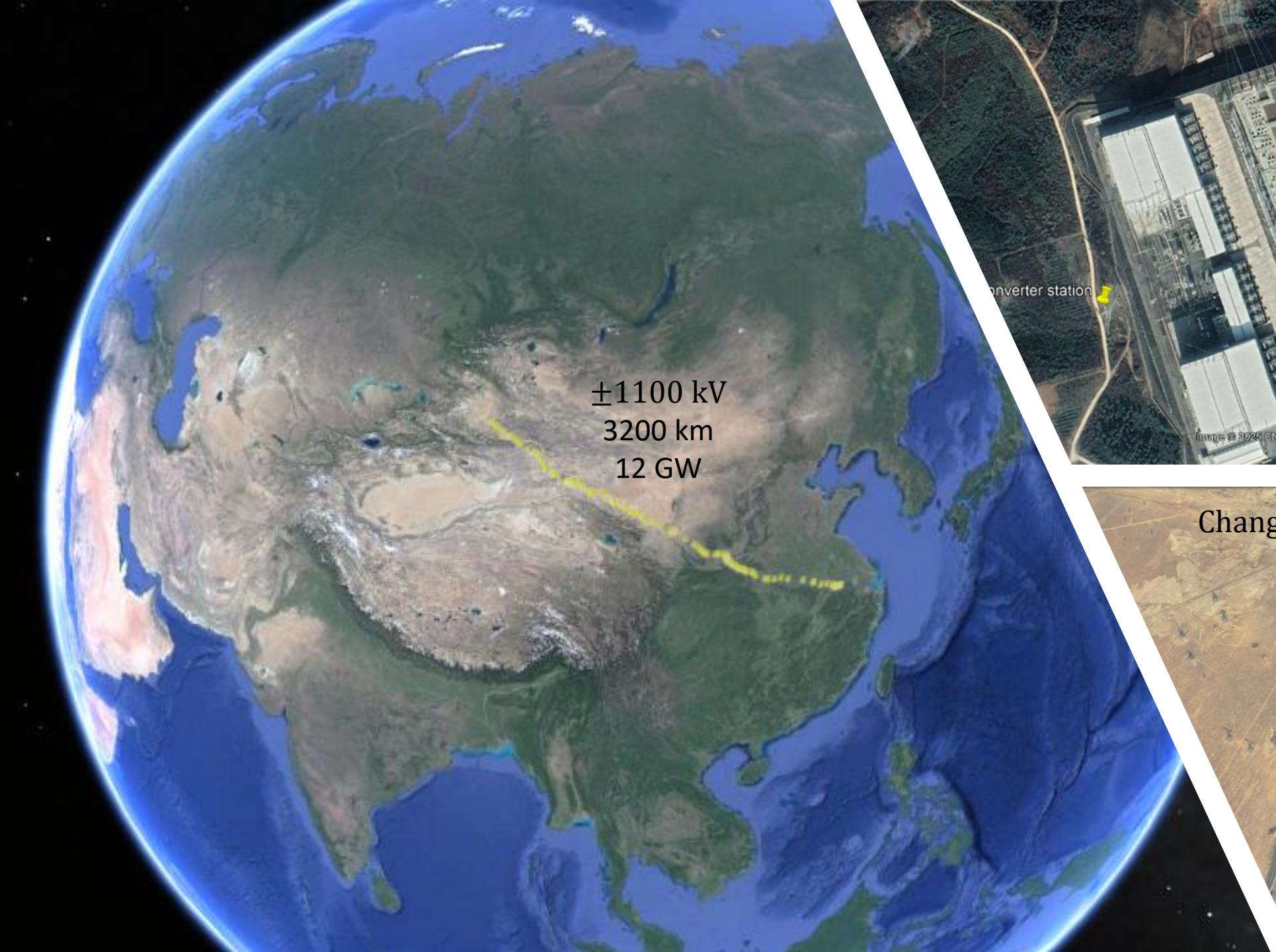
Figure 2 Changji - Guquan UHVDC transmission line route (Source: Zhundong)

https://hvdcnewschina.blogspot.mx/2017/01/world-longest-power-transmission.html

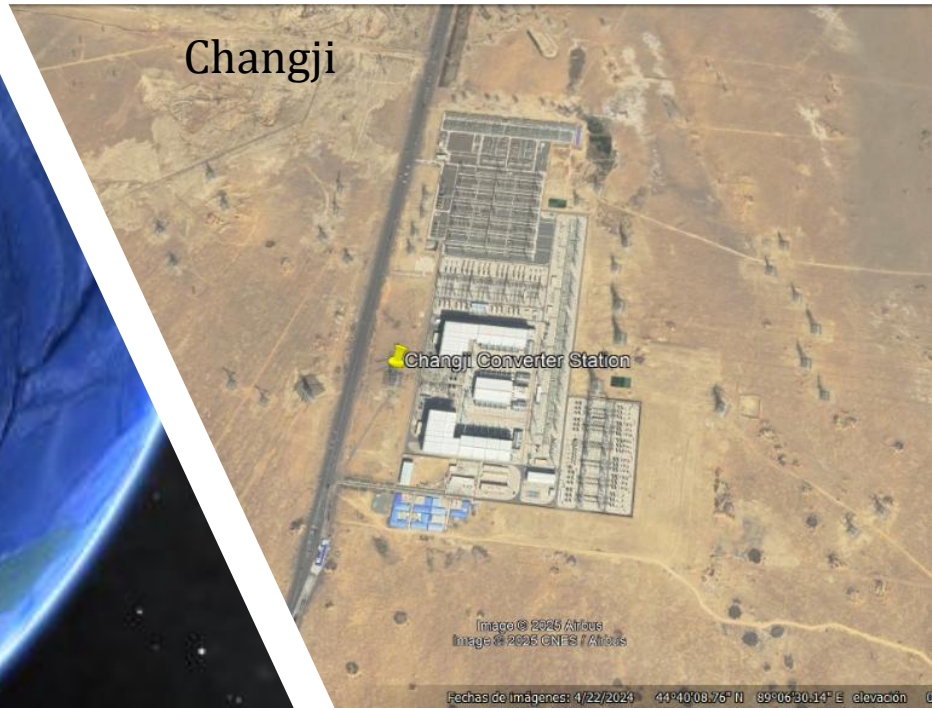
https://www.nsenergybusiness.com/projects/changji-guquan-uhvdc-transmission-project/

DC 1,100 kV Guquan Converter Station

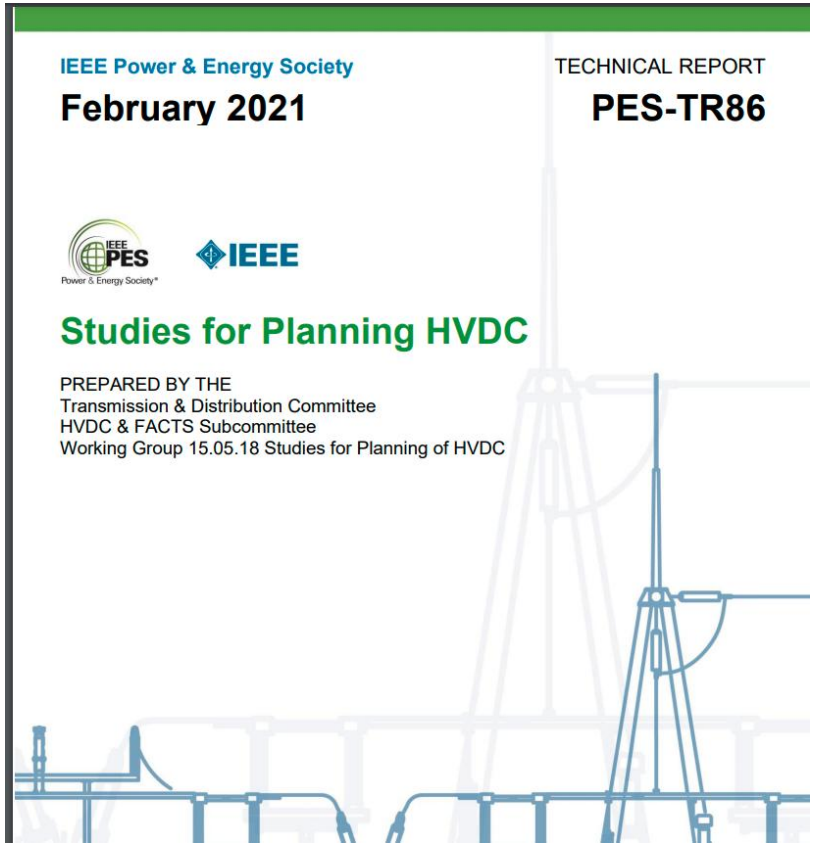
https://www.hbxhgf.com/


±1100 kV
3200 km
12 GW


onverter station
Guquan


Changji
Changji Converter Station

IEEE -PES



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High-Voltage DC Circuit Breakers - IEEE Power and Energy Society
www.ieee-pes.org › trending-technologies › high-voltage-dc-circuit-breakers
HVDC transmission systems are being built rapidly to integrate the renewable generation resources through point to point, multiterminal and **HVDC** grids due to ...

IEEE Transaction on Smart Grid
www.ieee-pes.org › images › files › pdf › Call_for_Papers_HVDC_Jan_2012
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control, design, and testing of **HVDC** systems and technologies from industry and academia worldwide. Preference will be given to papers that describe and ...

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presence of **HVDC** and AC transmission systems at the same support structure. Christian Romeis, Matthias Luther, Johann Jaeger. FAU Erlangen-Nuremberg.

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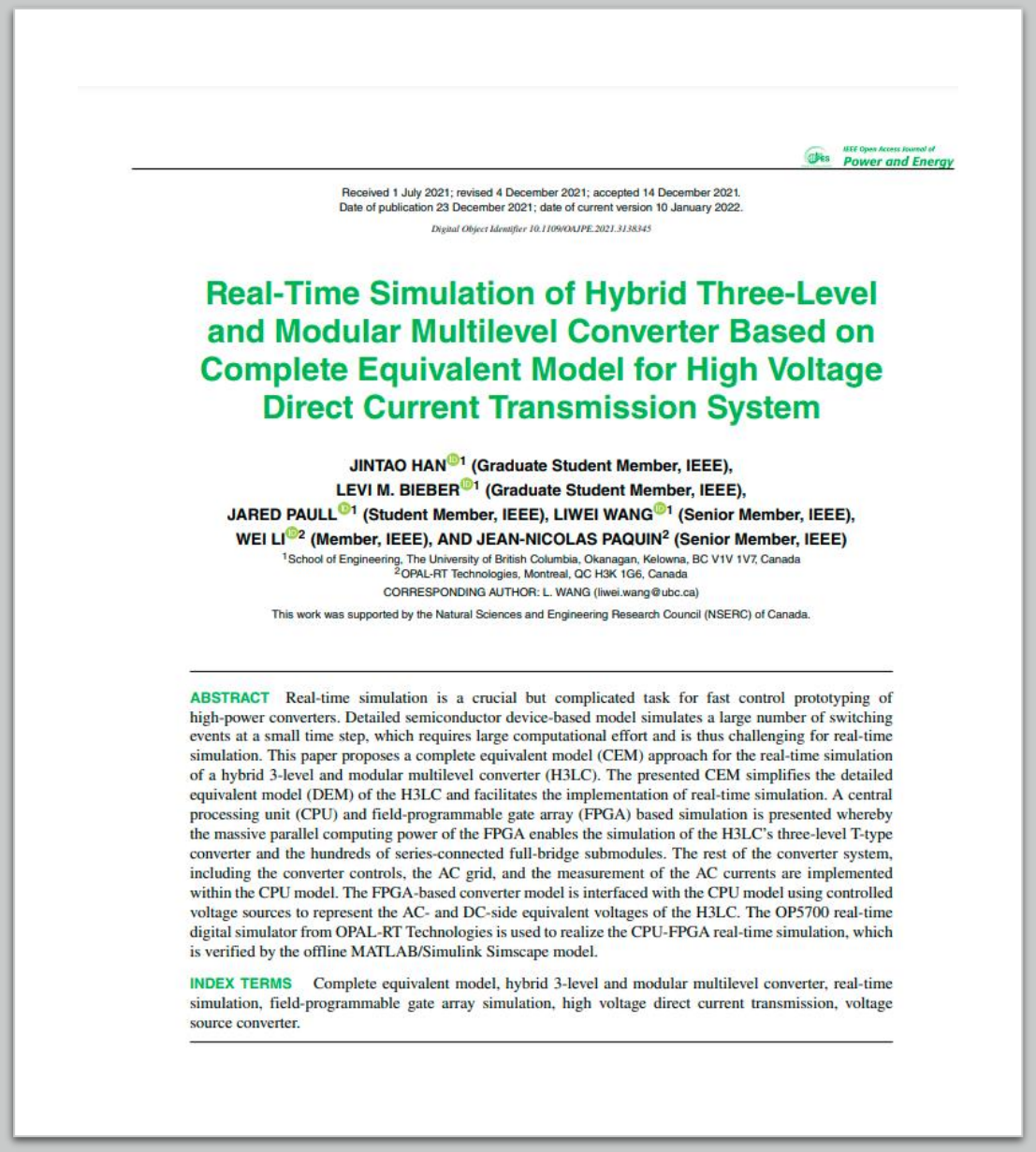

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Real-Time Simulation of Hybrid Three-Level and Modular Multilevel Converter Based on Complete Equivalent Model for High Voltage Direct Current Transmission System

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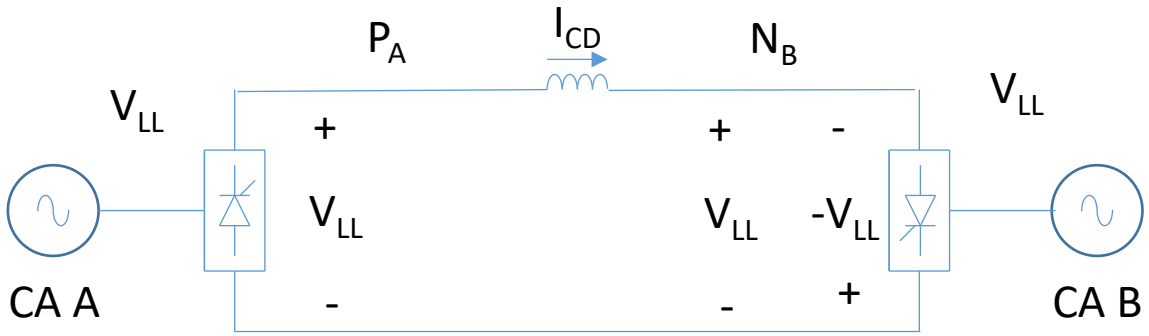
ABSTRACT Real-time simulation is a crucial but complicated task for fast control prototyping of high-power converters. Detailed semiconductor device-based model simulates a large number of switching events at a small time step, which requires large computational effort and is thus challenging for real-time simulation. This paper proposes a complete equivalent model (CEM) approach for the real-time simulation of a hybrid 3-level and modular multilevel converter (H3LC). The presented CEM simplifies the detailed equivalent model (DEM) of the H3LC and facilitates the implementation of real-time simulation. A central processing unit (CPU) and field-programmable gate array (FPGA) based simulation is presented whereby the massive parallel computing power of the FPGA enables the simulation of the H3LC's three-level T-type converter and the hundreds of series-connected full-bridge submodules. The rest of the converter system, including the converter controls, the AC grid, and the measurement of the AC currents are implemented within the CPU model. The FPGA-based converter model is interfaced with the CPU model using controlled voltage sources to represent the AC- and DC-side equivalent voltages of the H3LC. The OP5700 real-time digital simulator from OPAL-RT Technologies is used to realize the CPU-FPGA real-time simulation, which is verified by the offline MATLAB/Simulink Simscape model.

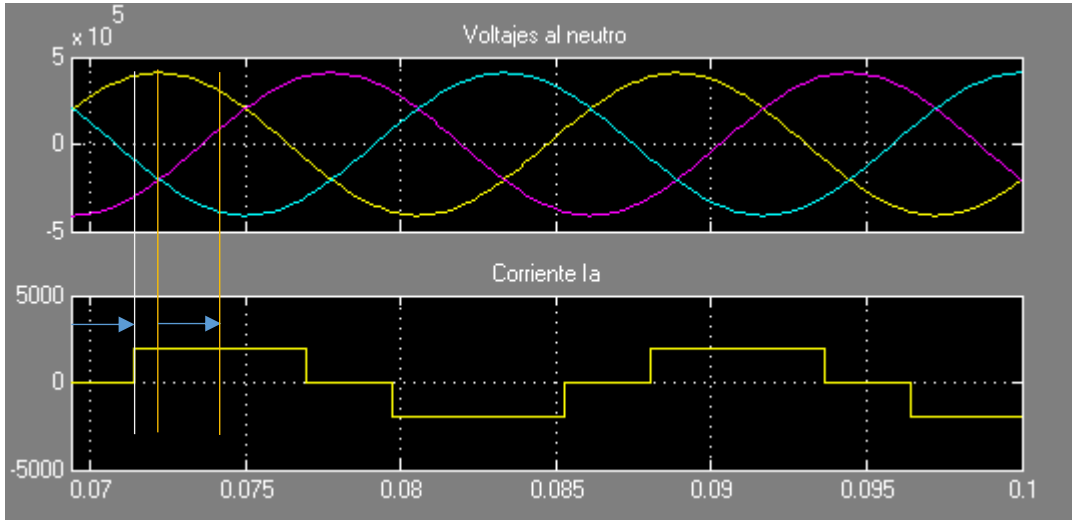
INDEX TERMS Complete equivalent model, hybrid 3-level and modular multilevel converter, real-time simulation, field-programmable gate array simulation, high voltage direct current transmission, voltage source converter.

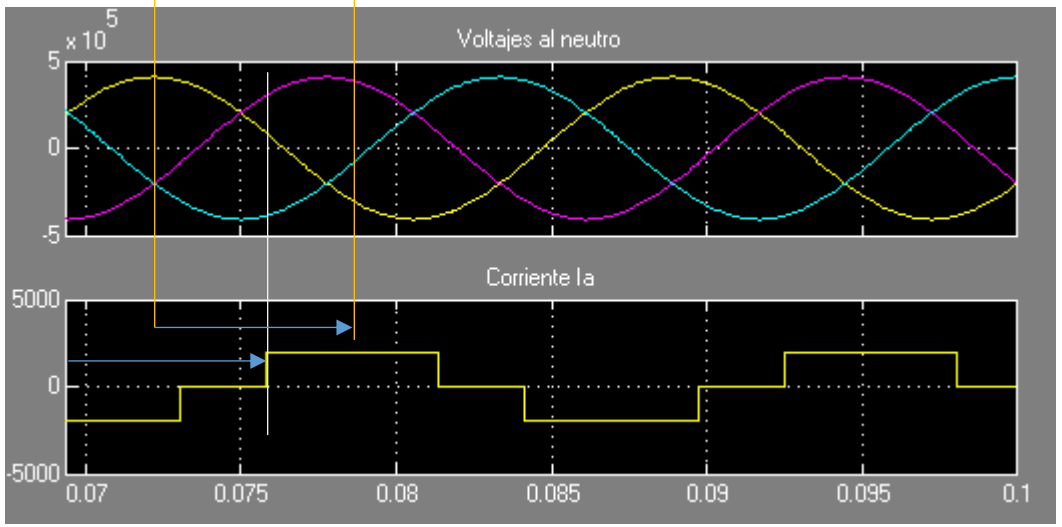
6 P Rectificador e Inversor – Flujo de potencia CA



$$\cos(\alpha_A) = \frac{\pi}{3\sqrt{2}}$$

$$\cos(\alpha_B) = -\frac{\pi}{3\sqrt{2}}$$





$$P_{1\phi} = \left(\frac{V_{LL}}{\sqrt{3}}\right)\left(\frac{\sqrt{6}}{\pi} I_{CD}\right)\cos(\alpha_A) = \frac{\sqrt{2}}{\pi} V_{LL} I_{CD} \cos(\alpha_A)$$

$$P_{3\phi} = \left(\frac{3\sqrt{2}}{\pi} V_{LL}\right)(I_{CD})\cos(\alpha_A) = V_{LL} I_{CD}$$

$$P_{1\phi} = \left(\frac{V_{LL}}{\sqrt{3}}\right)\left(\frac{\sqrt{6}}{\pi} I_{CD}\right)\cos(\alpha_B) = \frac{\sqrt{2}}{\pi} V_{LL} I_{CD} \cos(\alpha_B)$$

$$P_{3\phi} = \left(\frac{3\sqrt{2}}{\pi} V_{LL}\right)(I_{CD})\cos(\alpha_B) = -V_{LL} I_{CD}$$

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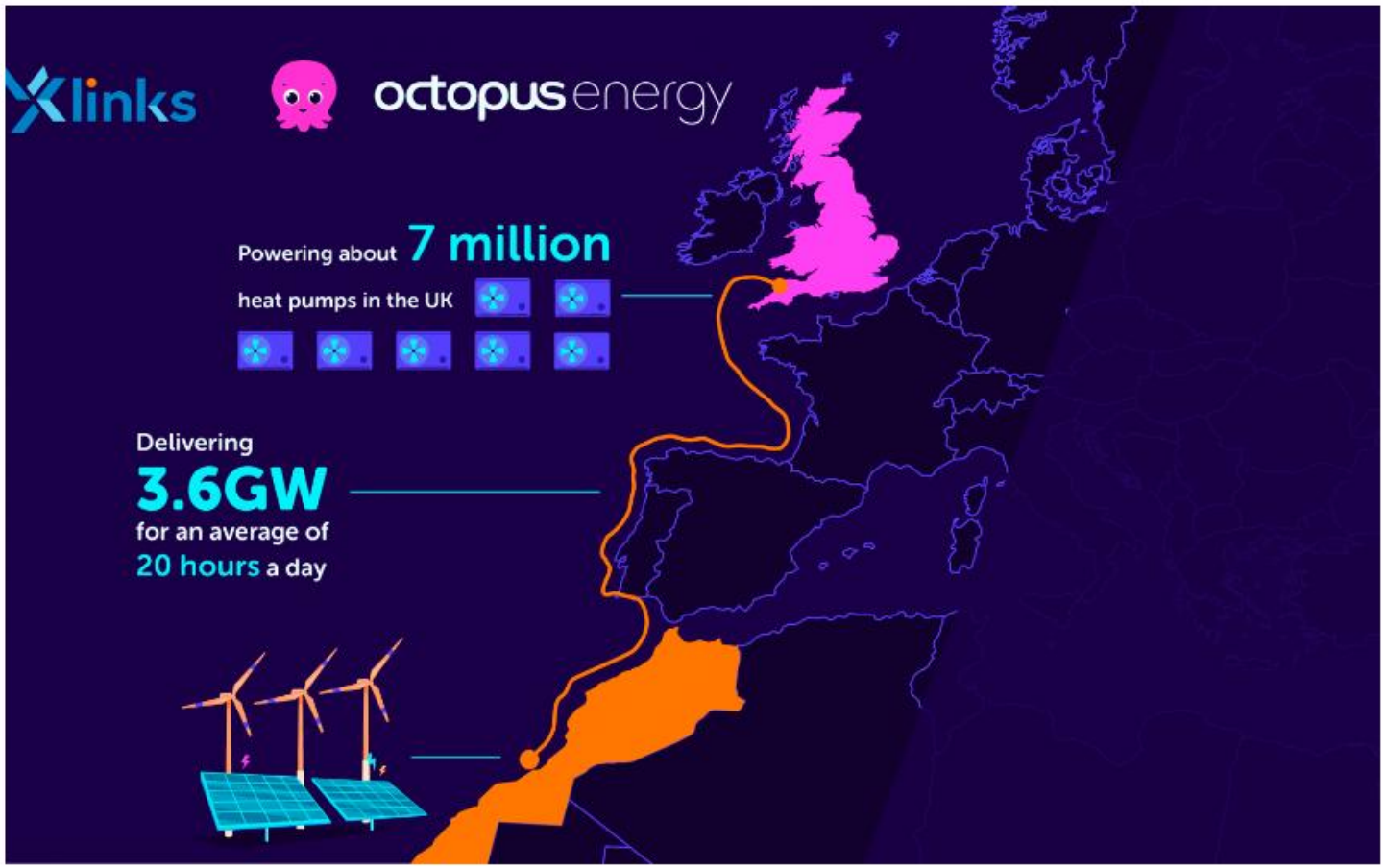
Reporter, Current±

Octopus invests in Morocco-UK power project Xlinks as it signs strategic partnership



The power supplied from the project would be enough to power about 7 million heat pumps all year round, the companies said. Image: Octopus Energy.

https://www.current-news.co.uk/news/octopus-invests-in-morocco-uk-power-project-xlinks-as-it-signs-strategic-partnership

HVDC ayuda en la transición energética

Gracias

Armando Llamas

Profesor Emérito ITESM