CONVERSATORIO ::

Colombia

Junio 10

Sistemas HVDC

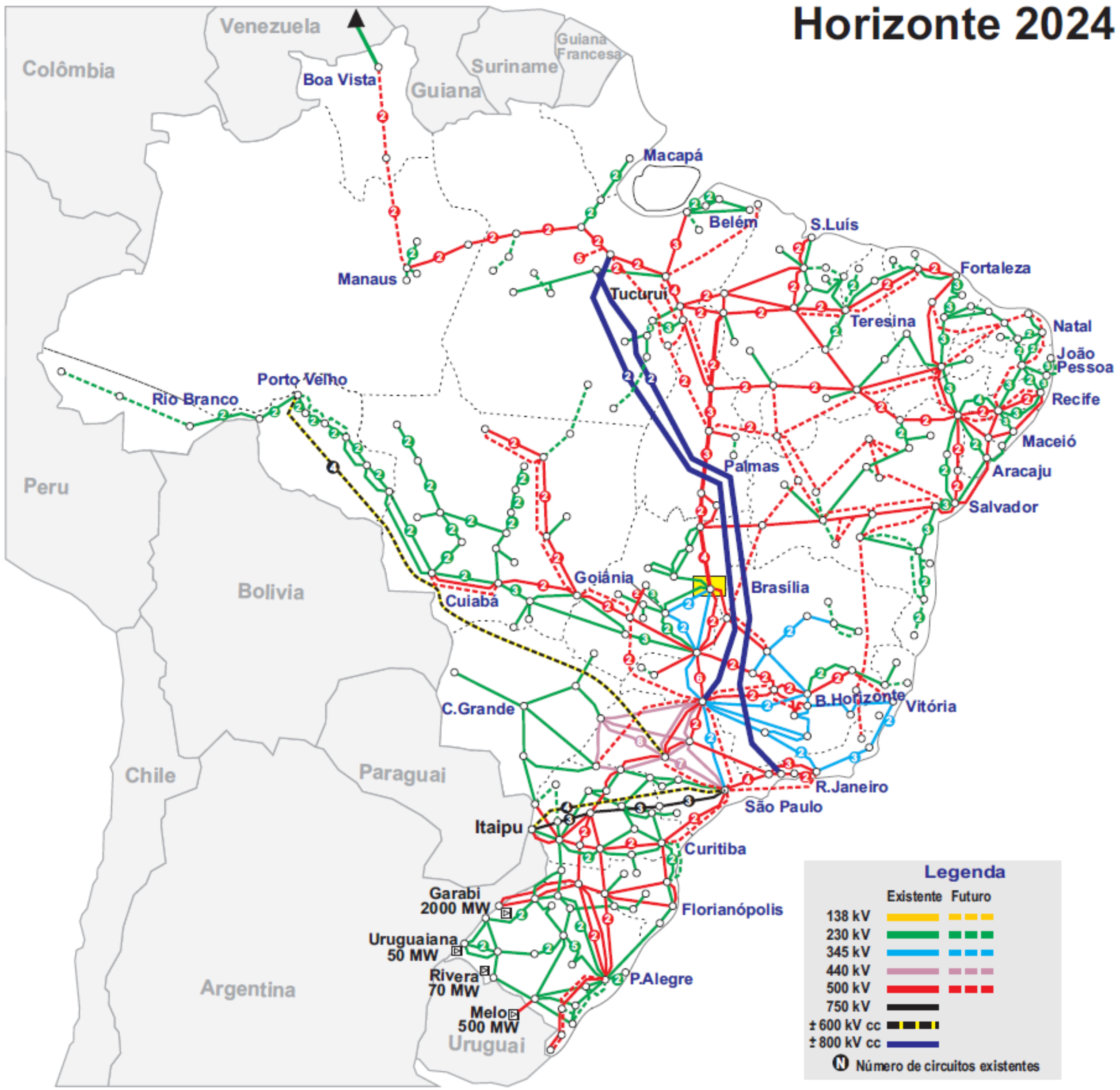
SESIÓN 2 :
Operación e impacto de Sistemas HVDC en redes existentes

HVDC Experience in Brazil – Challenges to HVDC Operation

ANTONIO RICARDO DE MATTOS TENORIO
ONS - Brasil

Un evento: CIGRE Colombia | Universidad Pontificia Bolivariana | 50 años Ingeniería Electrónica | 70 años Ingeniería Eléctrica | isa CONEXIONES QUE INSPIRAN

The Brazilian Interconnected Power System (BIPS)



- BIPS is one of the world’s largest synchronous network
- Complex Hydro-Thermal-Renewable source operated grid
- One ISO only→ ONS
- North-South oscillation mode (0.40-0.45 Hz)

8.5 million km^2

HVDC (LCC) Main Advantages

- Bulk power transmission over long distance (point-to-point)
- Asynchronous connection between systems with different frequencies
- Control of DC Power
- No stability issues related to large electrical distances
- Either no skin effect or Ferranti effect

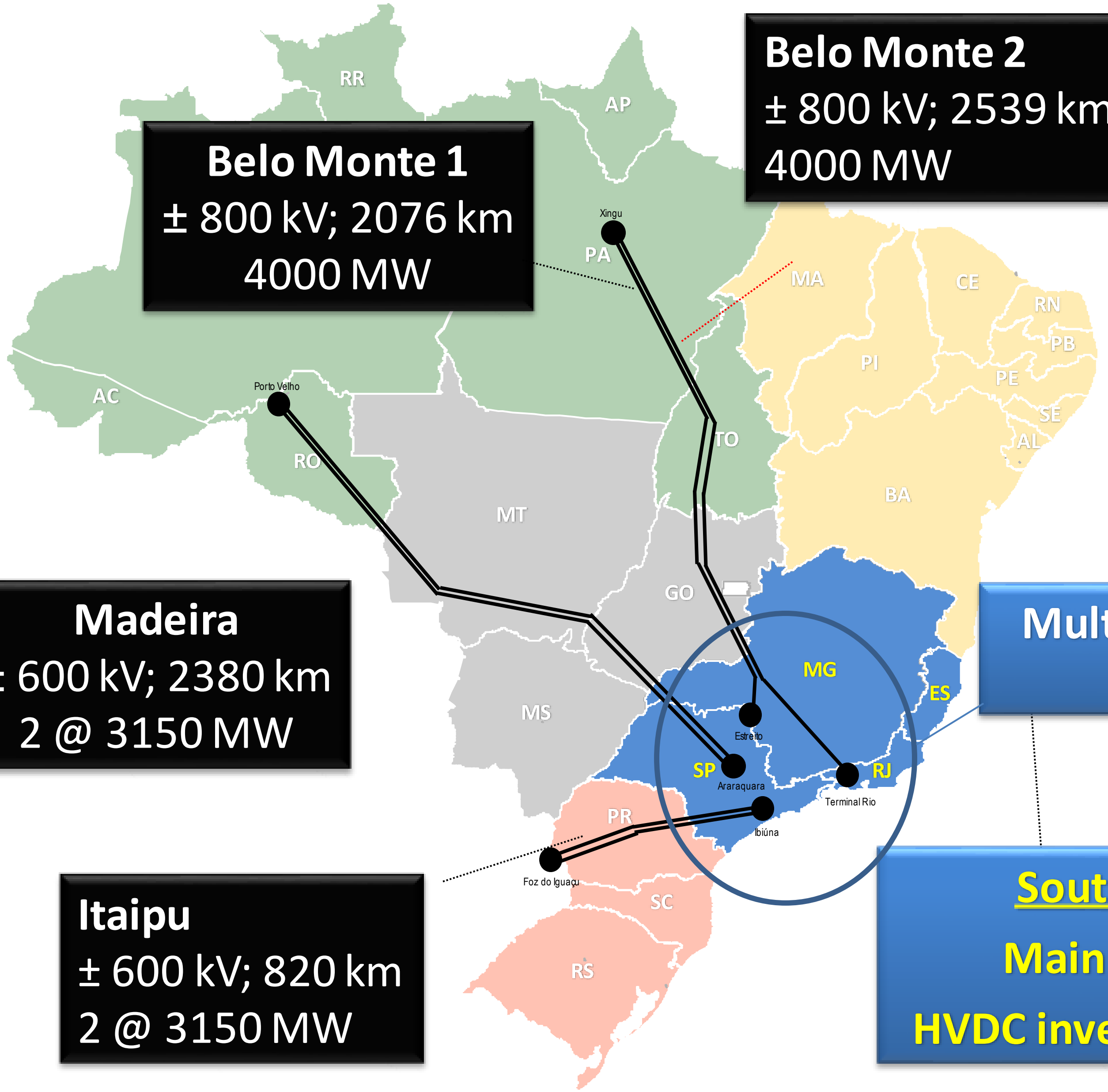
HVDC in Brazil – Main challenges

- Continental Country
- Tap power from large hydropower plants to load centers, e.g. Itaipu, Madeira & Belo Monte HPPs to Southeastern Brazil
- Mismatch between transmission and generation schedules (Madeira HVDC Project)
- Tap surplus of renewable energy into load centers, e.g. Bipole B (Graça Aranha to Silvania, close to Brasilia)
- Multi-infeed in Southeastern Brazil

HVDC Transmission in Brazil

Belo Monte 2
± 800 kV; 2539 km
4000 MW

Belo Monte 1
± 800 kV; 2076 km
4000 MW



Madeira
± 600 kV; 2380 km
2 @ 3150 MW

Multi-infeed in Southeastern Brazil

Itaipu
± 600 kV; 820 km
2 @ 3150 MW

Southeastern Brazil (2020)

Main Load Center ≈ 45 GW

HVDC inverters (6 bipoles) ≈ 20.6 GW

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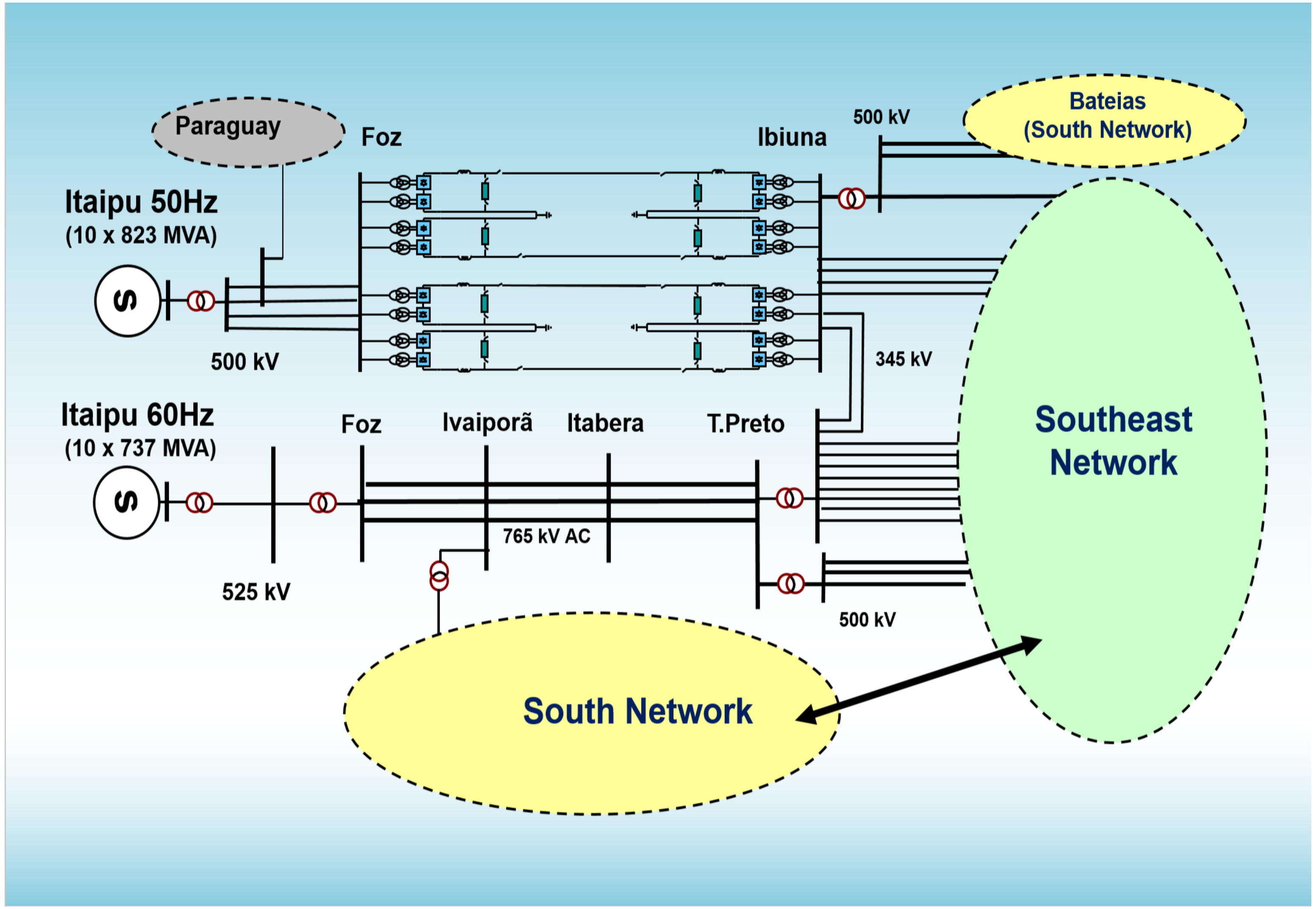
Experience and Challenges of the Itaipu Project

Itaipu Project – Challenges to the first Brazilian HVDC Link



Source: Workshop on performance & design requirements of HVDC links, CE-B4 Cigre-Brasil, 2011 (Furnas' presentation)

- **Binational Generation Project (Brazil & Paraguay)**
- **The largest hydropower plant at that time (1980s)**
- **The largest DC voltage level at that time (±600 kV)**
- **Two Bipoles rated at 3,150 MW each**
- **750 kV AC system in parallel, which was uncommon at that time**
- **Itaipu used an analogue-digital technology very advanced for that time**
- **Refurbishment to be accomplished soon**

Itaipu Project – Challenges to the first Brazilian HVDC Link

Foz do Iguaçu Converter Station

Ibiúna Converter Station

Source: Workshop on performance & design requirements of HVDC links, CE-B4 Cigre-Brasil, 2011 (Furnas' presentation)

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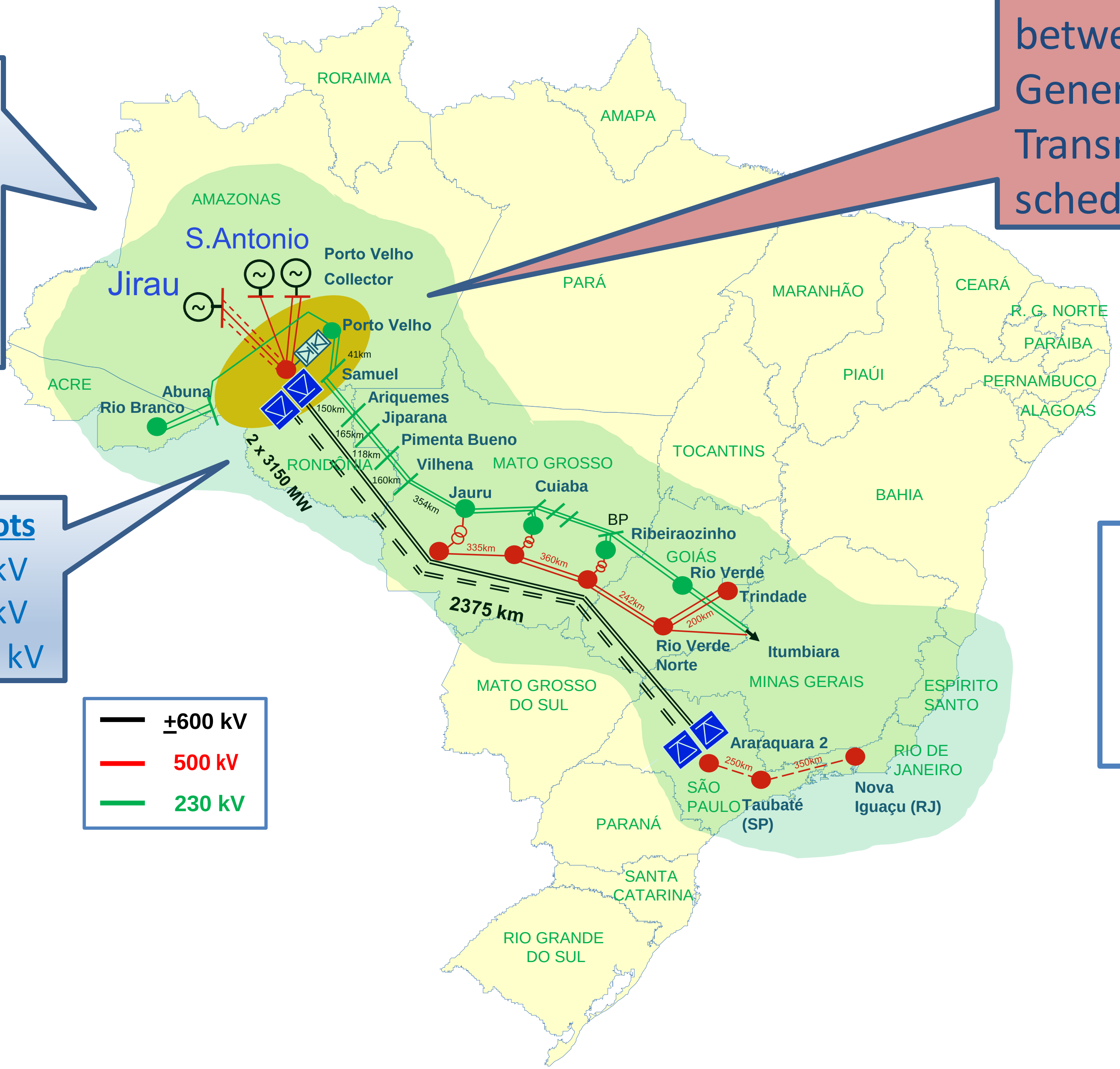
Experience and Challenges of the Madeira River Project

Madeira River HVDC Project – Main challenges

Generation Auction:
Santo Antonio Hydropower plant → 50*@82.25 = 4141 MVA
Jirau Hydropower plant → 50*@83.33 = 4166 MVA

Transmission auction – 7 lots
Bipole 1: 3150 MW, ±600 kV
Bipole 2: 3150 MW, ±600 kV
BtB : 2@400 MW, 500/230 kV

Mismatch between Generation and Transmission schedules

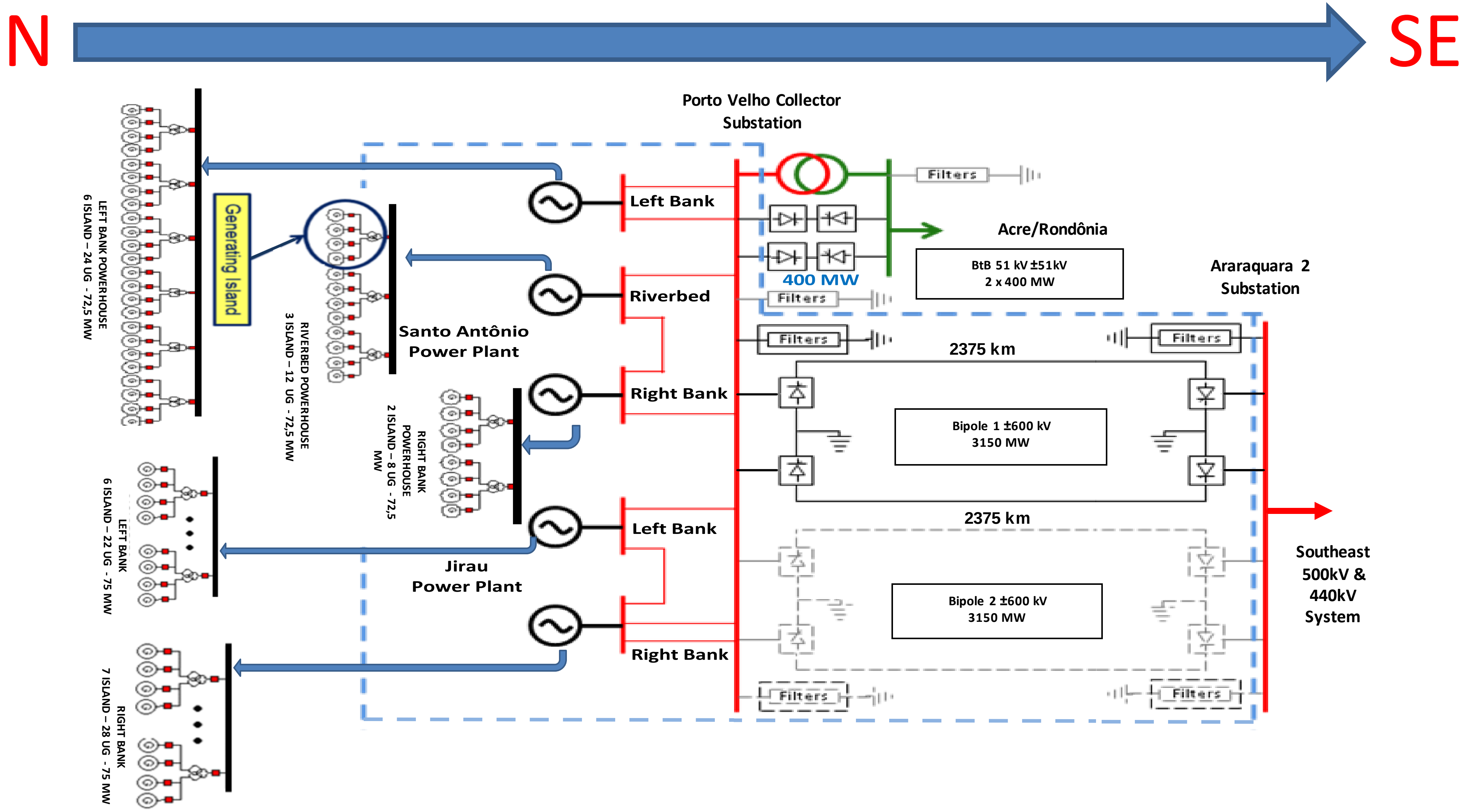


Operation
BtB – 2012
Bipole #1 – 2013
Bipole #2 – 2015

Remark: *originally 44 generating units

Brief Overview

6300 MW (SE) + 800 MW (ACRO)



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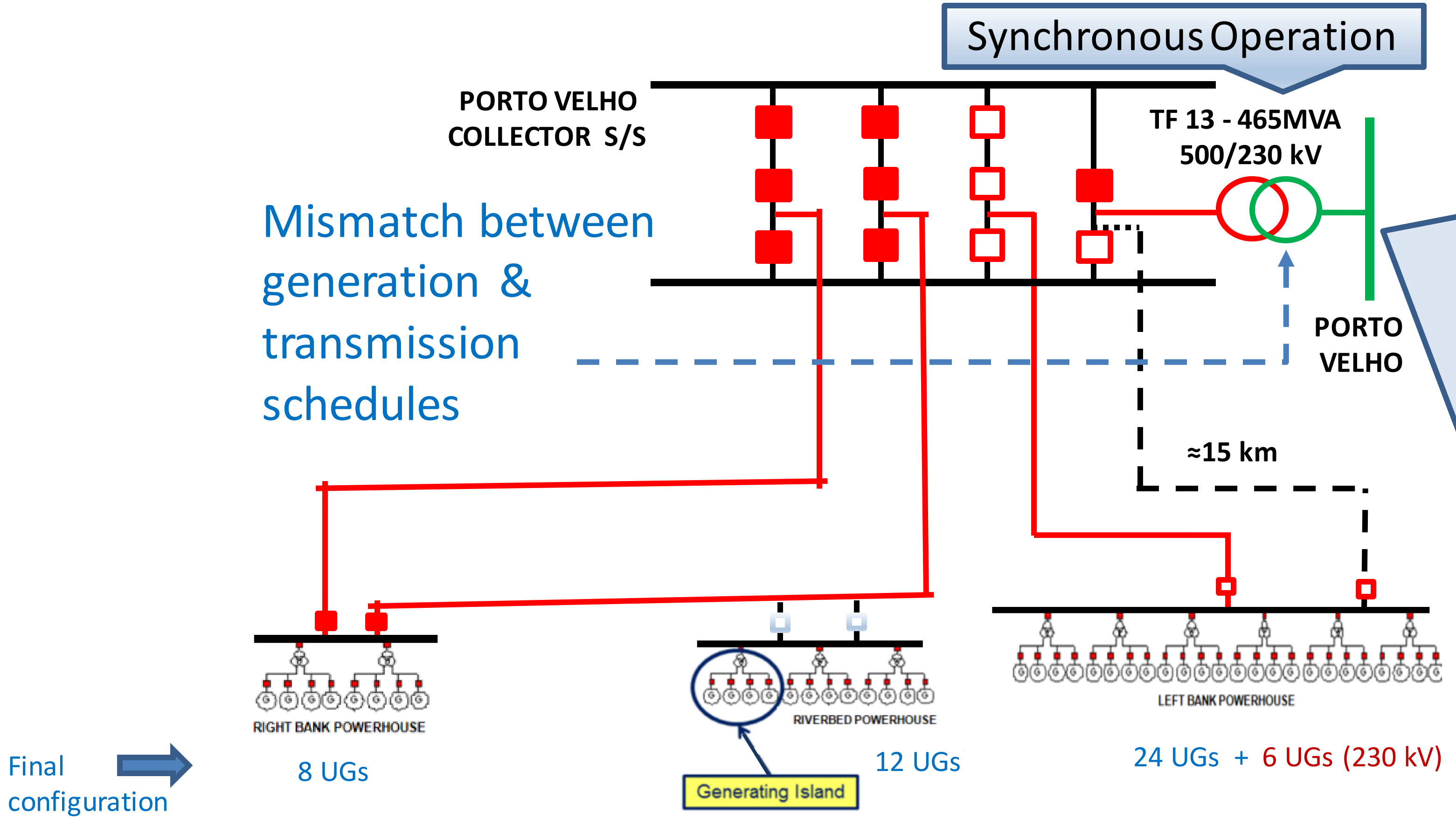
Operational Challenges of Madeira River HVDC Transmission

ONSET STAGE – COMMERCIAL OPERATION OF FIRST SAPP GENERATING UNITS



Right Bank Powerhouse	2012							
Generator Number	01	02	03	04	05	06	07	08
Commercial Operation	March 30	May 15	July 3	March 30	Sept 22	Oct 15	Nov 27	Dec 18

Left Bank Powerhouse	2012	2013						
Generator Number	09	10	11	12	13	14	15	17
Commercial Operation	Dec 29	Jan 18	March 12	April 10	June 5	June 28	Aug 13	Aug 2

Parallel 500/230 kV - 465 MVA Transformer in PVC Substation

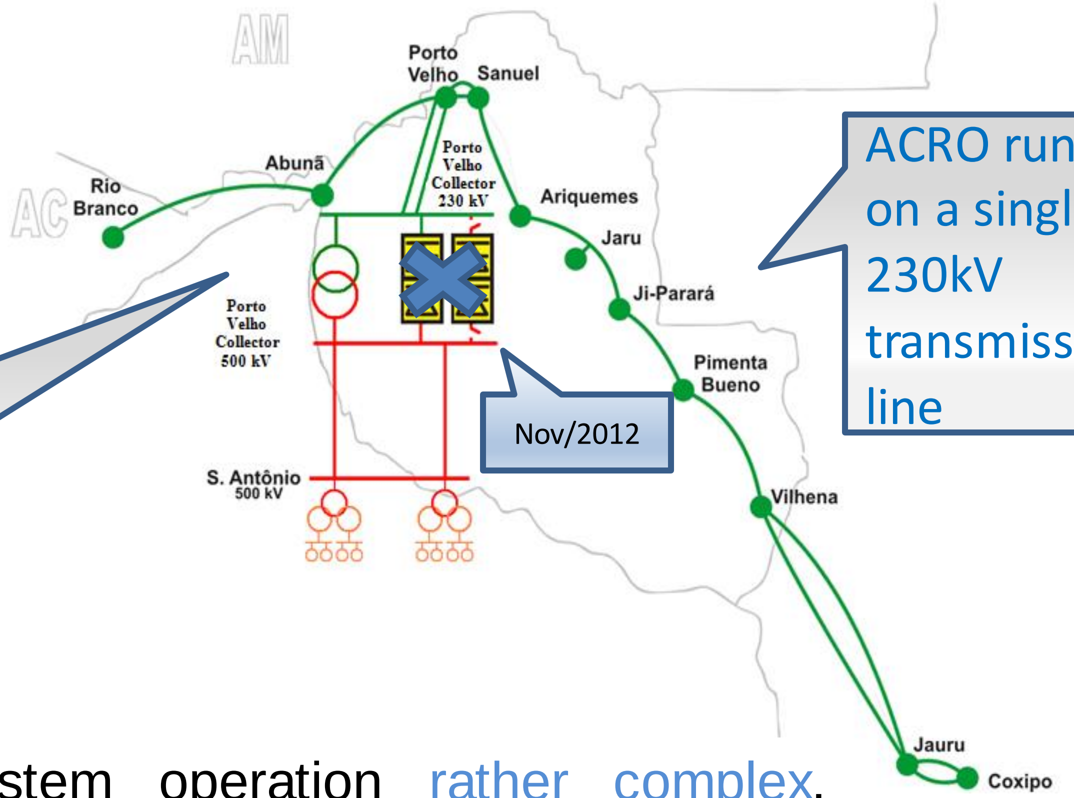
Why to connect this transformer?

- To commission SAPP generating units;

Where to connect this transformer?

- To the PVC 500 kV bay originally designed for the fourth 500kV tie circuit meant to intertie the left bank powerhouse of SAPP.
- Problems:
  - ✓Initially not relevant since the left bank powerhouse had a few generating units in operation and only eight generating units from the right bank powerhouse are connected by one 500kV tie circuit.
- This Figure also depicts the eight generating units on the right bank powerhouse already in operation connected to PVC substation through two 500kV tie circuits.
- The Tables show the Santo Antonio Power Plant generating units schedule for years 2012 and 2013.

1st STAGE – COMMERCIAL OPERATION OF FIRST SAPP GENERATING UNITS

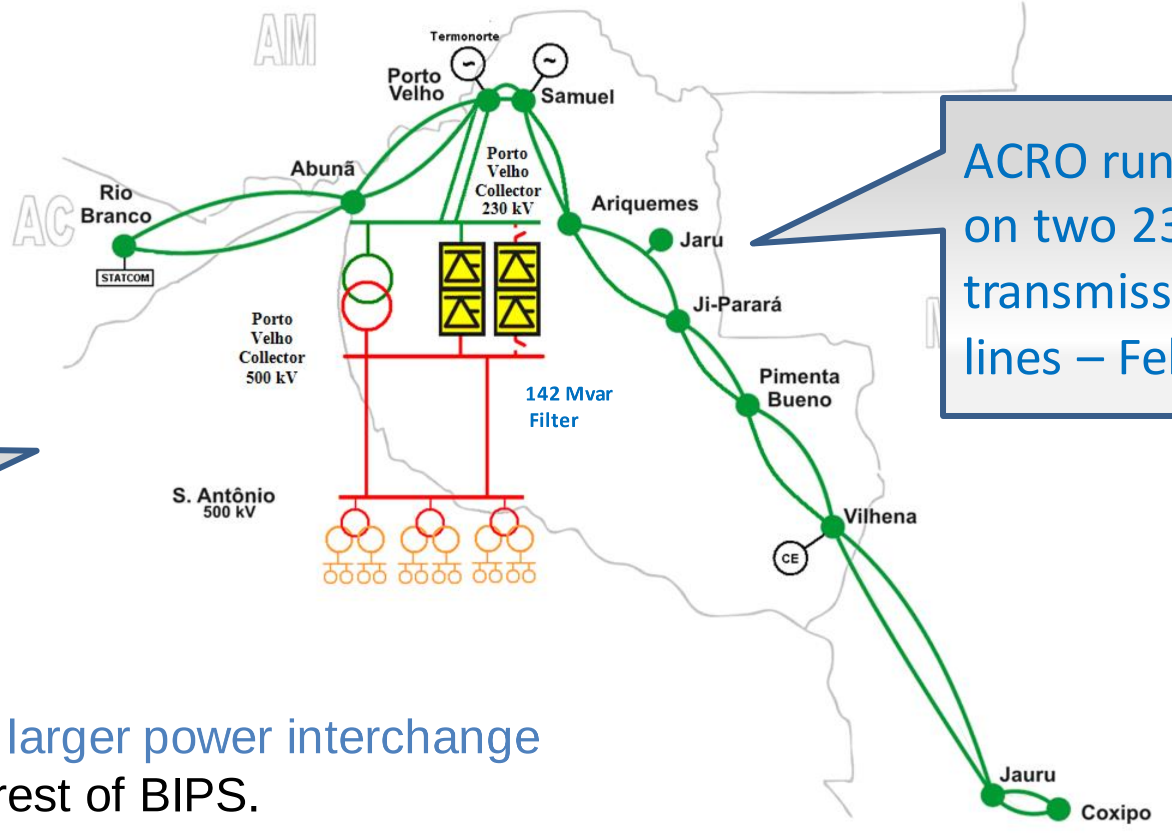


Synchronous operation of SAPP with BIPS through TF-13 (6 – 11 generators of SAPP)

ACRO running on a single 230kV transmission line

- This configuration made the system operation rather complex, especially from dynamic point of view.
- Each 230 kV circuit opening causes the ACRO interconnection to be broken resulting in the isolated operation of ACRO System from BIPS. This fact led to the need for installation of Special Protective Schemes (SPS) in order to make the whole operation of SAPP and BIPS as safe as possible.

2nd STAGE – COMMERCIAL OPERATION OF BACK-TO-BACK BLOCKS ON PVC SUBSTATION

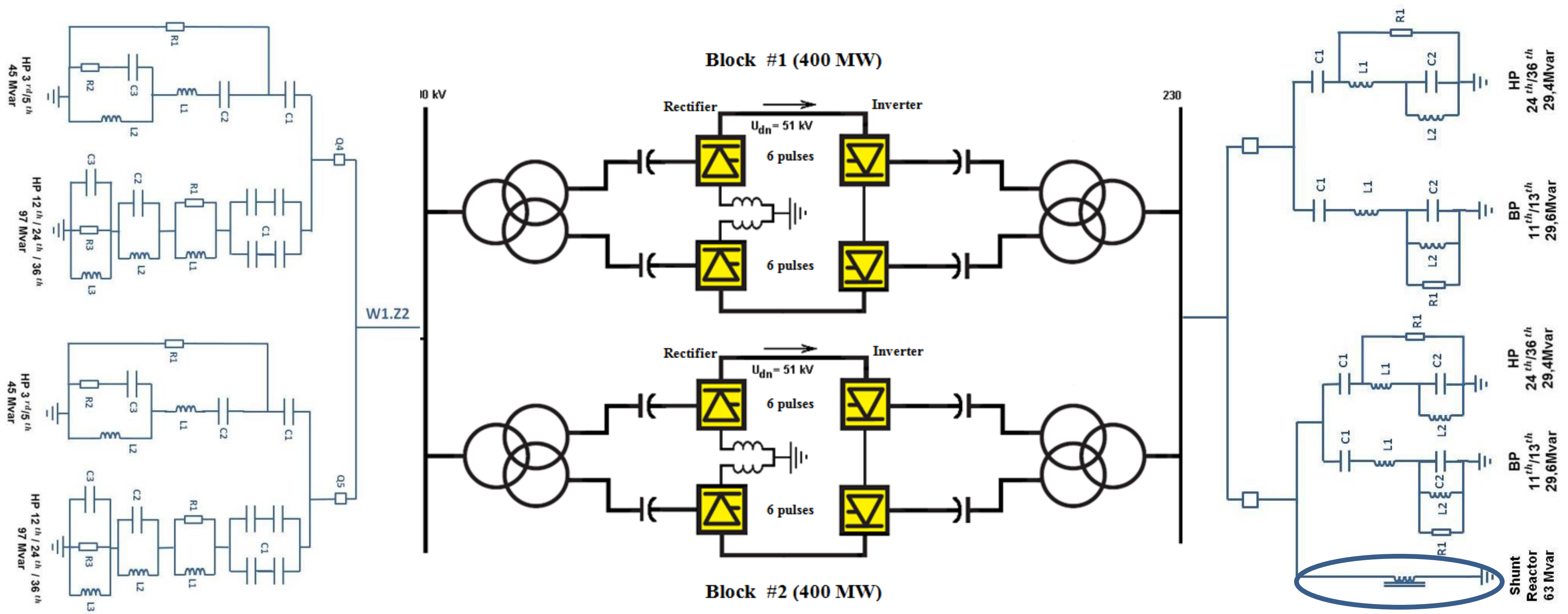


Synchronous operation between SAPP and BIPS through TF-13

ACRO running on two 230 kV transmission lines – Feb/2013

- This configuration has allowed a larger power interchange between ACRO System and the rest of BIPS.
- With the delay in Bipole #1 commissioning schedule, the only way to drain the SAPP energy towards BIPS it was running the BtB converter together with the parallel transformer.
- **System studies have shown that the asynchronous operation, i.e. no parallel transformer in service**, can only be done in a safe way when the ACRO System was in operation with three 230 kV lines between Vilhena and Porto Velho substations.

2nd STAGE – COMMERCIAL OPERATION OF BACK-TO-BACK BLOCKS ON PVC SUBSTATION



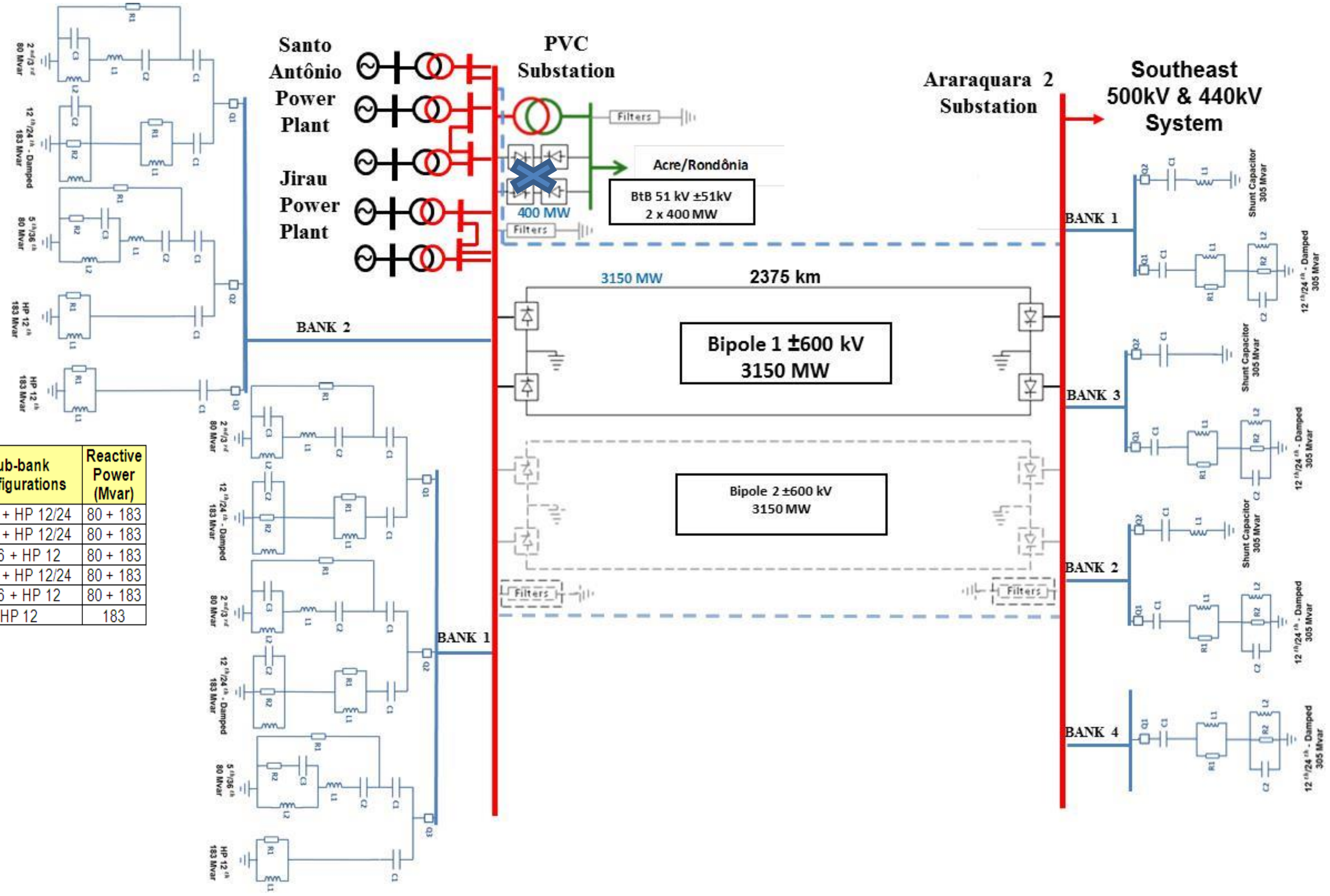
BtB Operation Mode	Minimum Number of Generating Units (SAPP)	Power Order (MW)	500kV Side - Minimum Number of Sub-banks (Mvar) to Fulfill AC Filter Performance and Rating
1 Block	4	20 - 400	1 sub-bank HP 3/5 (45Mvar) + HP 12/24/36 (97Mvar) (142 Mvar)
2 Blocks	8	80 - 800	2 sub-banks (2 x 142 Mvar)

BtB Operation Mode	Power Order (MW)	230 kV Side - Minimum Number of filter Sub-banks / Reactor to Fulfill the AC filter Performance and Rating	
		Filter Banks	Shunt Reactor
1 Block	20 – 80	HP11/13 + HP24/36 (59 Mvar)	63 Mvar
	81 – 400	(HP11/13 + HP24/36) + (HP11/13) + HP3) (2x59 Mvar)	63 Mvar
2 Blocks	40 – 200	(HP11/13 + HP24/36) + (HP11/13) + HP3) (2x59 Mvar)	63 Mvar
	201 – 800	2(HP11/13 + HP24/36) + (HP11/13) + HP3) (3x59 Mvar)	63 Mvar

3rd STAGE – COMMERCIAL OPERATION OF HVDC BIPOLE #1 (monopolar MR)

AC Filter and Reactive Power Compensation of Bipole #1 on the 500 kV side of PVC

Nov. 2013



Filter Banks	Sub-bank Configurations	Reactive Power (Mvar)
Bank 1	HP 2/3 + HP 12/24	80 + 183
	HP 2/3 + HP 12/24	80 + 183
	HP 5/36 + HP 12	80 + 183
Bank 2	HP 2/3 + HP 12/24	80 + 183
	HP 5/36 + HP 12	80 + 183
	HP 12	183

Filter Banks	Sub-bank Configurations	Reactive Power (Mvar)
Bank 1	HP 12/24	305
	Shunt Capacitor	305
Bank 1	HP 12/24	305
	Shunt Capacitor	305
Bank 3	HP 12/24	305
	Shunt Capacitor	305
Bank 4	HP 12/24	305

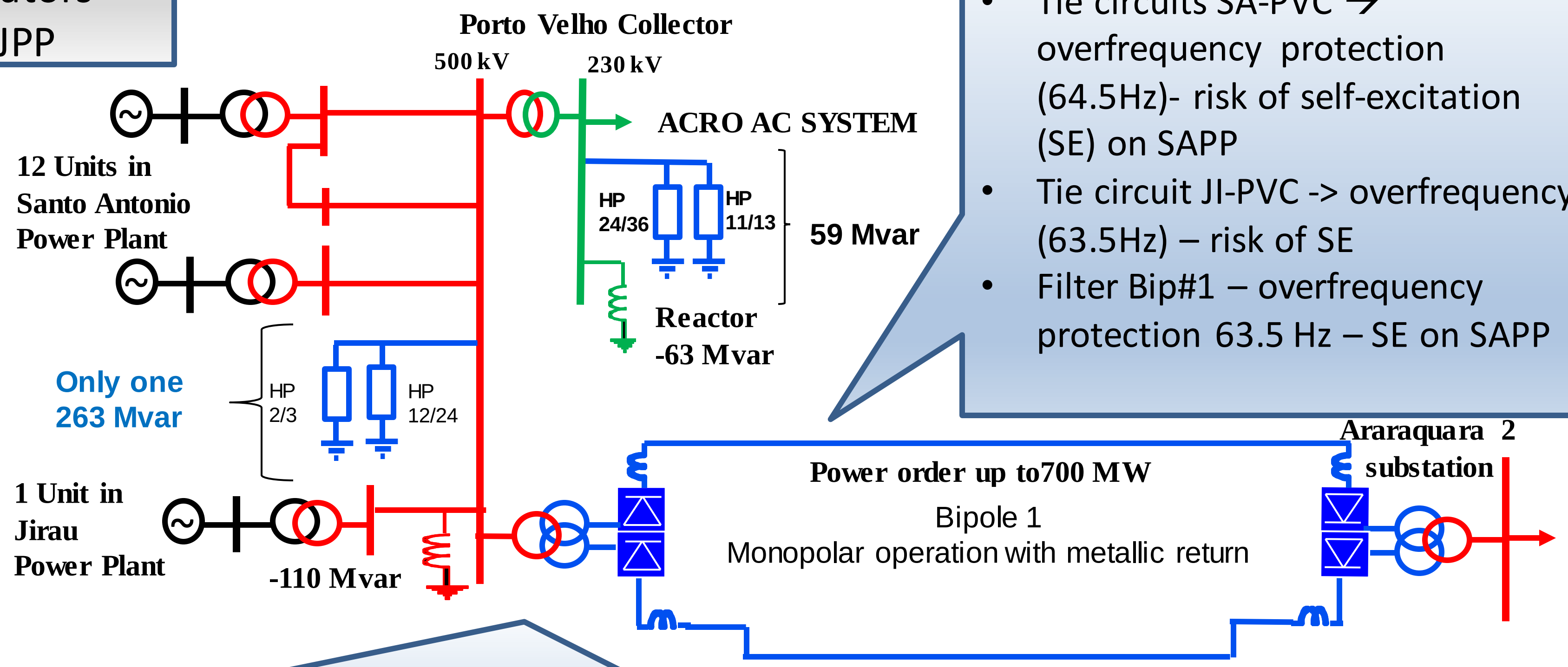
3rd STAGE – COMMERCIAL OPERATION OF HVDC BIPOLE #1

Bipole #1 in Monopolar Mode with Metallic Return Operation (Nov/2013) – up to 700 MW

- 1x263 Mvar filter sub-banks (harmonic rating only)
- Operation BtB was not allowed due to impossibility of running harmonic filters & reduced number of generators

11-15 generators – SAPP & JPP

- Block of Bip#1 → TF-13 trips
- Tie circuits SA-PVC → overfrequency protection (64.5Hz)- risk of self-excitation (SE) on SAPP
- Tie circuit JI-PVC -> overfrequency (63.5Hz) – risk of SE
- Filter Bip#1 – overfrequency protection 63.5 Hz – SE on SAPP



Energization of Bipole #1 Converter Transformers

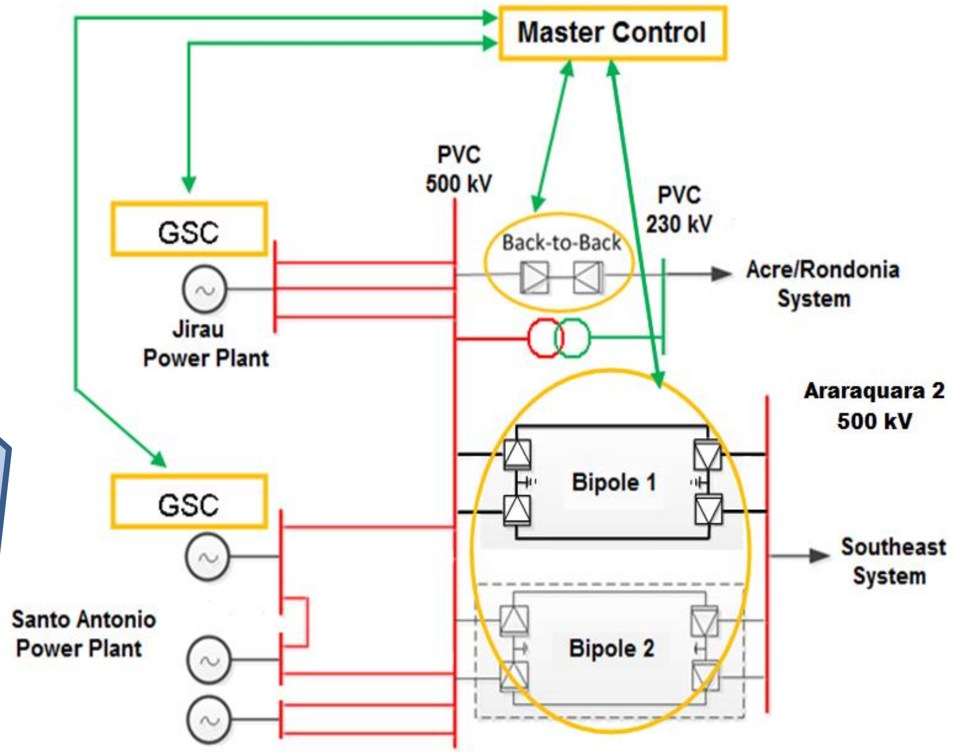
- At least 11 generating units in SAPP
- TF-13 pushes ≥ 240 MW to ACRO system

MC & GSCs – COMMERCIAL OPERATION OF HVDC BIPOLE #1

HVDC Master Control and Generation Station Coordinators (GSC)

With GSCs in Operation in SAPP and JPP:

- ✓ The control functions that demand coordination among HVDC bipoles, BtB blocks, SAPP, and JPP is accomplished by a Master Control and the needed information exchanged is performed by GSC.
- ✓ When the generation loss in any of the power plants, either SAPP or JPP, their respective GSCs inform the Master Control the number of remaining generating units in operation. With this information the Master Control, through the Max Filter function, shuts down the filters needed to match the reactive power generated by them with the total number of remaining generating units due to the risk of self-excitation of the Madeira River power plants.



MC & GSCs – COMMERCIAL OPERATION OF HVDC BIPOLE #1

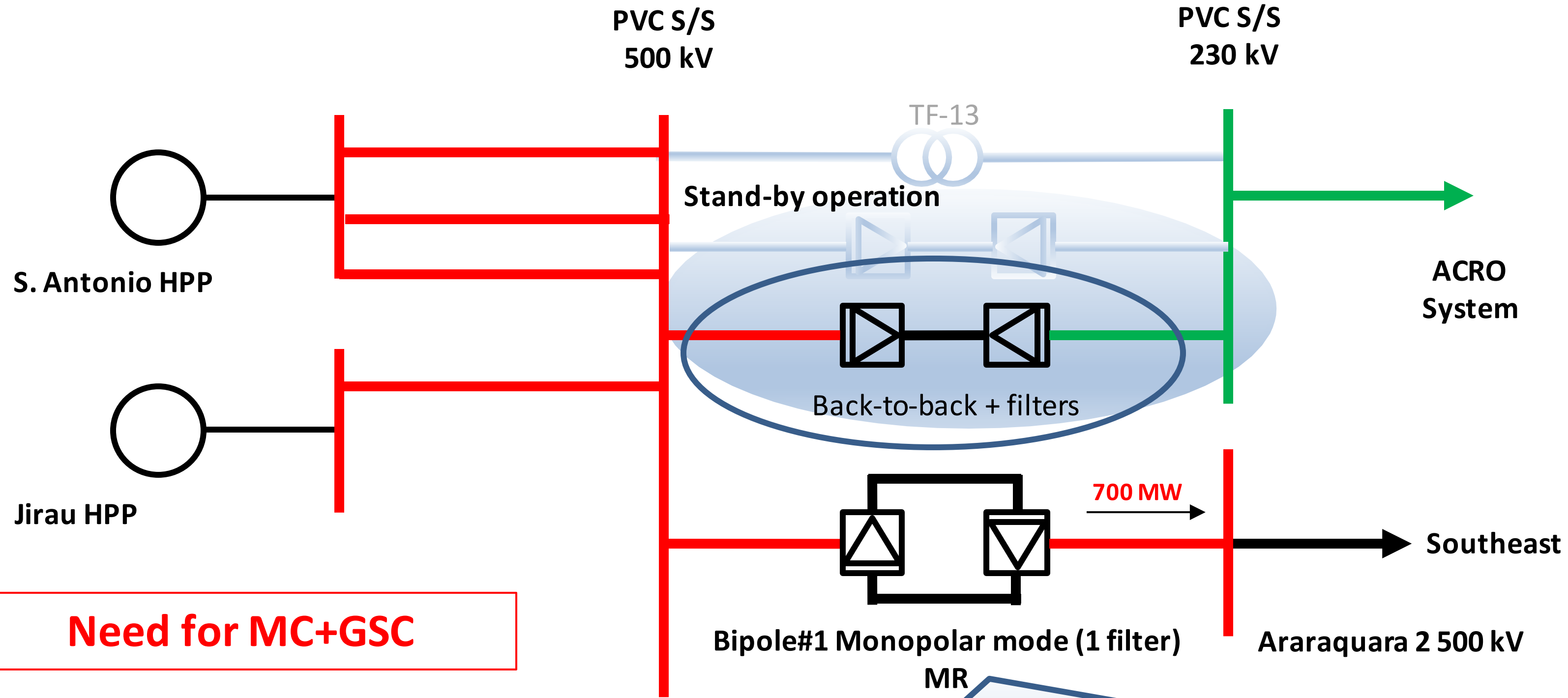
HVDC Master Control and Bipole/Bi-Block control

Function	Goal	Action	Location
Max Filter (PVC S/S only)	Avoid self-excitation managing the number of filters, generators and lines in operation.	Disconnect filters (automatic)	**Master Control (MRPC)**
Abs min filter	Avoid harmonic overload in filters (rating) as a function of the number of converters in operation	Connect filters (automatic)	Bipole/Bi-block control (RPC)
Umax	Limit overvoltages above a threshold value	- PVC Disconnetct filters if V > 555 kV Avoid connecting filters if V > 535 kV - ARA 2 Disconnect filters if V > 550 kV Avoid connecting filters if V > 539 kV Automatic	Master Control (MRPC)
Min filter	Fullfil criterion on harmonic filtering performance	Connect Filters Automatic/Manual	Bipole/Bi-block control (RPC)
Q-Control	Control the reactive power interchange with AC network depending upon DC power.	Connect/disconnect filters in ARA 2 Disconnect filters in PVC Automatic/Manual	**Master Control (MRPC)**

4th STAGE – COMMERCIAL OPERATION OF HVDC BIPOLE #1 (MR)

+ BtB IN OPERATION → asynchronous operation (w/o TF13)

Above 16 generating units



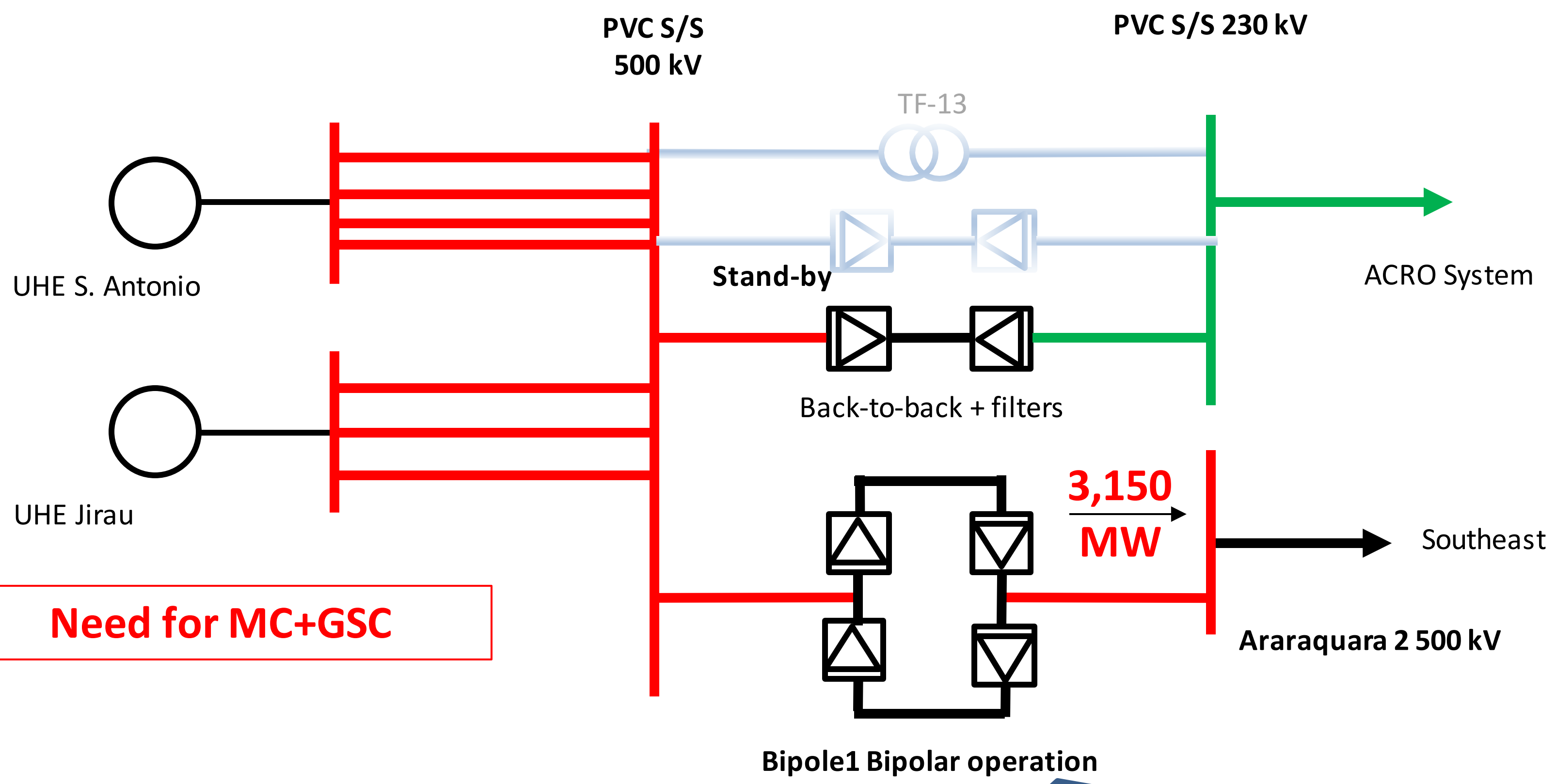
Need for MC+GSC

Asynchronous operation BtB/Bipole#1 (metallic return) and BIPS
TF-13 in hot stand-by → black-start of SAPP/JPP generators and energization of converter transformer (Bip#1 under restoration/switching)

5th STAGE – COMMERCIAL OPERATION OF HVDC BIPOLE #1

BIPOLE #1 (BIPOLAR MODE) AND BTB IN OPERATION

Above 18 generating units



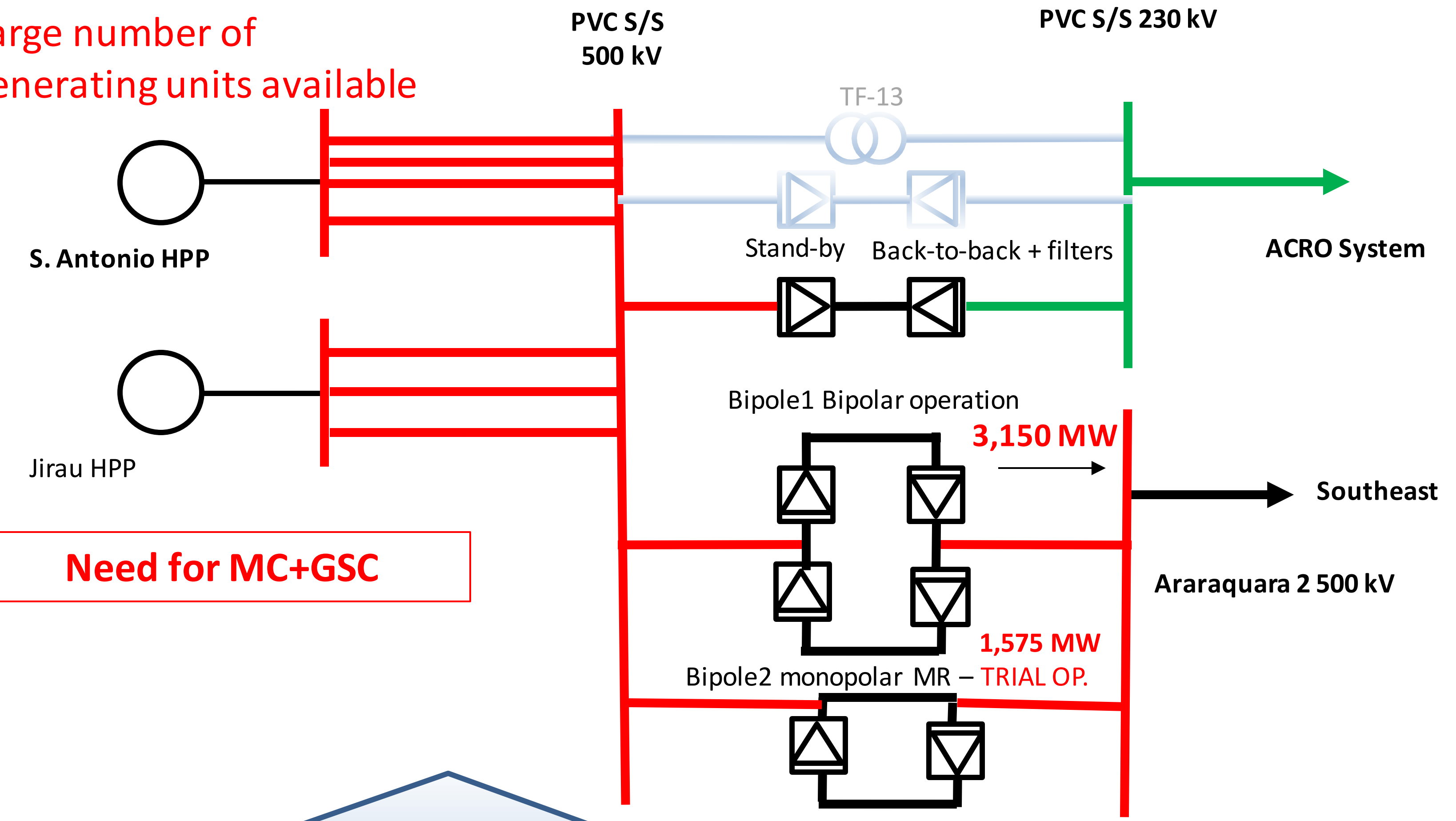
Need for MC+GSC

- Asynchronous operation BtB/Bipole#1 (bipolar mode) and BIPS
- TF-13 in hot stand-by → SAPP/JPP generators have black-start capability and energization of converter transformer only if CSD fails

6th STAGE – TRIAL OPERATION OF HVDC BIPOLE #2

BIPOLE #1 (BIPOLAR), BIPOLE#2 (MONOPOLAR MR TRIAL) AND BTB IN OPERATION

Large number of generating units available



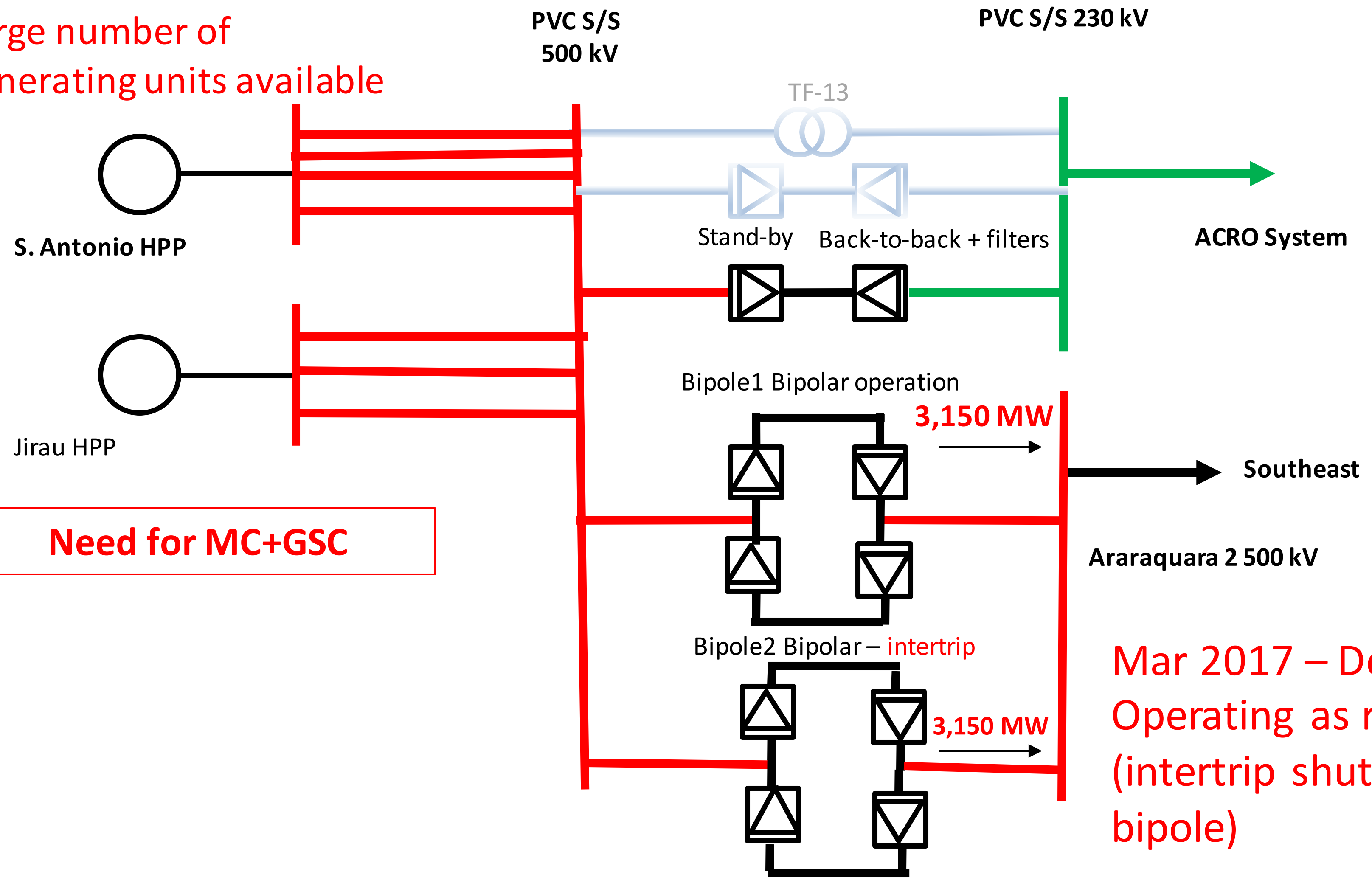
Need for MC+GSC

- Asynchronous operation BtB/Bipole#1 (bipolar mode) and BIPS
- TF-13 in hot stand-by → SAPP/JPP generators have black-start capability and energization of converter transformer only if CSD fails for Bip#1. Bip#2 depends on TF13 operation (ACRO).

7th STAGE – COMMERCIAL OPERATION OF HVDC BIPOLE #2

BIPOLE #1 (BIPOLAR), BIPOLE#2 (RIGID BIPOLE MODE) AND BTB IN OPERATION

Large number of generating units available



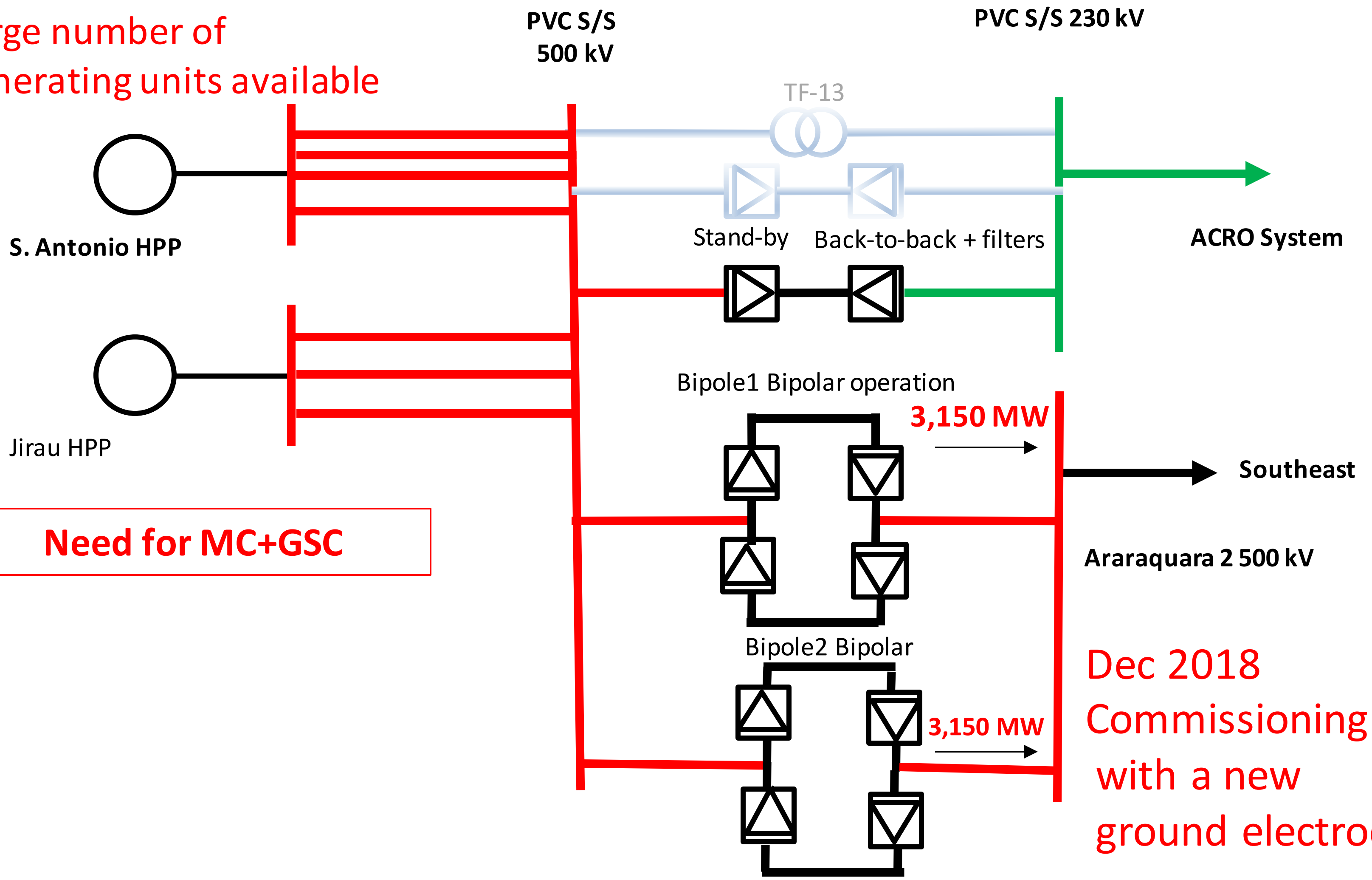
Need for MC+GSC

Mar 2017 – Dec 2018
Operating as rigid bipole (intertrip shuts down the bipole)

PRESENT STAGE – COMMERCIAL OPERATION OF HVDC BIPOLE #1,#2,BtB

BIPOLE #1 (BIPOLAR), BIPOLE#2 (BIPOLAR & MONOPOLAR) AND BTB IN OPERATION

Large number of generating units available



Need for MC+GSC

Dec 2018
Commissioning and operation with a new ground electrode in PVC S/S

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Challenges of the first 800 kV HVDC link in Brazil

Belo Monte Hydro Power Plant – main features

- Installed capacity – 18 generators @ 611 MW ≅ 11,000 MW (18 generators in operation since 2019). First generator was put in operation in Apr 2016.
- The 3rd largest in the world (capacity). The 1st largest HPP totally located in Brazil
- Auctioned in 2010, accomplished in 2019 (18th generator).
- Tapping power through Xingu-Estreito Bipole to Southeastern Brazil

Run-of-river Power Plant

Illustration of final stage of Belo Monte Hydro power plant (final stage)

Belo Monte Hydro Power Plant

Photo of early construction work - Belo Monte Hydro Power Plant

The First Brazilian, ± 800 kV HVDC Link - DC Line passing through 4 Federation States

±800kV,4000 MW, 2,076 km, HVDC LCC

The first 800 kV HVDC Bipole in the West

Source: BMTE

Planned vs Existing BIPS

System Planned for Dec, 2017

Weaker than planned!

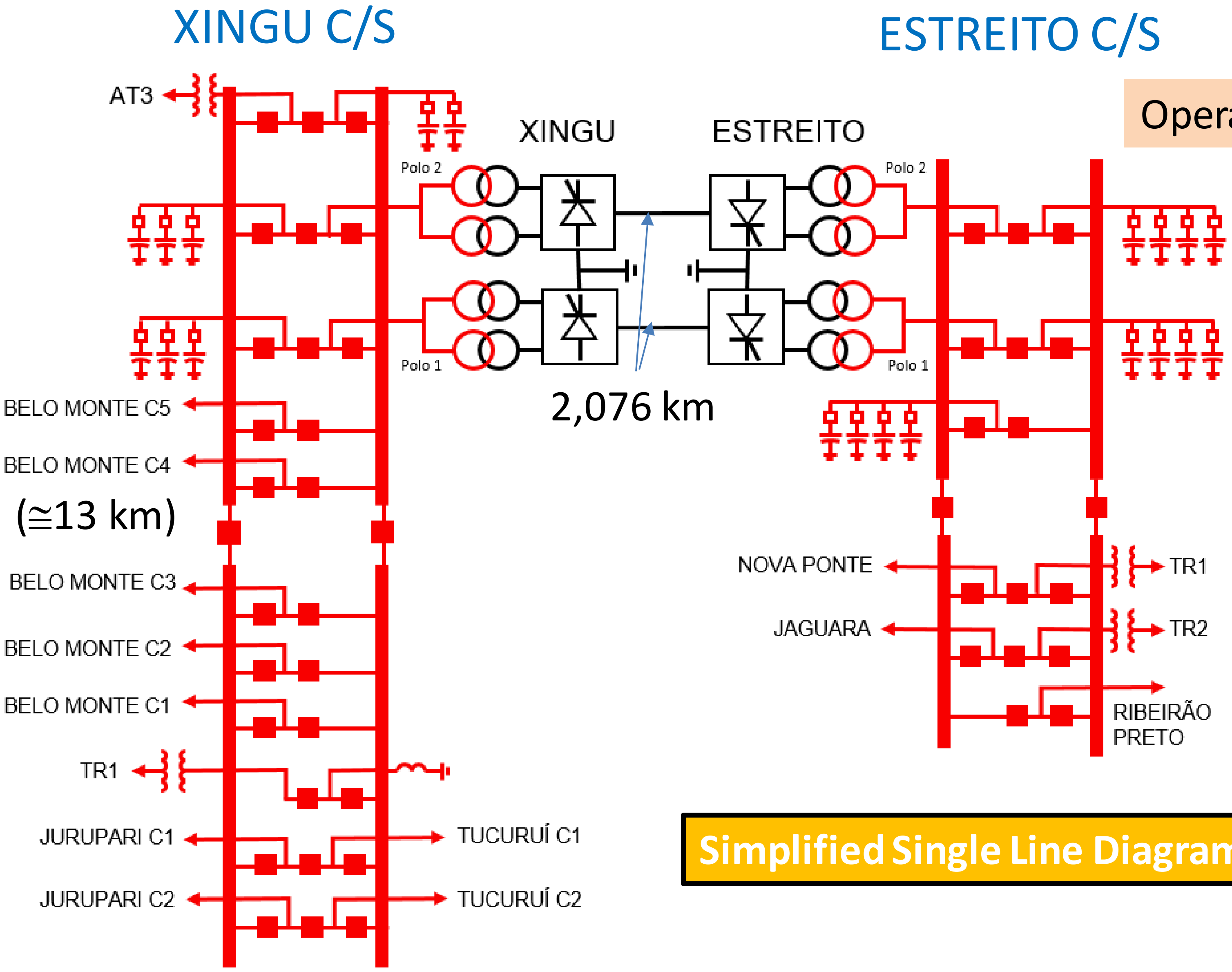
Existing System in Dec, 2017

±800 kV, 4000 MW Xingu-Estreito Bipole

Operation – Dec 2017

BM
18 Gen.

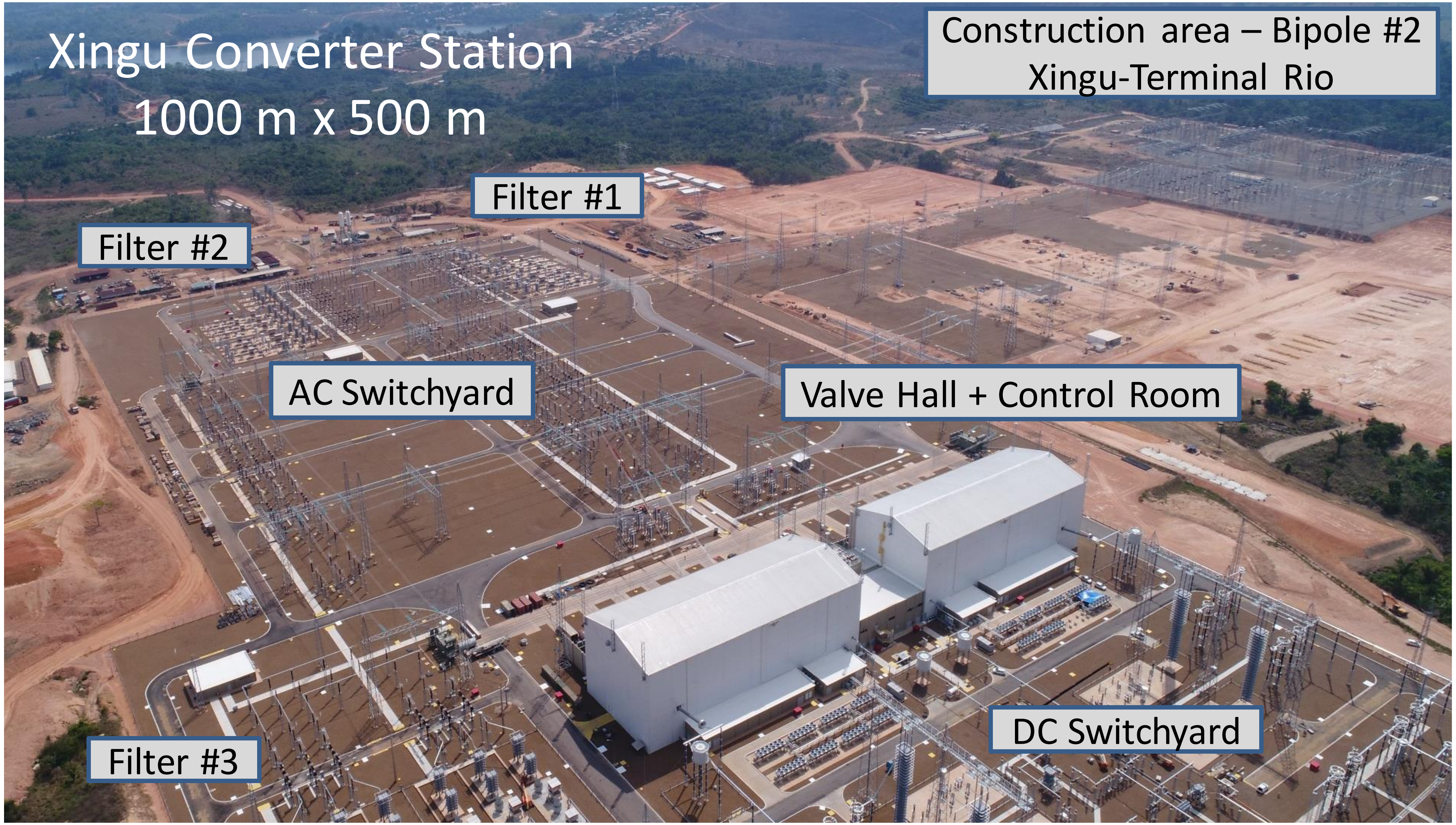
(≅13 km)



MW/SE

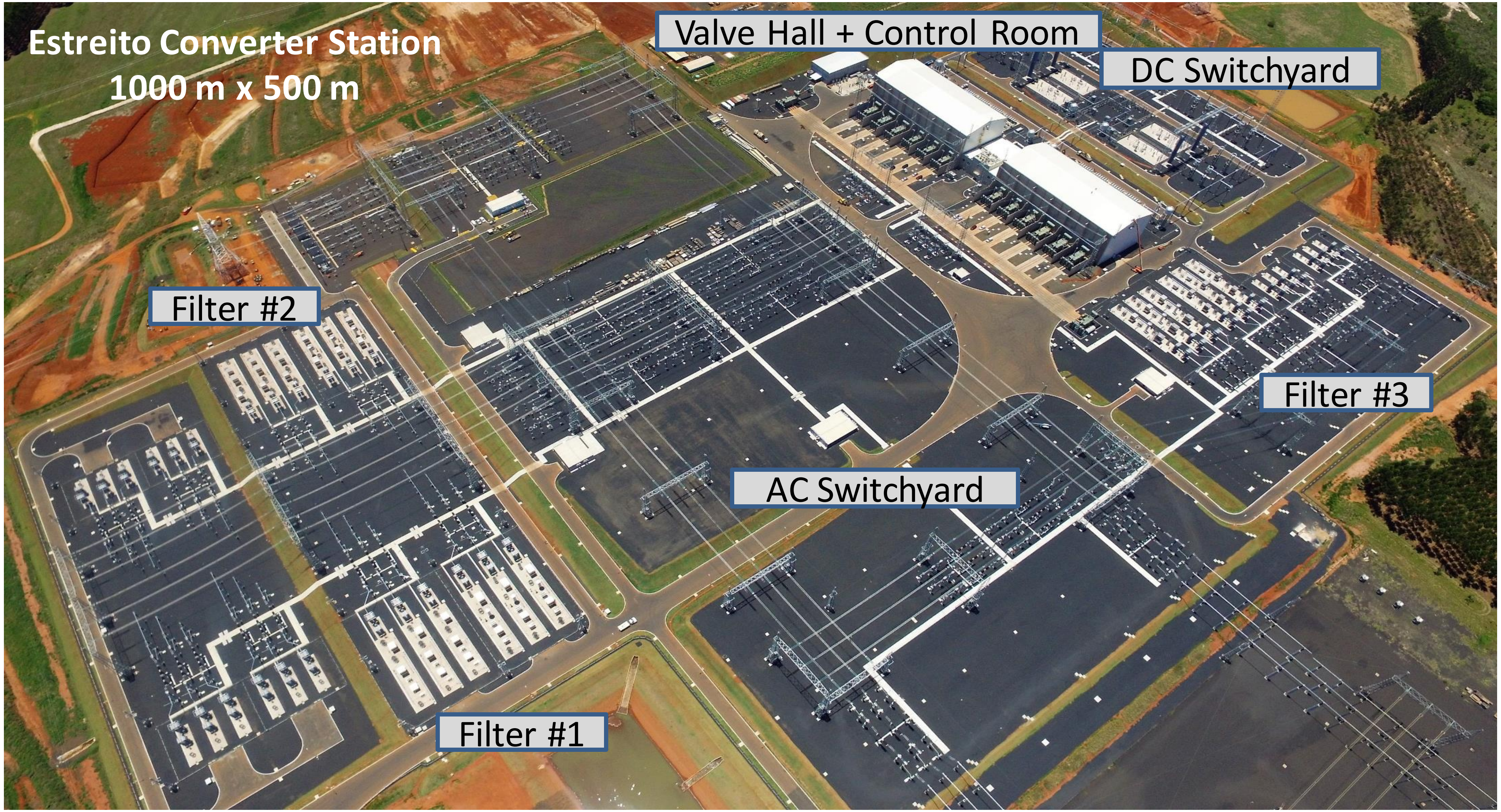
Simplified Single Line Diagram

±800 kV, 4000 MW Xingu-Estreito Bipole – Xingu C/S



Source: BMTE

±800 kV, 4000 MW Xingu-Estreito Bipole – Estreito C/S



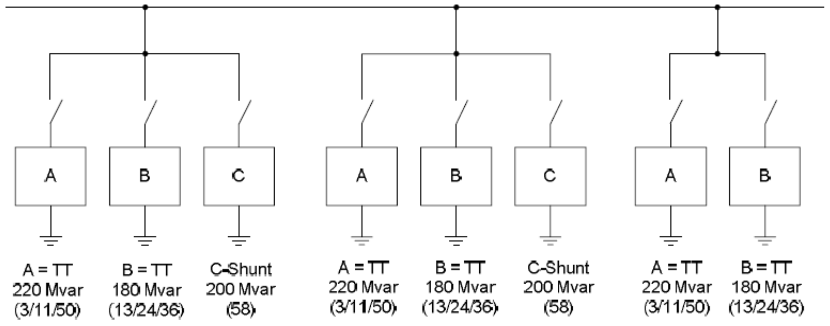
Source: BMTE

±800 kV, 4000 MW Xingu-Estreito Bipole

AC Filters

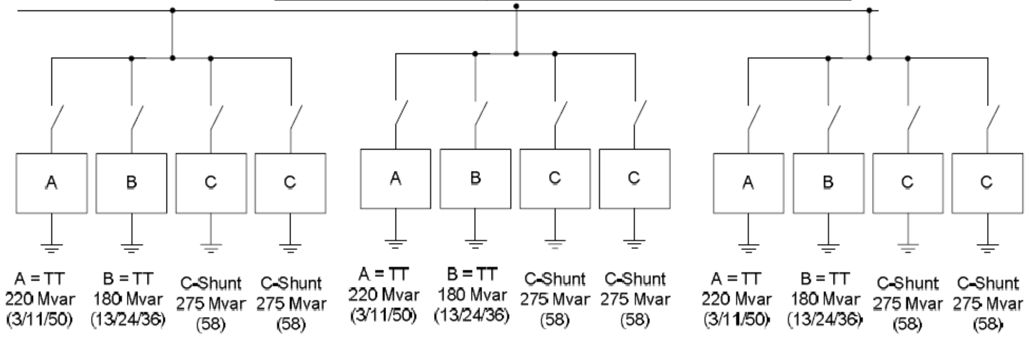
Terminal	Filter	number of filters	Tuning	Rated Power
Xingu	Type A	3	3rd°/11th°/50th°	220 Mvar
	Type B	3	13th°/24th°/36th°	180 Mvar
	Type C	2	Capacitor Bank (58th°)	200 Mvar
Estreito	Type A	3	3rd°/11th°/50th°	220 Mvar
	Type B	3	13th°/24th°/36th°	180 Mvar
	Type C	6	Capacitor Bank (58th°)	275 Mvar

Xingu – 8 AC filters



1600 Mvar

Estreito – 12 AC filters



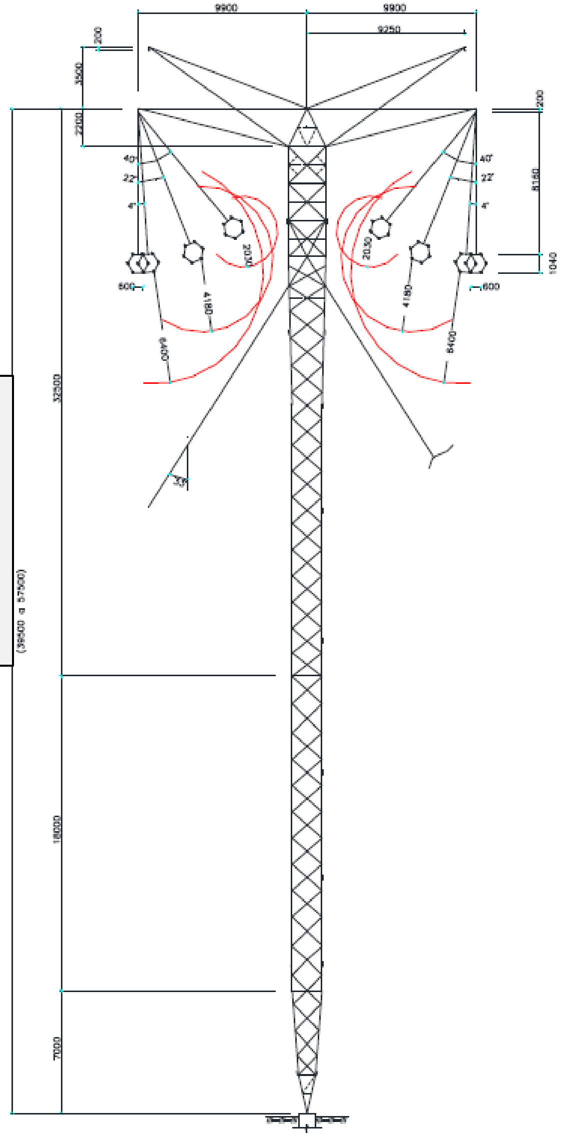
2850 Mvar

±800 kV, 4000 MW Xingu-Estreito Bipole

~20 m

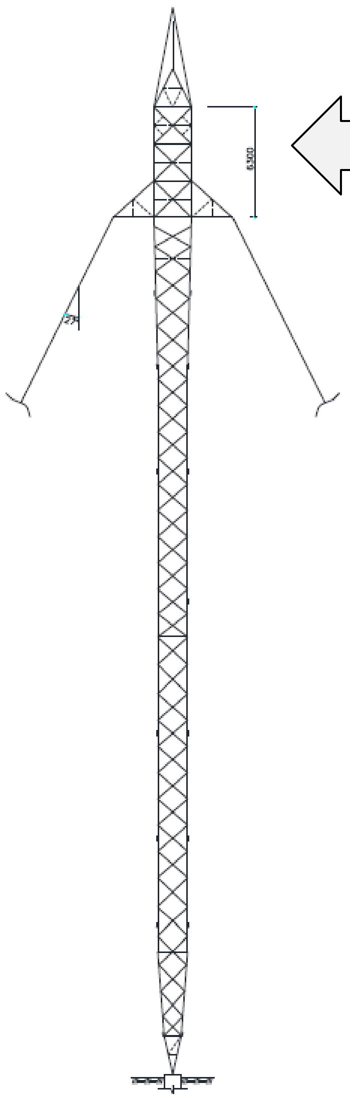
EL81

DC transmission line



40 to 60 m

Cotas em milímetro



Typical DC line tower silhouette (71%)

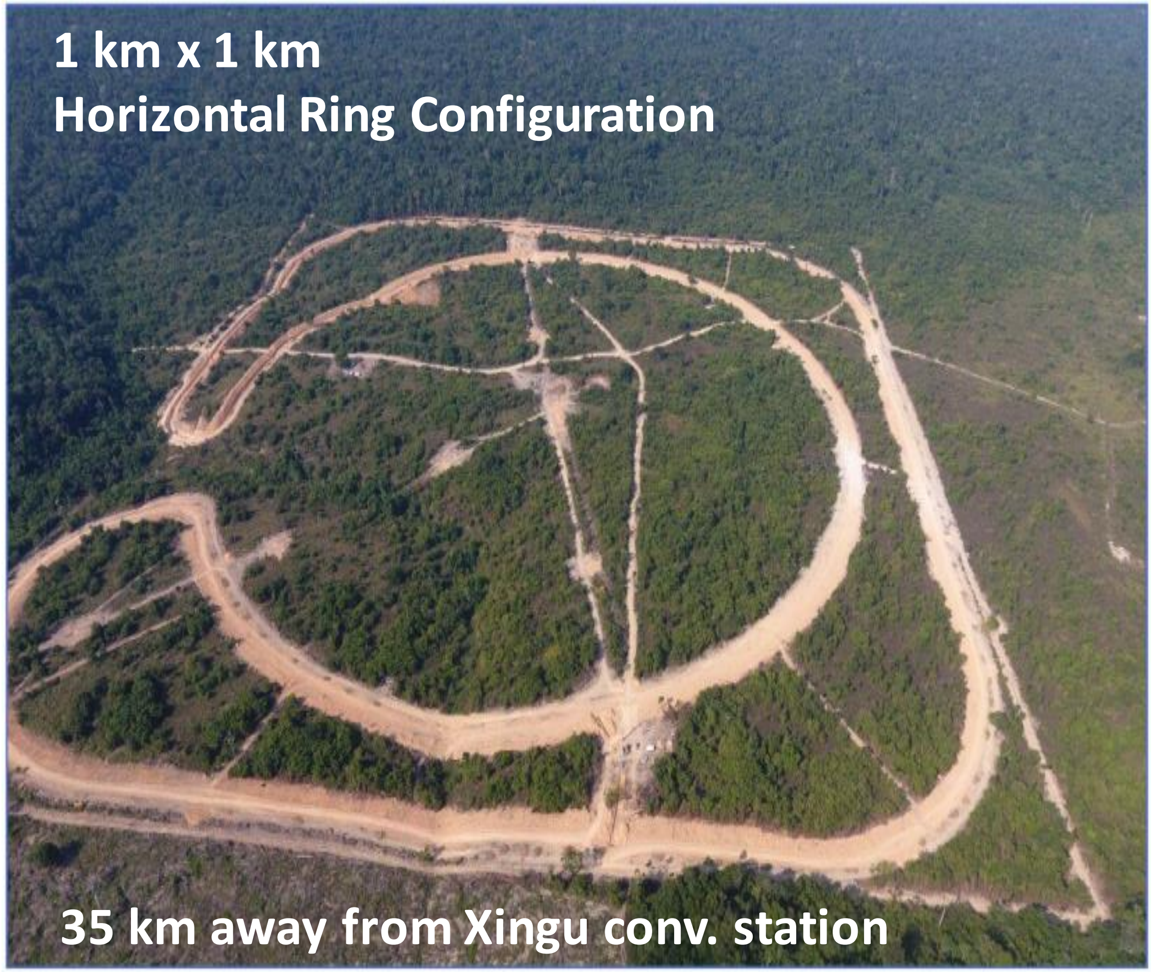
- ± 800 kV DC
- 6 conductors per pole
- 2,076 km

Source: BMTE

GROUND ELECTRODES

ESTREITO

XINGU



Source: BMTE

±800 kV, 4000 MW Xingu-Estreito Bipole

Equipment	Equipment Rating and Overload – Xingu Conv. Station (rectifier)			
	Continuously	30-minute (33%)	5-s (50%)	Minimum (10%)
Pole (Converter)	2000MW	2660MW	3000MW	200MW
Bipole	4000MW	5320MW	6000MW	400MW

Equipment	Equipment Rating and Overload - Estreito Conv. Station (rectifier)				
	Continuously	30-minute (33%)	5-s (50%)	10% for 4h	Minimum
Pole (Converter)	1635MW	2174.55	2452.5	1798.5	200MW
Bipole	3270MW	4391.1	4905.0	3597.0	400MW

Equipment	Equipment Rating and Overload	
	Continuously	30-minute (33%)
Ground Electrodes	2500A	3325A
800 kV DC Line	4000MW	5320MW

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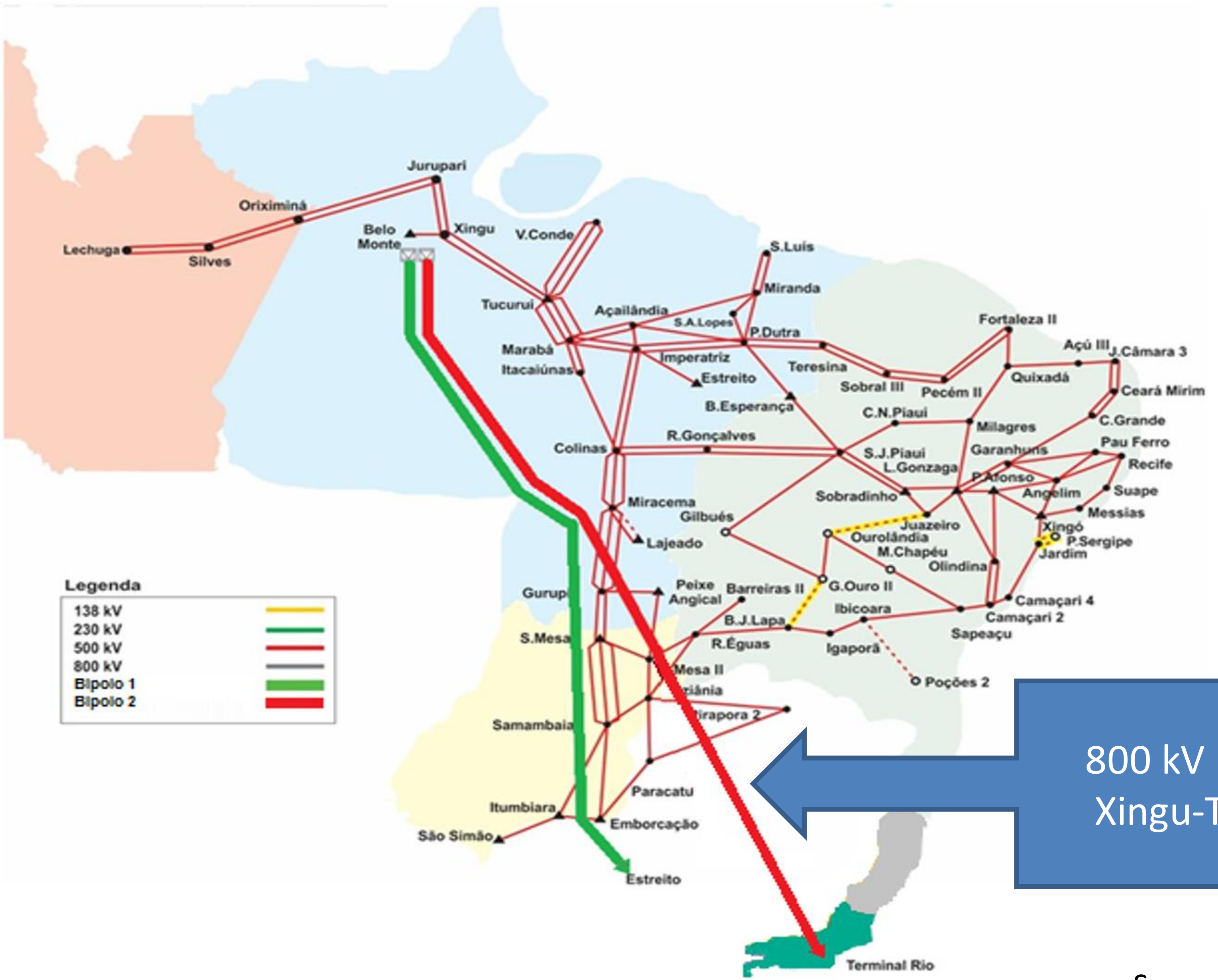
The second 800 kV HVDC link in Brazil

±800 kV, 4000 MW Xingu-Terminal Rio Bipole

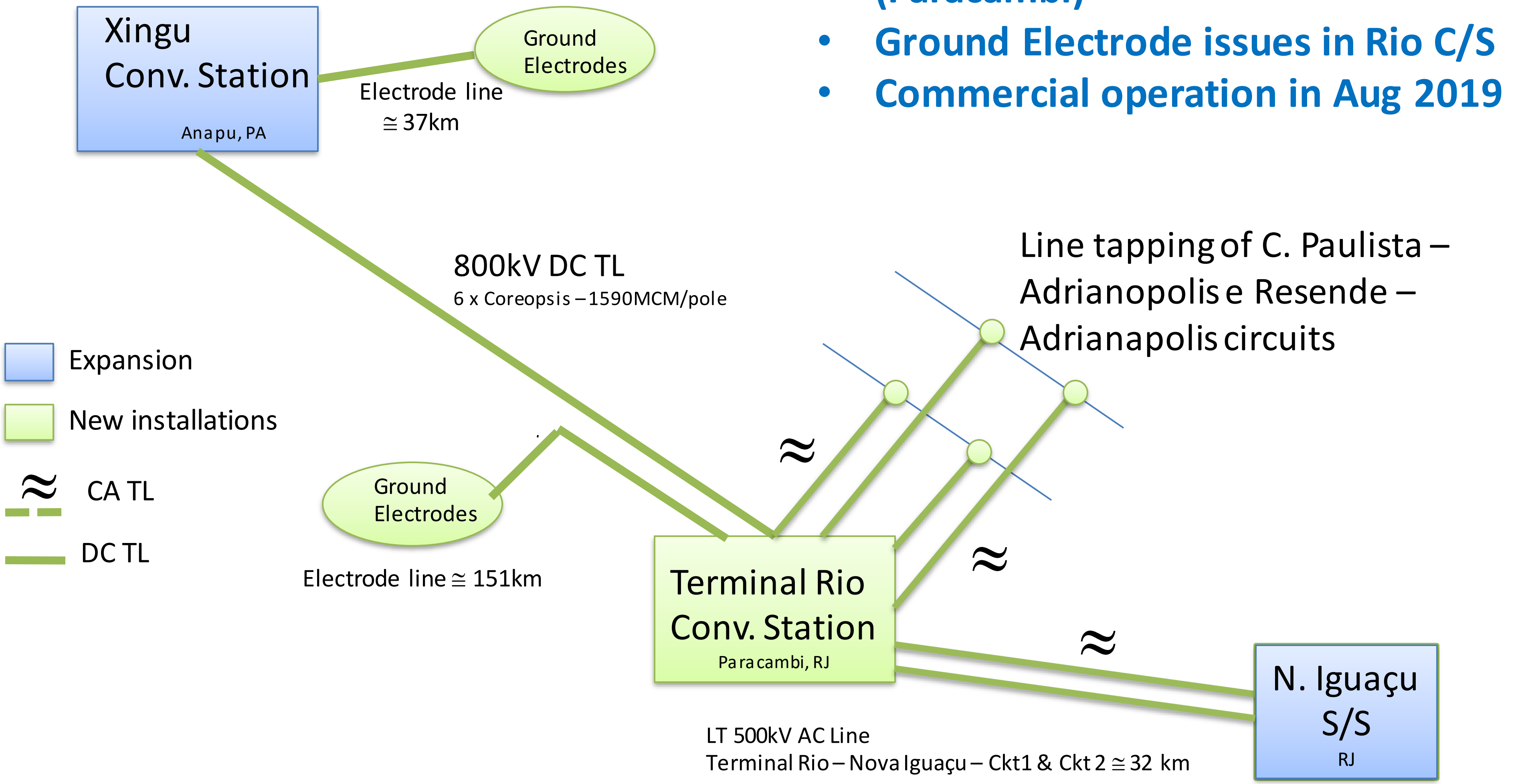


800 kV HVDC Bipole Xingu-Terminal Rio

Source: XRTE

±800 kV, 4000 MW Xingu-Terminal Rio Bipole

- The Longest Brazilian HVDC line (2,539 km)
- Deployment of the Master Control and integration with Bipolo #1 (Xingu-Estreito)
- Inverter at Greater Rio de Janeiro City (Paracambi)
- Ground Electrode issues in Rio C/S
- Commercial operation in Aug 2019



Source: XRTE

±800 kV, 4000 MW Xingu-Terminal Rio Bipole

Overload	Short-Term (5 s – 50%)	Long-term (30 min – 33%)	Emergency long-term (4 h – 10%)
Xingu → Rio (Inv.)	3978 A (1.59 pu)	3452 A (1.38 pu)	-
Rio → Xingu (Inv.)	3208 A (1.57 pu)	2798 A (1.37 pu)	2267 A (1.10 pu)
Overload cycle	Once each 2 hours 20 times / year	Once each 9 hours 20 times / year	Once each 30 min 20 times / year

±800 kV, 4000 MW Xingu-Terminal Rio Bipole

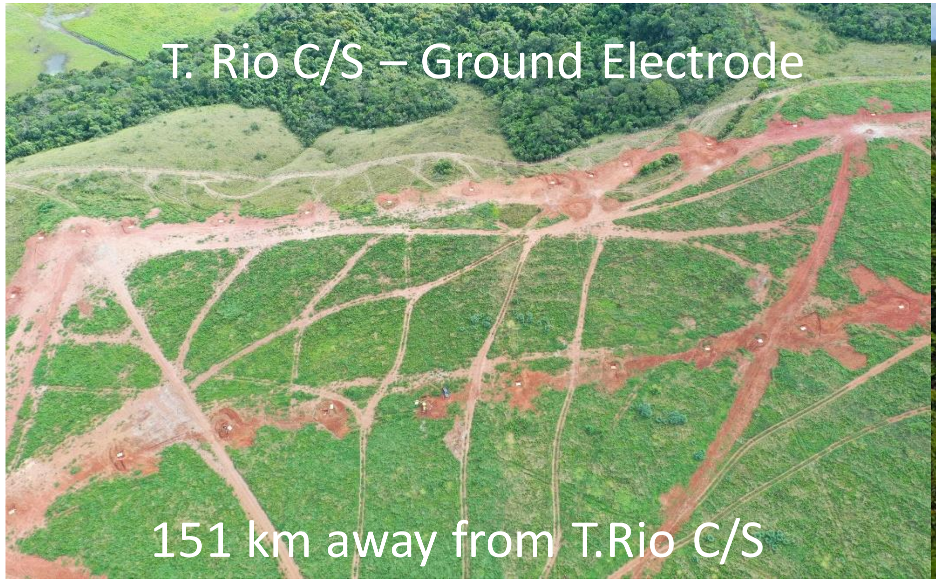
Source: XRTE

±800 kV, 4000 MW Xingu-Terminal Rio Bipole

Xingu C/S – Aerial Overview

Source: XRTE

±800 kV, 4000 MW Xingu-Terminal Rio Bipole



Source: XRTE

±800 kV, 4000 MW Xingu-Estreito /Xingu-Terminal Rio Bipoles

Special Protective Scheme (SPS) → **Master Control Bipole #2 Xingu-Terminal Rio**

Logic 1: Single outage at Xingu – Tucuruí 500 kV transmission line

Logic 2: Double outage at Xingu – Tucuruí 500 kV transmission line

Logic 3: Bipole (1 or 2) trip/block (or last pole trip/block)

Logic 4: Bipole (1 or 2) external contingencies

Logic 5: Outage of Generating Units at Belo Monte HPP

Logic 6: Split-bus configuration

Gracias

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Vigilada Mineducación