Benefits of HVDC Interconnection on Outage Mitigation in Puerto Rico

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***Abstract*—Puerto Rico's electric power system faces persistent reliability challenges due to aging infrastructure, geographic isolation, and frequent exposure to extreme weather events. To strengthen grid stability and resilience, the Caribbean Transmission Development Company (CTDC) is proposing a VSC-HVDC interconnection between two islands of Puerto Rico (PR) and Dominican Republic (DR). This paper presents the potential benefits of the proposed interconnector through a dynamic stability analysis of the PR grid under a simulated island-wide blackout event. Simulation results demonstrate that the VSC-HVDC link can significantly enhance the stability of the PR transmission system and ensure reliable operation of the power system during severe disturbances.**

***Index Terms*--HVDC, Interconnection, Puerto Rico, Stability, Transmission, Voltage-Source Converter.**

I. Introduction

Puerto Rico's electric power system has a peak electricity demand of 3,414 MW (June 2023) and a total generation fleet capacity of 5,749 MW. The total available generation capacity in any given hour, however, is substantially lower at below 4,300 MW. In addition, existing generating facilities in Puerto Rico (PR) often experience unplanned outages due to age of service and other factors [1]. This, combined with geographic isolation and frequent exposure to extreme weather events results in reliability challenges. As an islanded grid operated primarily by LUMA Energy and the Puerto Rico Electric Power Authority (PREPA), PR lacks interconnections with neighboring networks. This operational isolation severely limits external support during contingencies, resulting in pronounced vulnerability to both natural and technical disruptions. The absence of external tie-lines has contributed to extended blackouts and significant voltage and frequency stability challenges with considerable restoration times. (A more detailed account of significant outage events is provided in Section II).

In this regard, an HVDC (High Voltage Direct Current) link offers an effective remedy by enabling asynchronous connection with neighboring networks, overcoming technical limitations associated with long-distance AC transmission, and permitting controllable, high-capacity power transfer without increasing short-circuit levels [2]. HVDC technology enhances system robustness by providing precise and rapid control of both active and reactive power, supporting efficient frequency and voltage regulation [3].

To address these challenges in the PR system, Caribbean Transmission Development Company (CTDC) is developing Project Hostos, a Voltage Sourced Converter (VSC) HVDC transmission interconnector between Puerto Rico (PR) and Dominican Republic (DR), a neighboring Caribbean nation with a more robust and interconnected grid.

Additional benefits of Project Hostos include deferral of major transmission infrastructure investments in PR, lower marginal cost of generation in DR, and significant system integration support for PR's renewables generation targets in the coming decades [4].

This paper presents a dynamic stability analysis of PR's power system under an island-wide blackout event to demonstrate the potential benefits of Project Hostos in enhancing grid resilience and operational stability.

II. Recent Power Outage events

The PR power grid has been hit by a number of recent outage events leading to island-wide power outages, even for several months in worst cases [5]. These have caused significant economic and social damage to residents of the island.

The most significant outage occurred in 2017 during Hurricane Maria, which led to a total blackout, taking approximately 11 months to restore power to all customers. While generation facilities sustained limited damage, the transmission and distribution infrastructure suffered extensive failures, including the collapse of many transmission structures and distribution poles [5]. Other major outages include:

- Monacillos substation fire (June 2021), which left hundreds of thousands without power into the following day [6]

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- Costa Sur Power Plant switching station fire (April 2022), which triggered an island-wide blackout affecting approximately 1.5 million customers. The event caused a rapid frequency drop, cascading generator trips, and a full system collapse, which required multiple days for full restoration [7].
- Hurricane Fiona (September 2022) caused another complete blackout, with 90% of customers reconnected within two weeks [8].
- Tropical storm Ernesto (August 2024) disrupted power for around 700,000 customers and restoration took a couple of days [9], [10].
- Finally, on December 31, 2024, Puerto Rico experienced yet another full blackout, with most customers restored by the following day [11].

These events highlight the grid's continued vulnerability to both natural and technical disruptions and underscore the urgent need for system-wide resilience improvements. These range from conventional transmission network upgrades to use of state-of-the-art technologies such as VSC-HVDC.

III. HVDC Technology and Benefits

Voltage Sourced Converter (VSC) HVDC has been increasingly adopted to address the operational and stability challenges faced by modern power grids, especially those with high integration of renewable energy. Conventional Line-Commutated Converter (LCC-HVDC) schemes have been widely used for long-distance, high-capacity bulk power transfers, but present inherent limitations in terms of reactive power management, bidirectional capability and vulnerability to commutation failure under weak grid conditions [12]. In contrast, VSC-HVDC offers a transformative set of features, including grid forming [13] and black start operation [14].

Figure 1 shows the basic main circuit and control structure used for VSC-HVDC. A VSC-HVDC transmission consists of at least two forced-commutated VSCs and common DC link, including DC capacitors and DC cables, or lines. The coordination of active power control between the stations is realized by designating only one converter controlling the DC side voltage whereas the other converter controls the flow active power. For reactive power control, each converter station can be switched between two main control modes: "AC voltage control" or "Power factor control".

In AC voltage control mode, the converter adjusts its reactive power to maintain a specific AC voltage at a regulated bus. This mode is typically used to address voltage stability issues and compliance with grid code requirements. In power factor control mode, the converter regulates the exchange of reactive power between the converter station and the AC grid to maintain a target power factor.

In addition, VSC based HVDC converter with series-connected IGBT valves can control active power and reactive power independently by adjusting the firing angle or modulation index of the IGBTs. This switching control allows simultaneous adjustment of the amplitude and phase angle of

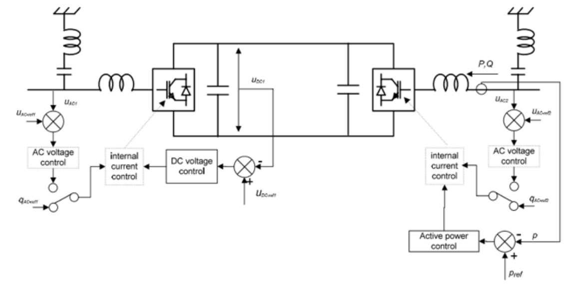

Figure 1. Fundamental VSC-HVDC Circuit Structure

the converter AC output voltage. Due to this decoupled control frame, VSC-HVDC can independently regulate active and reactive power flows, enabling reactive power support even when no active power is transmitted. This capability makes VSC–HVDC particularly well-suited for enhancing the operational resilience of power grids subject to frequent outages and high renewable variability, as in Puerto Rico.

IV. Models And Assumptions

A. Network Models

The base case model of the transmission system of Puerto Rico in PSS/E format was provided by CTDC. This base transmission network model was updated based on the information in the latest Integrated Resource Planning (IRP) to reflect the status of PR grid before the fault event. Table 1 summarizes the power flow data in the base case.

TABLE I. Power Flow Data in Puerto Rico System

Parameter	Value
Total system generation	2565 MW
Total system load	2514 MW
Total system reactive load	911 MVAr

In the study case, the HVDC Interconnector is developed connected to the Mayaguez substation in Puerto Rico and the Quisqueya substation in Dominican Republic system [15]. In order to accommodate the injected power from the HVDC link, the existing generators in the PR system were uniformly scaled down. Moreover, since this study focuses on analyzing the impact of the HVDC on the PR system, the DR network was modeled as a voltage source generator with the equivalent impedance at the POI (Quisqueya substation).

The high-level transmission network map of PR is shown in Figure 2 with a representative PSS/E single line diagram shown in Figure 3 [15]. The red circle indicates the POI at Mayaguez substation at 230kV voltage level.

B. HVDC Model

A generic VSC-HVDC model was utilized with the parameters provided in TABLE II. It should be noted that these parameters are simplified to support a system-level stability analysis compared to time-domain EMT level for more detailed HVDC studies.

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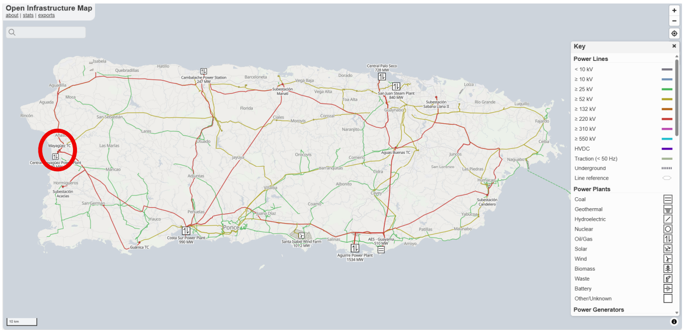

Figure 2. Puerto Rico Transmission Network

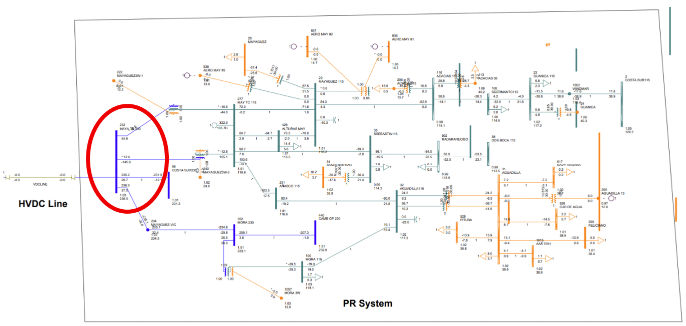

Figure 3. Puerto Rico Transmission Network PSS/E Single Line

TABLE II. VSC-HVDC MODEL PARAMETERS

Parameter	Value
Rated DC Voltage	±320 kV
DC Line Resistance	2 ohm
DR Converter	
DC Control Mode	Voltage
DC Setpoint	640 kV
AC Control Mode	Voltage
Converter Size	600 MVA
Converter Q Capacity	314/-314 MVAr
PR Converter	
DC Control Mode	Power
DC Setpoint	500 MW
AC Control Mode	Voltage
Converter Size	600 MVA
Converter Q Capacity	331/-331 MVAr

C. Dynamic Model

Due to the unavailability of the dynamic stability model for the Puerto Rico system from LUMA at the time of the study, engineering assumptions were made to develop dynamic models for the generating units near the Costa Sur Power Plant. Generators located far away from the fault location were modeled as negative loads in the dynamic stability analysis.

The WECC type J generator model GENTPJ1 is used to represent the generator model for all power plants. The control system implemented in this model is presented in Figure 4.

The IEEE type 3 excitation system model IEEET3 is used to represent the excitation control system for all power plants. The control system implemented in this model is presented in Figure 5.

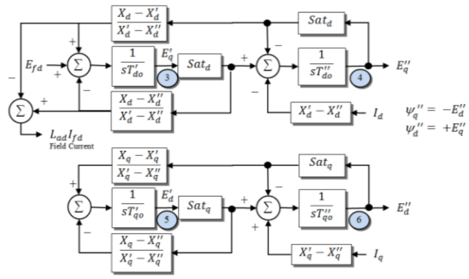

Figure 4. GENTPJ1 Model Diagram

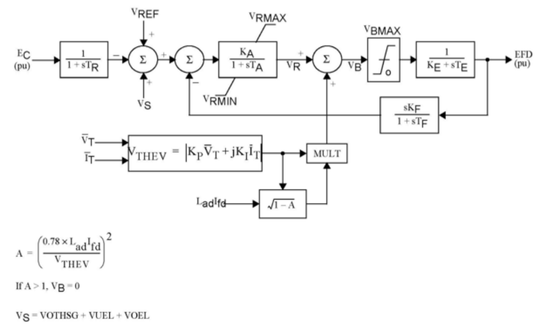

Figure 5. IEEET3 Model Diagram

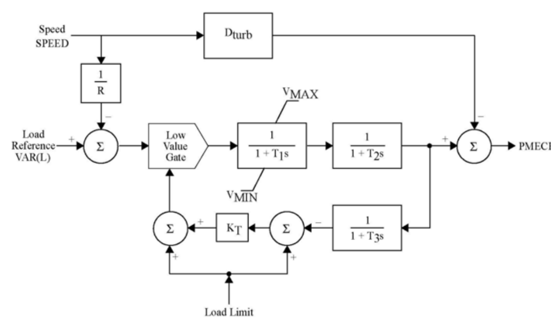

Figure 6. GAST Model Diagram

The gas turbine governor model GAST is used to represent the governor model for all power plants. The control system implemented in this model is presented in Figure 6.

The Hitachi Energy HVDC Light Model HVDCLIGHT1 was used to simulate the dynamic responses of the HVDC system. The control system implemented in this model is presented in Figure 7.

V. SIMULATION

For the purpose of modeling and analysis of potential benefits of adding the VSC-HDC Project, the island-wide blackout event caused by a catastrophic failure at the Costa Sur Power Plant on 4/6/2022 was selected for the simulation.

A. Event Description

To model the blackout event, a simplified fault definition is used in this study and summarized as follows:

- At t=1 second, a three-phase fault was applied at the Costa Sur 230kV substation

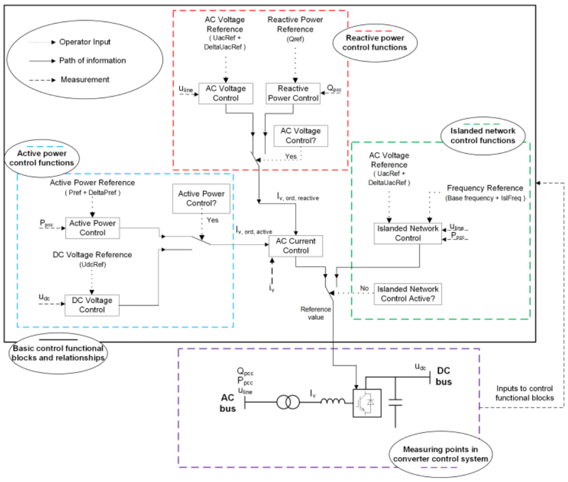

Figure 7. HVDCLIGHT1 Model Diagram

- After 360 ms (22 cycles), the fault was cleared, and the following power plants were tripped, resulting in an approximate generation drop of 800 MW:
  - Costa Sur ST Unit
  - Costa Sur GT Unit
  - EcoElectrica ST Unit
  - EcoElectrica CT Unit
- The simulation was run to t=60 seconds.

B. *Base Case Results (without Project Hostos)*

The simulation results indicate that the PR system without the HVDC Project became unstable and failed to converge, leading to unstable system performance caused by the fault event. To provide a complete picture of unstable system, protection operation is ignored.

Figure 8. shows the real power (P) and reactive power (Q) responses of the C.S.5 power plant near the fault location. Figure 9. shows the voltage responses of Costa Sur 230kV substation and the POI of the HVDC system (Mayaguez).

C. *Study Case Results (with Project Hostos at 500 MW)*

The simulation results indicate that the PR system can produce stable responses with positive damping for the disturbance simulation when the HVDC Project is connected and operating at a full capacity of 500 MW.

Figure 10. shows the real power (P) and reactive power (Q) responses of the C.S.5 power plant near the fault location. Figure 11. shows the voltage responses of the Costa Sur 230kV substation and the POI of the HVDC system (Mayaguez).

D. *Study Case Results (with Project Hostos at 400 MW)*

To assess the impact of HVDC operating conditions on the stability of the PR system, a sensitivity scenario was developed by reducing the HVDC power to 400 MW.

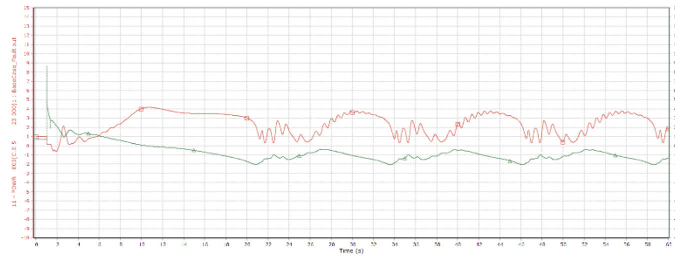

Figure 8. P/Q Responses of C.S.5 Power Plant in the Base Case

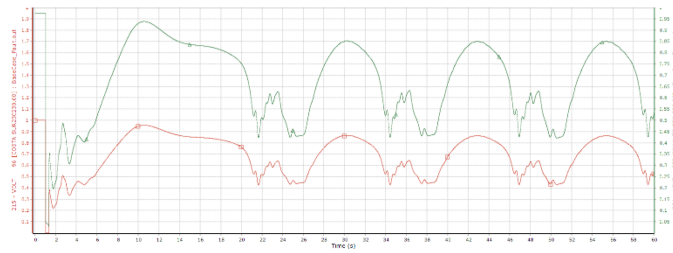

Figure 9. Voltage Responses of Costa Sur 230kV and Mayaguez 230kV in the Base Case

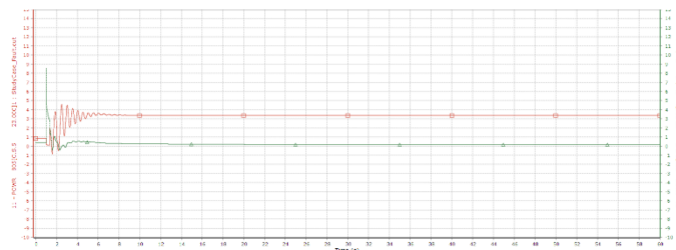

Figure 10. P/Q Responses of C.S.5 Power Plant in the Study Case with HVDC 500 MW

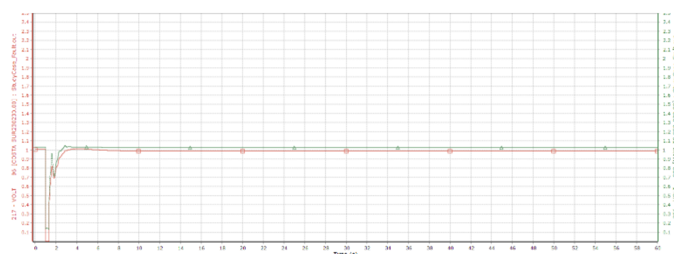

Figure 11. Voltage Responses of Costa Sur 230kV and Mayaguez 230kV in the Study Case with HVDC 500 MW

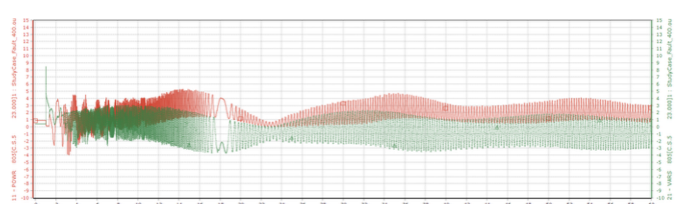

Figure 12. P/Q Responses of C.S.5 Power Plant in the Study Case with HVDC at 400 MW

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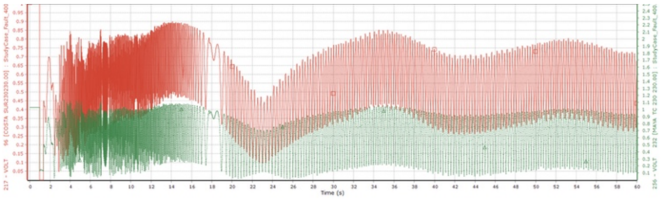

Figure 13. Voltage Responses of Costa Sur 230kV and Mayaguez 230kV in the Study Case with HVDC at 400 MW

Figure 12. shows the real power (P) and reactive power (Q) responses of the C.S.5 power plant near the fault location. Figure 13. shows the voltage responses of the Costa Sur 230kV substation and the POI of the HVDC system (Mayaguez 230kV).

The simulation results indicate that the PR system still becomes unstable following the disturbance scenario when Project Hostos is operating at a reduced capacity of 400 MW.

VI. Conclusion

Puerto Rico's electric power system has a peak electricity demand of 3,414 MW (June 2023) and a total generation fleet capacity of 5,749 MW. The total available generation capacity in any given hour, however, is substantially lower at below 4,300 MW. In addition, existing generating facilities in Puerto Rico (PR) often experience unplanned outages due to age of service and other factors. This, combined with geographic isolation and frequent exposure to extreme weather events results in reliability challenges.

A dynamic stability analysis was performed to evaluate the impacts of Project Hostos (VSC-HVDC interconnector) on stability of the PR power grid under severe fault conditions. The island-wide blackout event at the Costa Sur Power Plant on 6 April 2022 was selected for the analysis. Simulation results indicate that the PR transmission system with Project Hostos operating at full capacity will remain stable under the blackout event. Without the VSC-HVDC interconnector, the PR system experiences non-convergence and instability under the same fault condition leading to a full blackout. It should also be noted that Project Hostos' stability benefits will diminish when it operates at a reduced capacity.

In addition to significant stability benefits of Project Hostos, it will also further allow for future integration of higher levels of renewable energy resources gearing up towards island's net zero goals.

As a follow-on work to this stability analysis, it is recommended that a more detailed time-domain EMT-type study be performed with vendor specific data. This will enable a more comprehensive assessment of the system including sub-synchronous torsional interactions, harmonics and sub-harmonics, sub-transients and transients among others.

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