21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2013 Grid of the Future Symposium

The Upgrade of the Northern Terminal of the Pacific NW-SW HVdc Intertie Celilo Converter Station (USDOE-BPA)

Paper XX

B.C Furumasu **D. J. Kell** **K. A. Mitsch**
M.A Reynolds

POWER ENGINEERS Inc — **Portland, Oregon, USA**
TransGrid Solutions — **Winnipeg, Canada**
USDOE-Bonneville Power Administration — **Vancouver, Washington, USA**

SUMMARY

Many major HVdc links around the world are reaching end of reliable service lifetimes of the terminal apparatus and control systems. One of the most significant and largest HVdc links in the United States West Coast is owned by the USDOE Bonneville Power Administration (BPA) in the North and by the Los Angeles Department of Water & Power Department (LADWP) in the South. This project is known as the Pacific DC Interties (PDCI) System and is a critical part of the NW-SW Intertie capacity within the WECC NERC Regional Network. Terminal facilities were replaced and upgraded at the Southern terminal near Sylmar, California, USA 9+ years ago.

BPA has now embarked on a significant refurbishment and capacity increase of the Northern Terminal at the Celilo HVdc Terminal located near the Dalles, Oregon, USA. The BPA Refurbishment and Upgrade Project are composed of two significant parts:

1. Upgrade of the Celilo HVdc Terminal Facilities, Controls & Apparatus,
2. Re-insulation of the existing +/- 500 kV HVdc transmission line.

This project is unique in two major ways; The Northern HVdc terminal will be refurbished and upgraded to allow power transfers to a new link rating of 3,800MW. This paper will discuss the unique challenges of upgrading only the northern terminal of the link and how the up-rating will be coordinated with the existing Southern end HVdc Terminal. Given the aging fleet of HVdc terminals worldwide, and the conservative design employed in most of these existing projects, there is a unique opportunity for existing owner/operators to investigate the possibility of upgrading the capacity of their systems in a similar fashion to the PDCI. This paper will highlight some of the PDCI changes and provide a possible insight for other systems to be upgraded during the refurbishment process. By providing link rating increase, the economic justification for additional plant investment makes HVdc refurbishment projects far easier to support in the commercial sense.

KEYWORDS

HVDC REFURBISHMENT_UPGRADE_PACIFIC HVdc INTERTIE_USDOE_BONNEVILLE POWER ADMINISTRATION

1. Introduction

BPA is in the process of upgrading their portion of the PDCI. This project consists of two major components:

1. Upgrade of the Celilo terminal
2. Re-insulation and upgrade of the dc transmission line.

The upgrade of the converter will include the complete furnishing of a new ±560 kV bi-polar (12-pulse per pole) converter station rated at 3800 MW. All ac and dc filters will be replaced with new filters in the Northern Celilo HVdc Station, and AC &DC Filters will be upgraded in the Southern Sylmar HVdc Terminal in a coordinated schedule between BPA and LADWP. The transmission line upgrades include new insulation for operation at +/- 560 kV dc for North to South transfers, shunting of splice fittings, replacement of dampers and installation of failure containment deadends.

This project is unique in two major ways; only the northern portion of the link is to be upgraded and the Celilo terminal converter equipment will be up-rated to 3,800MW. This paper will discuss the following aspects of the PDCI upgrade project:

1. History of the PDCI
2. Upgrade Project Justification
3. Proposed Stages of Development
4. Unique Challenges of the PDCI upgrade project
5. Conclusions

Figure 1 PDCI Route

2. Ownership & History of the PDCI

The PDCI is jointly owned by BPA and a group of Southern California Utilities referred to as the Southern Partners. The Southern Partners are: LADWP, Southern California Edison and the municipalities of Glendale, Burbank and Pasadena. BPA owns, operates and maintains the northern terminal – Celilo and the dc transmission line down to the Nevada – Oregon border (NOB). The Southern Partners own the Southern terminal– Sylmar and the dc line from NOB to Sylmar. LADWP operates and maintains the Southern Partner's portion of the link.

The Pacific Inter-tie was ***first built in 1969 as a bipolar system rated at +/-400kV, 1440MW*** with 3 x 133kV mercury arc series groups rated for 1.8kA (converter 3 and 4). Over the next 35 years, the PDCI went through numerous upgrades. The ***current link capacity is +/- 500 kV, 3100 MW a significant, but not ultimate rating of the existing link.***

To provide a historical background for the reader, the following significant PDCI modifications have incrementally increased the reliablity and link capacity.

1. In 1977, Current upgrade based on studies of design margin in the equipment raised the current to 2.0kA using inherent capacity of the valves and bringing the rating to 1600MW
2. In 1984, the system was upgraded to +/-500kV by adding 1 x 100kV, thyristor valve group rated for 2kA, which increased the bipolar rating to 2000MW.
3. In 1989, 12-pulse parallel thyristor valve groups where added (Converter 1 and 2), rated for +/-500kV, 1.1kA, which increased the PDCI capacity to 3100MW.
4. In 2003, the mercury arc valves of Celilo Converters 3 and 4 were replaced with thyristor valves of the same rating, maintaining the current rating of converters 3 and 4 at 2kA, and the station rating of 3100MW. Control replacement was also part of the 2003 project, but was abandoned due to financial constraints at that time.
5. In 2004, at Sylmar, the parallel +/-500kV 1100MW converters were replaced with a new +/-500kV 3100MW converters and the original mercury arc converters 3 and 4 were retired. The replacement was required as a result of extensive damage sustained at the Southern terminal during the 1994 Northridge earthquake.

The existing system configuration is as shown in Figure 2.1. A Photograph of Celilo is shown below in Figure 2.0.

Figure 2.0

Celilo Terminal

(USDOE-BPA)

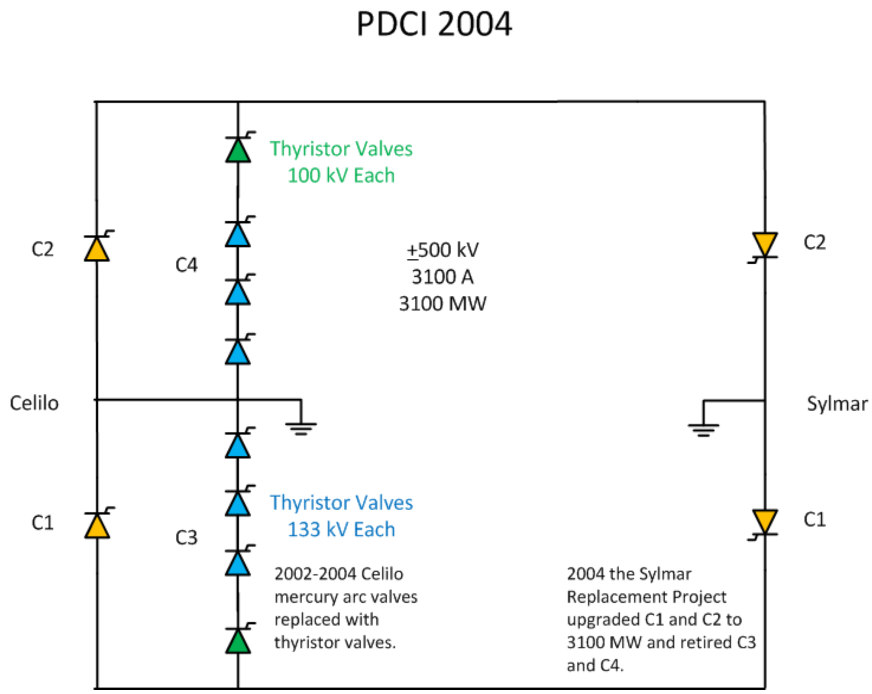


Figure 2.1 Existing PDCI configuration

During the PDCI evolution, the Celilo terminal changes and apparatus modifications have created very complex Protection & Control (P&C) system archetectures. Most all of the exisitng P&C systems are either non-supported by the original OEMs or are completely unsupported by the OEMs as they have been reorganized over time. These changes, system complexity, and growing migration of Operations and Mainteance staff into retirement and the availablity of spare parts, has created a situation that will have serious availablity impacts as the PDCI continues to age. Many of its systems and components are operating beyond their expected service life.

These factors prompted careful examination to determine the best approach for the future of the Celilo terminal.

Additonal commercial sensitivities have been created by the very high usage of the PDCI and the very rapid growth of re-newable energy sources in the Northwest in the form of widely distributed Wind Generation facilities, which are growing in importance to the Southern California CAISO and the major distribuiton utilities in Southern California (LADWP, SCE, Municipalities in the LA Basin)

3. Upgrade Project Justification

In order to determine what the best approach was for BPA to maintain its existing commitment to continued reliable operation of the PDCI, extensive engineering studies and economic analysis were performed on several alternatives. Two alternatives emerged as the most viable for continued reliable operation of the link;

1. **Sustain**

   For the Celilo terminal, retain the existing four converter architecture and replace systems and components as they reach their end of life. The dc line would also require substantial improvements to bring the line performance up to current USDOE-BPA and Utility Standards. This option retains the existing rating for the converter terminal.

2. **Upgrade**

   Replacement of the existing Converter 1 & 2 equipment with new dc converter equipment capable of the entire station rating. The dc line would require re-insulation to allow operation at a higher dc voltage. The Upgrade alternative also allows the opportunity to increase power transmission capability in the N to S direction by taking advantage of some latent capability in the Sylmar Converters. The dc line would also require substantial improvements to bring the line performance up to current standards.

Figure 3 shows a relative economic comparison for the two alternatives in terms of estimated capital expenditures per year over the next 25 years. Although the Upgrade is more expensive initially it is the lowest cost option overall when compared to the Sustain option. A "greenfield" replacement was also considered to reduce outage impact, but that alternative was more expensive and added several years to the project for land acquisition and environmental reviews.

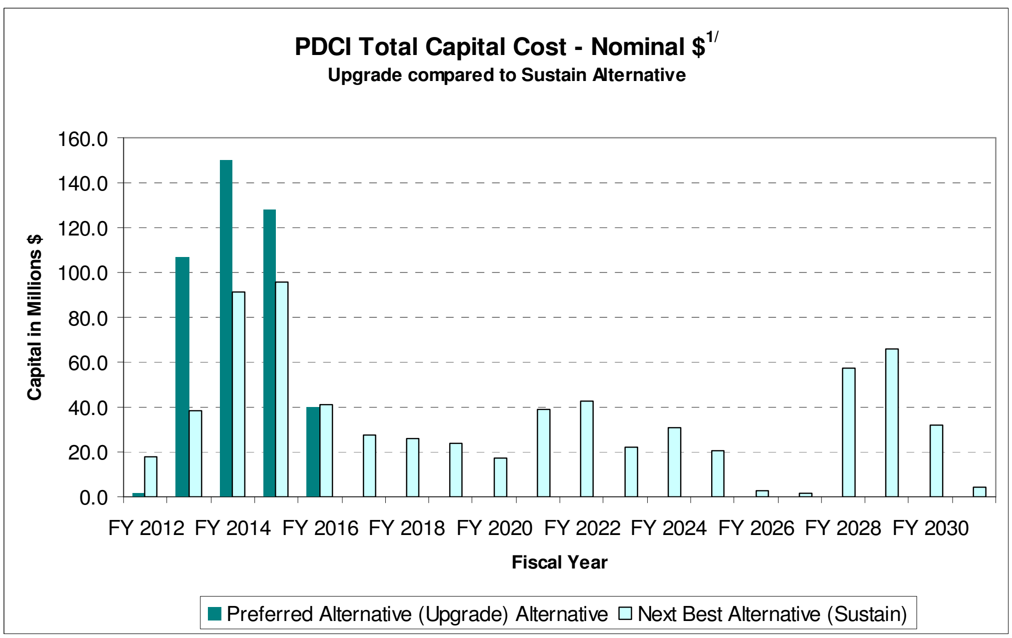


Figure 3 Economic Comparison

The Upgrade option also has several other benefits such as: utilizing one vintage of technology, reducing maintenance and spare part inventory for a simplified station configuration and the possibility of dynamic scheduling for the link. When compared to the Sustain option it is one large project instead of a stream of a multiple projects over 25 years. This will substantially save on contract administrative costs as well.

Ultimately BPA chose the Upgrade alternative as the best approach to maintaining reliable and economic operation into the future. As part of the Upgrade project, latent capabilities of the Sylmar converters will also be realized in three stages to increase the power transfer in the north to south direction.

From Figure 4 the green line represents the voltage profile along the line for maximum power in the N>S direction with the existing 3100 MW rating. The dc line is approximately 20 ohms resulting in a voltage drop of about 60 kV at Sylmar at full power. Part of the engineering analysis of the upgrade was a study of the Sylmar terminal to determine the maximum voltage that Sylmar could tolerate in inverter mode and was found to be just under 500 kV. Another result from the Sylmar study found that with additional transformer cooling augmentation the rated current could be increased from 3.1 kA to 3.41 kA. As a result the desired ultimate rating of the Celilo terminal was chosen as +/-560kV, 3.41kA and 3800MW. In this manner, the PDCI can meet its existing commitment to the region for reliable operation while building in future capacity.

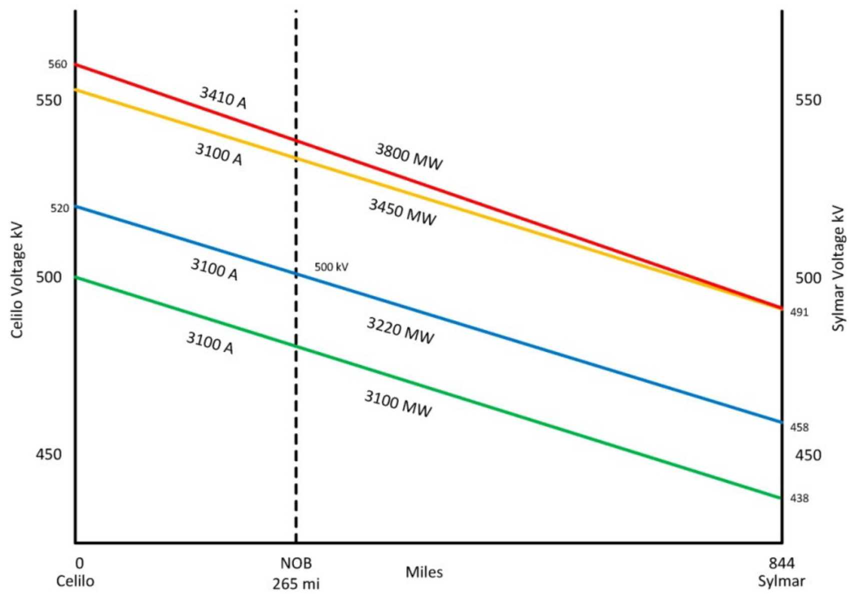


Figure 4 PDCI Voltage and power ratings (Existing: 3100MW, Stage 1:3220W, Stage 2:3450MW, Stage 3:3800MW)

4. Proposed Stages of Development

Based on the justification outlined above, the following proposed stages of development for the PDCI upgrade will take place:

During the engineering analysis for the Upgrade, BPA worked with the Southern Partners to determine if there was interest in making capacity upgrades at the same time BPA made its upgrades. Although the Southern Partners found the upgrade option desirable, due to economic constraints and other factors they chose not to participate in the full upgrade at this time. Because of this, the project was broken down into three stages, as indicated below. In this way, increases in N>S power ratings, and the attendant capital investment by the owners, can be accommodated as system conditions and economic factors dictate.

Project Stage 1.

At this point the scope of work includes major changes at the Celilo Converters 1&2 (circa 1989) (Figure 5.1) and modify the BPA portion of the transmission line (circa 1970). In additon to changes at the Northern Terminal, the control system at the LADWP Sylmar Terminal will be replaced and tested in tandem with the Northern Terminal (Celilo) controls to confirm the stablity and fault recovery performance of the new operating mode for the PDCI . ***The rating of the transmission system will be rerated to 3220 MW*** with a maximum voltage of 500 kV at the Nevada-Oregon border (NOB) for North to South power flow. Celilo HVdc Terminal facilities will be designed to reliably operate at ***a maximum rated voltage of +/-520 kV and a maximum current of 3100 amperes for this phase***. The new Celilo Converters will be designed and constructed to meet the requirements of all 3 phases as will be described below. The harmonic filtering to be installed in stage 1 shall be sufficient for all phases. Reactive compensation shall be sufficient for stages 1 and 2. Line losses would remain the same as the current is not increasing. This is indicated as the blue line in Figure 3 Extensive new harmonic impedance analysis and back ground harmonics measurements were provided in the HVdc specification. Given the age of the aparatus, and the significant commerical risk resulting from reuse, a completly new set of HVac filters and VAR shunt capacitor banks will be installed using the most modern synchronous PCB technology and better capacitor unit designs.

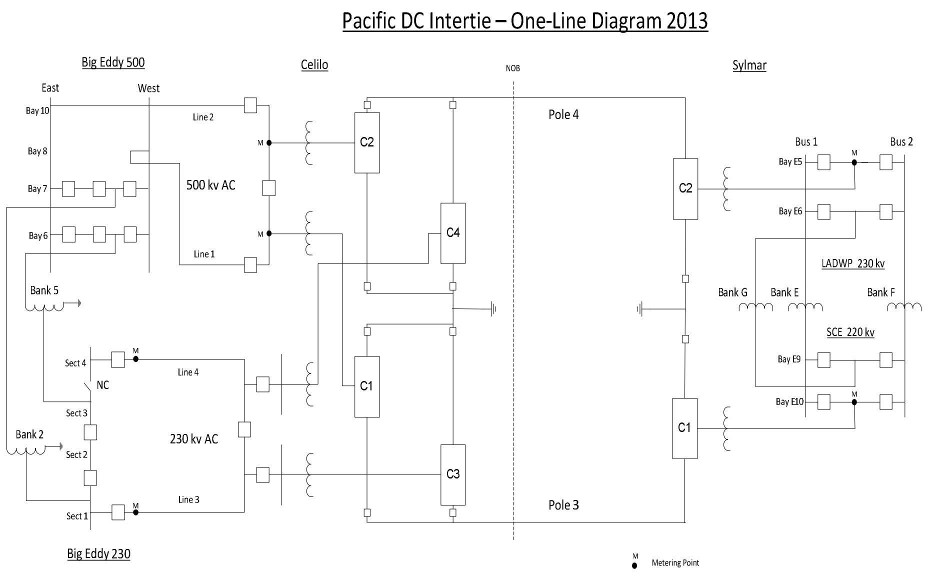


Figure 5.1 Exisitng Celilo HVdc Station "as found"

Project Stage 2.

This next stage of the project involves only Sylmar (Southern Terminal) changes changes. Modifications will be made to the BPA HVac network and modifications to the Sylmar-NOB part of the transmission line for increased operating voltage as well as ac network reinforcements in the Southern end. **The rating of the line at this milestone will be 3450 MW**. Celilo will operate at **+/-556 kV, 3100 amperes**. Line losses would remain the same as the current is not increasing. This is indicated as the yellow colored line shown in Figure 4.

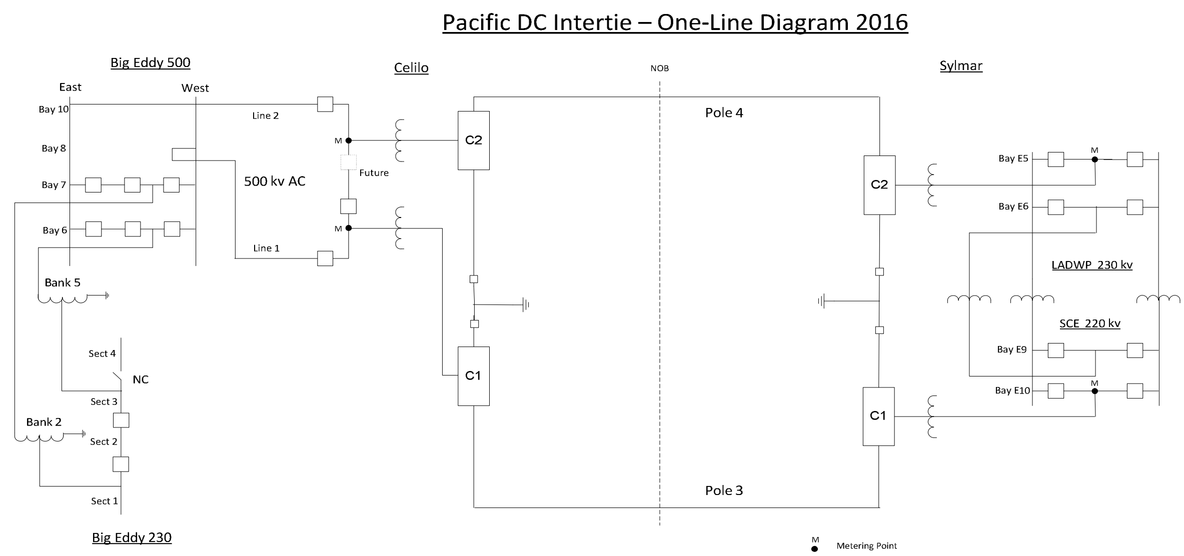
Project Stage 3.

At this point there will be required additional reactive compensation for the new Celilo converters and BPA HVac network modifications will be added to provide support for the Project Stage 3 rating. This phase requires that further modifications be made to the Sylmar-NOB portion of the transmission line and portions of the California ac network will be reinforced. The Sylmar Converter Station will require additional transformer cooling to be installed on the exisitng ABB converter transformers along with control system software changes within the already replaced control system hardware platforms.

The ***PDCI will then achieve the ultimate rating of 3800 MW for N to S power transmission***, with Celilo operating at +/-560 kV and 3410 amperes (Figure 5.2). It must be noted that increased HVdc transmission line losses will occure at this higher level of HVdc current. This effect (I*2 x R) is indicated as the red line in Figure 3.

Long term planning studies have shown significant WECC (Western Interconnection) benefits for increasing capacity on the PDCI well into the future. BPA used GridView™ which is a production cost analysis tool that evaluates the societal benefit of reducing HVac grid congestion. Using this model, several PDCI ratings were compared with various hydroelectric and thermal generation scenarios. Some ***key findings were that the PDCI was fully loaded for over 600 hours per year (at the full rating)***. Increases in PDCI ratings could reduce network congestion by hundreds of hours per year depending on generation and load patterns. WECC wide variable operating costs could be reduced by several millions.

The WECC 10-Year Regional Transmission Plan, September 2011, also indicates long range benefit from increasing capacity on the PDCI (Path 65). The majority of long range WECC study cases indicate congestion and high utilization for the PDCI. According to the WECC report the combined Path 65/66 (PDCI + California-Oregon AC Intertie) are the most heavily utilized and congested paths of all WECC



paths studied.

Figure 5.2 – Celilo Station – "Ultimate Rating Configuration"

5. Unique Project Challenges

The staged development for the PDCI upgrade project, is presenting unique challenges in the following areas

1. Testing

   Operational testing of an HVdc system rated for 3800MW will be a significant commercial issue for most owner/ operators. Not only is the commercial arrangement complicated and expensive for testing, but also the configuration of the remaining operational facilities presents unique challenges. During the construction and commissioning of the new equipment, BPA intends on providing as much capability as possible using the remaining Pole # 3 &4, throughout the upgrade construction period, but the control complexities and the interface between the new system and the old will always have significant uncertainties and failure modes which need to be guarded against.

   A further challenge for PDCI upgrade project will be the ability to test the Celilo converter equipment to the full rating of 3800MW during stage 1, due to transmission and Southern end Terminal capacity limitations. Since the final stage 3 implementation is not expected to occur for a number of years after the initial commissioning, provisions have been made for back-to-back operation of the Celilo converter that will permit full voltage and current tests for the converter. A virtual re-commissioning series of tests will be part of a much extended testing period, which is un-common in most installations.

   Maintaining some capacity online during construction is of primary importance and several safeguards are being instituted to prevent failure modes from escalating into full Bipolar outage events. This is very important in the safeguarding of the system against events that have serious impacts on the commercial power markets served by the PDCI. Primary importance and several safeguards are being instituted to prevent failure modes from escalating into full Bipolar outage events.

   These previously mentioned challenges present a unique partnership and risk sharing between the HVdc OEM ABB, and the owner/operator. It is virtually impossible to craft a specification and contract that fully insulates each party from the unforeseen circumstances such a project presents. In order to manage the testing and commissioning period BPA has brought on outside HVdc expert consultants from the USA and Canada, in which includes experienced former BPA HVdc experts, and started a long organizational change process to assure the right engineering resources are available during all aspects of the design, manufacturing, and commissioning activities. BPA and the OEM ABB will perform extensive HVdc Simulation Tests with the actual controls (from both terminals) coupled to a RTDS™ WECC Network representation. These tests will confirm and allow the two owner/operators to exercise almost all possible modes of operation, including extensive “staged fault test”, SSR, and SSI sensitivities, and a host of other tests which would not be possible to conduct on the real WECC Power Network.

<u>BPA has ordered as part of the project a significant RTDS™ simulation hardware platform, that will be maintained at the Celilo Converter Station for the duration of the HVdc operations of the PDCI</u>. This HVdc simulation capability will form the basis of an extensive training and maintenance/trouble shooting tool, to assure adequately trained BPA technical staff with a powerful tool to keep the converter station operational well into the future. This new in-house capability for BPA will position USDOE-BPA as a leader in the operational studies and modification expertise of HVdc Links in North America.

In order to ensure system requirements are met, converters 3&4 will be maintained during construction and if needed during commissioning and during the first year of operating the upgraded converter for emergency use if required. This requires some upfront planning from BPA and ABB as well as a significant outage coordination process managed through the WECC’s outage management system.

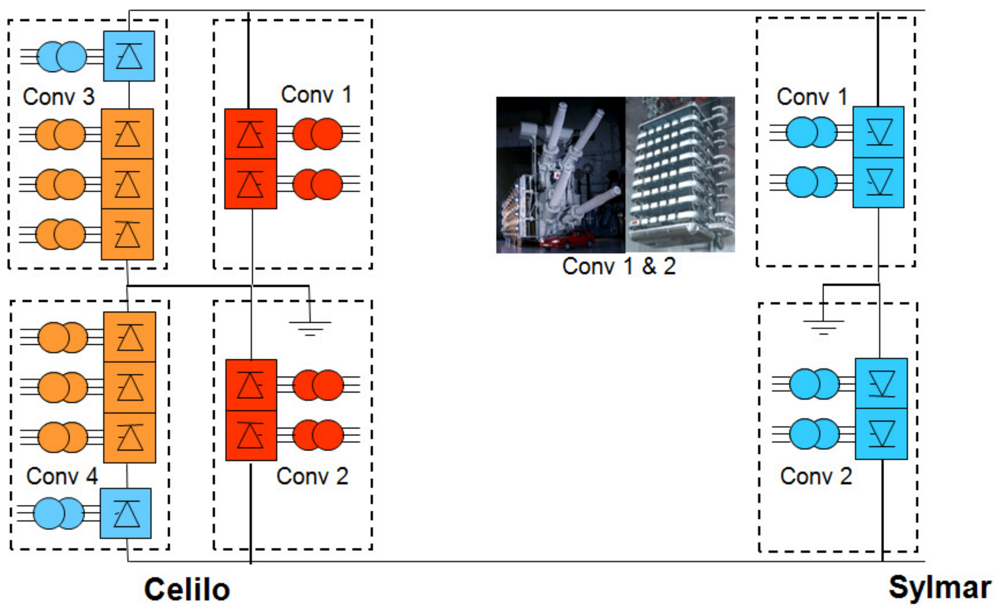


Figure 5.3 Existing converters to be retained

2. Valve Hall

The existing converter 1 and 2 valve halls will be reused for the new valves. This situation would not have been possible, except for the fact that BPA engineering staff had specified that the existing valves could be cross parallel connected in the future, such that the valve to floor and the valve top to ceiling clearances allowed the existing valve hall to accommodate the new valve design. This allows the new converter valves to have ***over three times the power rating with a 12 % increase in voltage compared*** with the existing valves. Therefore the new valves will fit in the existing valve hall, with only minor alterations to the valve suspension structures. The building structure itself was examined and found to meet all current seismic performance requirements

(IEEE-693 for Apparatus, ASCE/SEL-7-10 covering buildings, and ASCE Guide 11 for Substations). The overall requirements for the Siesmic performance in this zone have been established by USGS as (***moderate zone performance***).

3. Substation & Converter Building Area Requirements

   As converters 3&4 and the converter 1&2 buildings are being maintained, the available area for the new ac filters and reactive power support is restricted to the existing Converter ! & 2 switchyards. Certain parts of the exisitng HVac switchyard layout are being expanded toaccomodate both the initial and ultimate space for all of the filter and shunt capacitor bank additons on the 500 kV bus(s) at Celilo.

4. Electrode and Electrode line

   The electrode and electrode lines were assessed for the increased rating of the Celilo Converter. Similar investigation is underway in the by the Southern Owners in the Los Angeles area. No anticipated modifications on the existing electrode system are expected, and the existing limits of 144,000 Ampere-Hours per year will continue to be adequate for the upgraded converters.
   The assessments on the Northern Terminal electrode included excavation to visually inspect the electrodes, the cables and joints in several locations and included a timed current injection into the electrode line and electrode with temperature measurements at selected locations. It was found that electrode is in excellent physical condition with no apparent evidence of overheating, corrosion, or degradation ***even after 40 years of operation***. Furthermore, the electrode can operate for 26 minutes at 3,100 Amps before reaching its thermal limit. Limits at other current levels are as shown in Figure 6 No active monitoring at either electrode site is anticipated during this project, due to the intermittent use of the existing electrodes, to adhere to the operational limits established during the original PDCI impact studies (sponsored by NACE and other interested parties including the legacy Bell Telephone & General Telephone Engineering Departments (now disbanded, or significantly restructured)

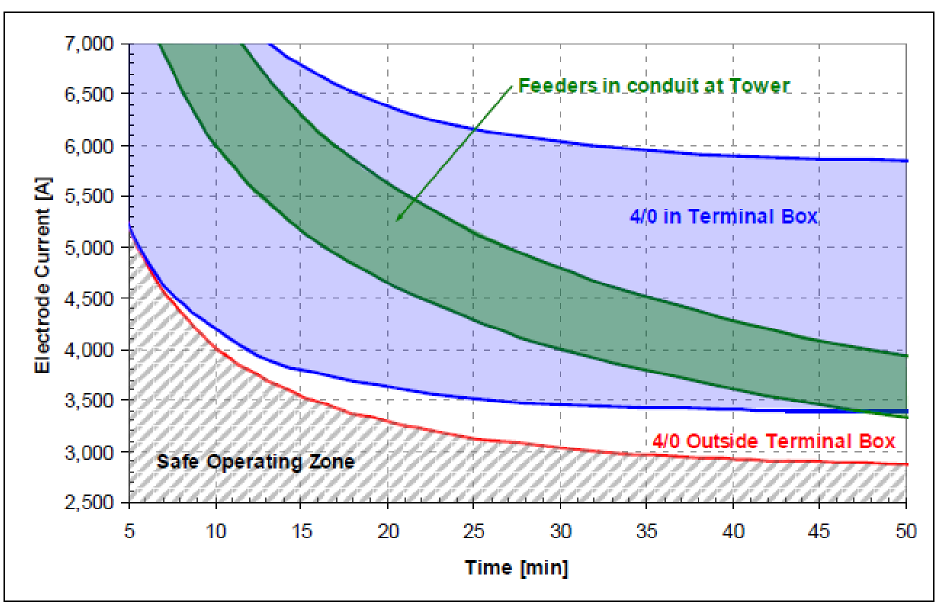


Figure 6 Time Durations and Ampacity of Critical Components

6. Conclusions

At the end of 2012 the Celilo Converter Station Upgrade project was awarded to ABB. The terminal will be completed by December 2015 and the transmission line work for the Northern portion of the PDCI is scheduled to be done by November 2017.

Incremental increases in the power rating for the PDCI of 3220, 3450 and 3800 MW will be realized by this project, and capacity increases beyond the 3220 MW initial stage will be accomplished with transmission line upgrades, modifications to the Sylmar Converter Terminal, and ac system enhancements on both the ac systems supporting the Northern and Southern converter terminals.

USDOE-BPA and ABB will be enhancing and improving the WECC Network with a new, highly reliable and increased capacity PDCI, that will ensure a bright future for one of the legacy and historically intersting HVdc links in the Western USA.

BIBLIOGRAPHY

[1] M. Reynolds, **Commissioning of the Pacific HVDC Intertie Upgrade Project**, Coauthor, 4th International Conference on AC & DC Power Systems, London, UK October 1985.

[2] M.Reynolds, **Operating Experience of the Celilo HVDC Terminal**, Co-author, HVDC Operational Conference, Winnipeg, Manitoba, Canada, September 1987.

[3] M.Reynolds, **Completion and Initial Operation of the Expanded Four-Converter Celilo-Sylmar Pacific Northwest to Pacific Southwest Intertie**, Co-Author, SC 14, CIGRE 1990 Conference, Paris, France, September 1990.

[4] CIGRE B4**, Compendium of HVDC Schemes throughout the World,** Contributing co- author, CIGRE B4/AG B4.04 September 2012, CIGRE Conference, Paris, France (continuous publication).

[5] CIGRE **HVDC Performance Reporting Protocal** Contributing author, CIGRE SC B4

[6] CIGRE JWG B4-43/A3/B3, **Increased System Efficiency by use of New Generations of Power Semiconductors**, September 18, 2008

[7] K. Mitsch, D. Kell, B. Furumasu, **The Pacific Inter-Tie Celilo Up-Rate Project**, Paper 24, October 2013, Brasilia, Brazil