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# Celilo Pacific DC Intertie Upgrade presentation

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## SUMMARY

The Pacific HVDC Intertie transmission (PDCI) was originally commissioned in the end of the 1960's. It was then a bipolar transmission with three series connected converter groups per pole and with a rating of +/-400 kV and 1440 MW. Since then it has been improved by various complementary installations to respond to increasing transmission needs and the ratings of today are +/-500 kV and 3100 MW by including both series connected and parallel connected converters. The Celilo station has continued to work with these complementary installations as briefly referred here. It is now over 40 years old and aging systems and equipment failures are contributing to deteriorating reliability of the PDCI. With the aim of preparing the Celilo station for another 30-40 years of life a feasibility study was carried out in 2009. As a background for the study the general assumption that major electrical equipment and thus also HVDC stations has a lifetime of 30-40 years was considered. Special attention was given to the HVDC specific equipment: converter valves, converter transformers and HVDC control equipment. This study compared two alternatives: 1. retain the existing four converter architecture and renew obsolete equipment to extend its life while keeping the rating of the link the same and 2. change to a traditional two converter bi-pole architecture while increasing the rating to take advantage of some latent capabilities in the Sylmar terminal. An upgrade in line with alternative 2 indicated several advantages such as the possibility for increased power transfer, higher availability and reliability, lower losses and easier operation and maintenance. A decision was then taken by BPA to upgrade the Celilo station and do it to take advantage of the potential of the Sylmar station. As substantial upgrade of the southern part of the line will be necessary to utilize the full upgrade of the Celilo station, it is expected that the PDCI will initially be operated up to 3220 MW at +/-520 kV.

This paper presents the highlights of the chosen configuration as well as the background from the historical development of the Intertie from the 1960's to today. Also highlights from the study comparing retained or new architecture are provided with special emphasis on evaluation of life time of equipment and components to be kept or exchanged and on the advantages of the upgrade. For the chosen configuration basically all equipment will be exchanged while important buildings and other structures will be reused. Main items thereof are the exchange of basically all equipment and the re-use of the existing Converter 1 and 2 valve halls for housing the new +/-560 kV, 3800 MW thyristor valves as well as various mechanical switchyard elements such as gantries and towers. The converter transformers will have unit rating of 770 MVA and will be installed in the same positions as the existing transformers for Converters 1 and 2.

## KEYWORDS

HVDC – Celilo – Upgrade - Pacific Intertie

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## 1. INTRODUCTION

The Pacific HVDC Intertie (PDCI) transmits power between the Celilo converter station at the Dalles, Oregon and the Sylmar converter station in the Los Angeles area in California, over 1358 km, see Figure 1. At the beginning of the 1960s, Federal authorities exploited major hydropower resources on the Columbia River in the north-western US. These power resources could be provided at electricity rates so far below the production costs in the Los Angeles area as to make long-distance transmission economic. It was shown that HVDC was economic from a distance point of view and necessary for stability reasons. This power has continued to be economic to the Los Angeles area especially in the peak spring high water seasons. In dry years it would be possible to provide power to the north. To continue to take advantage of this power available in the north, the Celilo converter station will be renewed and upgraded for another 30 to 40 years of life.

The Celilo station is owned by Federal authorities, Bonneville Power Administration (BPA) and Sylmar by the Sylmar Partners, Los Angeles Department of Water and Power (LADWP), Southern California Edison (SCE), and the Cities of Glendale, Burbank, and Pasadena.

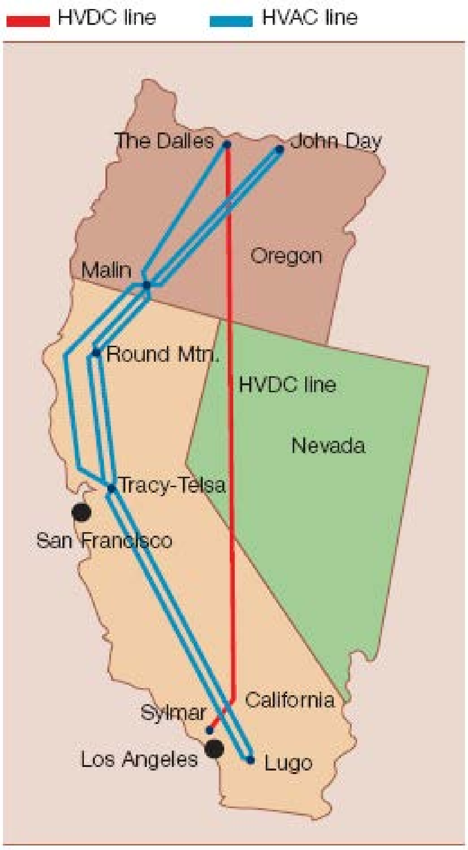


Figure 1 The Pacific HVDC Intertie with parallel ac lines.

Herein the background from the historical development of the Intertie from the 1960's to today and highlights from the study comparing retained or new architecture are described. Special emphasis is on the evaluation of life time of equipment and components to be kept or exchanged and on the advantages of the upgrade and how this has led to the chosen configuration.

## 2. PACIFIC HVDC INTERTIE DEVELOPMENT: FROM 1440 MW, +/-400 KV TO 3100 MW, +/-500 KV

The original installation consisted of a bipolar scheme with 3 series connected mercury-arc valve converters per pole for 1440 MW, ± 400 kV [1]. This entered into operation 1970.

Until today a number of upgrades have been made of the converter stations both of voltage and current. These upgrades were implemented to take advantages of an originally generous HVDC line design. Already in 1977, it was verified that the mercury-arc valves would be able to operate with the current increased to 2000 A, which raised the power rating to 1600 MW. In 1985 the Intertie was expanded with a fourth series-connected thyristor valve converter to attain 2000 MW, ± 500 kV. In 1989 a complementary parallel pole with thyristor valves was installed increasing the power to 3100 MW. In 2004 the Sylmar station was completely rebuilt to one converter per pole for 3100 MW, +/- 500 kV to simplify operation and prepare for another 30-40 years of operation. At the same time the Celilo station was renewed by exchanging the original mercury-arc valves for new thyristor valves [2].

## 3. PDCI LIFE EXTENSION FOR ANOTHER 30-40 YEARS

The Celilo Converter Station is over 40 years old and aging systems and equipment failures are contributing to deteriorating reliability of the PDCI. A comprehensive BPA, see chapter 5, study of in-kind equipment replacements required to sustain acceptable performance over the next 30 years revealed that the present value of required investments would exceed the cost of replacing the entire converter station with a modern two converter terminal. The complete replacement option would be simpler to operate, substantially less costly to maintain and would reduce terminal losses. This approach would largely mirror the 2004 Sylmar Replacement Project which replaced the four converter terminal, including the obsolete mercury arc valves, with a modern two converter terminal. Installing all new converter equipment at Celilo would also provide an opportunity to upgrade the terminal power rating for a relatively low incremental cost which could support additional PDCI capacity.

Preliminary planning studies found that the a.c. transmission system supporting both Celilo and Sylmar converters would require increasing degrees of reinforcement depending on the level of PDCI upgrade implemented. PDCI bipole loss during heavy north to south power flow is a severe disturbance with widespread performance impacts for the western interconnection transmission system. Any increase in PDCI north to south transfer rating will increase the severity of this disturbance and will be studied extensively as part of the Western Electricity Coordinating Council (WECC) Path Rating Process to ensure that system performance criteria are met for all PDCI outage contingencies. While the higher rating will increase outage impacts, the Celilo Converter Station modernization will significantly improve PDCI reliability and reduce the probability of bipole outages.

Based on the results of the PDCI alternatives study, three potential levels of upgrade were identified:

- 3220 MW – This level would maintain the existing 3100 A current rating but would increase the Celilo voltage to 520 kV. This would limit the voltage at NOB (Nevada Oregon Border) to 500 kV thereby requiring no line upgrades south of NOB. The Celilo-NOB line portion would be upgraded. Control modifications would be required at Sylmar. Preliminary BPA studies indicate that no a.c. transmission system reinforcements will be required to support this 120 MW rating increase beyond existing projects already scheduled.
- 3450 MW – This level, referred to as the voltage only upgrade, would maintain the 3100 A current rating while increasing Celilo voltage to 556 kV. This would make full use of the Sylmar converter voltage capability in inverter mode. No additional line upgrades would be required for the Celilo-NOB line. Substantial NOB-Sylmar line modifications would be required including insulator replacement and raising or replacing a large number of towers to provide adequate ground clearance. Unspecified AC transmission system reinforcements would be required to support this 350 MW rating increase.
- 3820 MW – This level, referred to as the voltage and current upgrade, would increase the current rating to 3410 A, which is the maximum inherent capability of Sylmar terminal, and increase Celilo voltage to 560 kV. No additional line upgrades would be required for the Celilo-NOB line. Additional line upgrades would be required for the NOB-Sylmar line to provide additional clearance for increased conductor sag. Sylmar transformers would require additional cooling capacity. Unspecified AC transmission system reinforcements would be required to support this 720 MW rating increase.

In December 2011, BPA Executive Management approved proceeding with the Celilo complete replacement option with the new terminal designed to support the full 3820 MW level capable of operating at 560 kV and 3410 A. The relatively small incremental cost increase to extend the Celilo converter rating and Celilo-NOB line capability beyond 3220 MW to 3820 MW would preserve the opportunity for future upgrade of the PDCI to more fully utilize the inherent capacity of the existing Sylmar converters. However, because of the high costs and uncertain benefits for the Sylmar Owners, they are unable to support a PDCI uprating beyond the 3220 MW level at this time.

## 4. GENERAL CONSIDERATIONS FOR UPGRADE OR RENEWAL OF HVDC SCHEMES

It is assumed as a general rule that major electrical equipment and thus also HVDC stations has a lifetime of 30-40 years. As the technical life of most equipment in the HVDC Converter stations generally fulfils the expected 30 – 40 years it is from pure technical point of view only minor replacement needs during the expected lifetime mainly of equipment or components with moving parts. In addition it could be desirable to replace control and protection hardware in a shorter time perspective due to the rapid development of capacity and speed of electronic components.

### *4.1 Converter valves*

Mercury-arc valves were used in all early HVDC installations up to 1970. The mercury arc technology required a substantial amount of maintenance work with continuous “rotation” of the valves into a separate workshop to achieve life times in the range of 30-50 years. There have however been other reasons for exchanging the mercury-arc valves before the end of their technical lifetime especially the significant environmental disadvantage with the large amounts of pure mercury that was present in each of these installations. This has in some cases speeded up the decisions to exchange the mercury-arc valves for thyristor valves.

In the 1970’ the technology changeover to thyristor valves came. The oldest installation still in operation, Eel River entered in operation 1972 and was delivered by General Electric from the US. A majority of thyristor valves installed then are still in operation. The Skagerrak 1&2 thyristor valves have been in continuous operation for more than 30 years and are now being scheduled to continue operation until 2027, which will result in at least 50 years operation.

The valve hall environment, cleanliness and humidity, are important for the high voltage valves performance, especially the insulating structure and the optical fibres. Sensitive components inside the high voltage valves are the optical fibres and the distribution components of the water cooling system.
There are no indications of an increased fault frequency of the thyristors from any of ABB’s plants due to ageing; on the contrary the fault frequency seems to be decreasing. From this it can be concluded that none of the thyristor converters are approaching their technical end of life. It looks very probable that thyristor valves, with proper maintenance including exchange of sensitive components and components becoming obsolete can be used at least as long time as the line or the cable used to connect the stations, which can be assumed to some 50-60 years.

The technology development has increased power and voltage handling capability of thyristors at an extraordinary rate during the more than 30 years that the technology has been in use. Thus it would be more likely that owners of plants decide to upgrade their thyristor valves with modern state of the art thyristors to achieve a higher power capability or to lower the losses than for expiring technical life.

### *4.2 Converter transformers*

The statistical failure rate for converter transformers is around 1 failure per 200-300 transformer years of operation. Some failure types have contributed heavily to this. The initial mercury-arc valves suffered initially from many arc-backs, which stressed the converter transformers by repeated short circuit currents and decreased their lifetime. During the initial operation of the Itaipu transmission, there occurred some infant failures, which contributed to the high failure frequency. Many failures in various schemes have later been explained by insulation deterioration due to contaminated oil. These confounding factors make it therefore difficult to estimate an exact lifetime for a converter transformer.

For converter transformers used in thyristor valve converters and with insulating oil specified according to the latest recommendations an increased lifetime compared to today's statistics is expected. Some activities will continue to be important for lifetime such as preserving the operating condition of the insulation system including the oil and the connectors and moving parts of the tap changers. Today it would be possible to use a Mature Transformer Management Program (MTMP) to evaluate condition assessment, remaining life time, risk for failure etc. and also understand which services could mitigate risks and prolong life. On line monitoring of critical parameters such as gas content, moisture, temperature and load conditions, tap changer status and advanced calculations for upgrade of power could inform when and which actions would be necessary.

A proper oil treatment and maintenance of tap changers could continue to keep the converter transformers fit for operation during the 30 – 40 years lifetime indicated for the converter stations.

### *4.3 HVDC control and protection*

Today there is a very large collected experience of HVDC plants with electronic control systems, around 100 HVDC transmissions have been taken into operation. Many of the schemes are still in operation using their original control systems.

In some schemes controls have been replaced when complete renewals of stations have been made e.g. to increase the power transfer capability. In some installations the control systems have been exchanged after some 25-30 years. This has often been made in connection with other changes to the plant. In CU a control replacement was executed after 27 years in operation with the aim for an extension of additional 25 years in operation. In Skagerrak 1&2 a similar exchange was made after 30 years of operation.

To make a control equipment operate impeccable during a long time, the availability of spare parts and support is also very important. In most cases, enough spare parts for the controls can be delivered from the beginning to last during the expected lifetime of the plant.

In the programmed control system (μProcessor based) that has been in use in many HVDC control systems since 1980 smaller changes and improvements can often be made without requiring additional hardware. For larger expansions it might be required to replace or add some computer units. In these situations it is necessary to assure that new generations of control systems will be backwards compatible with earlier generations. This means that for example software that was utilized for Itaipu, more than 25 years ago, can still be compiled and run on the latest generations of the corresponding control equipment.

## 5. CELILO FEASIBILITY STUDY FOR INCREASED LIFE

The study performed 2009 presented various upgrading possibilities for the PDCI Celilo converter station. The definitions of viable configurations were made considering the capabilities of the Sylmar converter station, which was modernized a few years earlier. Two configurations were chosen for detailed study.

The <u>Celilo Base Case configuration</u> implies keeping the existing architecture with 3100 A and 500 kV per pole and with the present 4-converter configuration, with two parallel converters per pole. To retain the architecture the main task was the exchange of equipment necessary to achieve another 20 years of operation. Exchange of equipment referred to most of the converter valves, the converter transformers and also other insulated high voltage equipment and the HVDC control and protection.

The <u>One converter per pole case</u> was equivalent with the today installation in Sylmar. The suggested rating per pole was 3410 A, +/- 560 kV, which is coherent with the maximum Sylmar station capabilities for power direction Celilo to Sylmar. This configuration would be all connected to the 500 kV a.c. side.

For comparing the two configurations various parameters were considered and investigated.

The One converter per pole case would simplify the configuration to become equivalent with the Sylmar station. In addition the modification would allow for an increased rating from 3100 MW to 3820 MW, measured on the Celilo d.c. line connection. Physically the new thyristor valves for full power could be contained in the existing buildings for Converters 1&2. To fully utilize this increase, modifications to increase the d.c. line insulation and coolers for the Sylmar converter transformers would be needed.

The One converter per pole case is a more complete renewal of equipment than the Base Case and implies a higher direct investment cost. This shall be viewed against the various technical and economic advantages such as the higher rating and the expected longer life 30-40 years against 20 years. The higher direct voltage will give as well as higher rating also lower line losses by around 75 MW when operating at 3100 MW than for the Base Case. Converter station efficiency will also be improved: losses would go down to around 0.67% compared to 0.79% for the Base case.

The simplicity of the One converter per pole case gives lower failure rate and higher availability and less maintenance which all contribute to the expected longer life. Predicted unavailability and failure rate would decrease to roughly half, as compared to keeping to-days configuration. Also scheduled maintenance would require less effort for a simpler and more modern station and could be limited to around 500 man-hours per year.

After evaluation of the study BPA decided to choose the One converter per pole alternative with the possible staging shown in Chapter 3.

## 6. CELILO UPGRADE PRESENTATION

The decision to go for the One converter per pole configuration implied that the Celilo upgrade would be made so that the Sylmar capacity could be fully utilized and for full coordination with the Sylmar station. This resulted in that the dc line voltage will be raised to +/-560 kV in the Celilo end and graded down to +/-500 kV at the Sylmar end. By that the power transmission capacity will be increased to 3820 MW in the direction from Celilo to Sylmar, while it will be unchanged in the reverse direction. Initially, until the southern part of the dc line has been upgraded, Celilo will be operated with +/-520 kV, called Phase 1. Operational staging for 3450 MW and 3820 MW according to Chapter 3 are called Phase 2 and Phase 3 respectively.

In December 2012, BPA signed a contract for implementation of this new upgrade of the Celilo converter station to be commissioned late 2015. Main items thereof are the exchange of basically all equipment and the re-use of the existing Converter 1 and 2 valve halls for housing the new +/-560 kV, 3820 MW thyristor valves and placement of the converter transformers as well as various mechanical switchyard elements such as gantries and towers.

The station is arranged as a symmetric configuration of the two poles of the bipole, see Figure 2. This includes the symmetric configuration of a.c. filters around an a.c. tie breaker, which connects the poles. On the dc side it is possible to transfer operation of one pole to metallic return to avoid ground current.

The normal control mode shall be constant power at the rectifier d.c. bus. It is anticipated that in the beginning the direct voltage at the Oregon-Nevada border shall be controlled to maximum 500 kV by the inverter constant gamma and tap changer control. After the d.c. line insulation for the southern part of the line has been raised the d.c. voltage at the Sylmar station shall be controlled at the inverter. The inverter control angle gamma shall be kept constant to the Gamma reference.

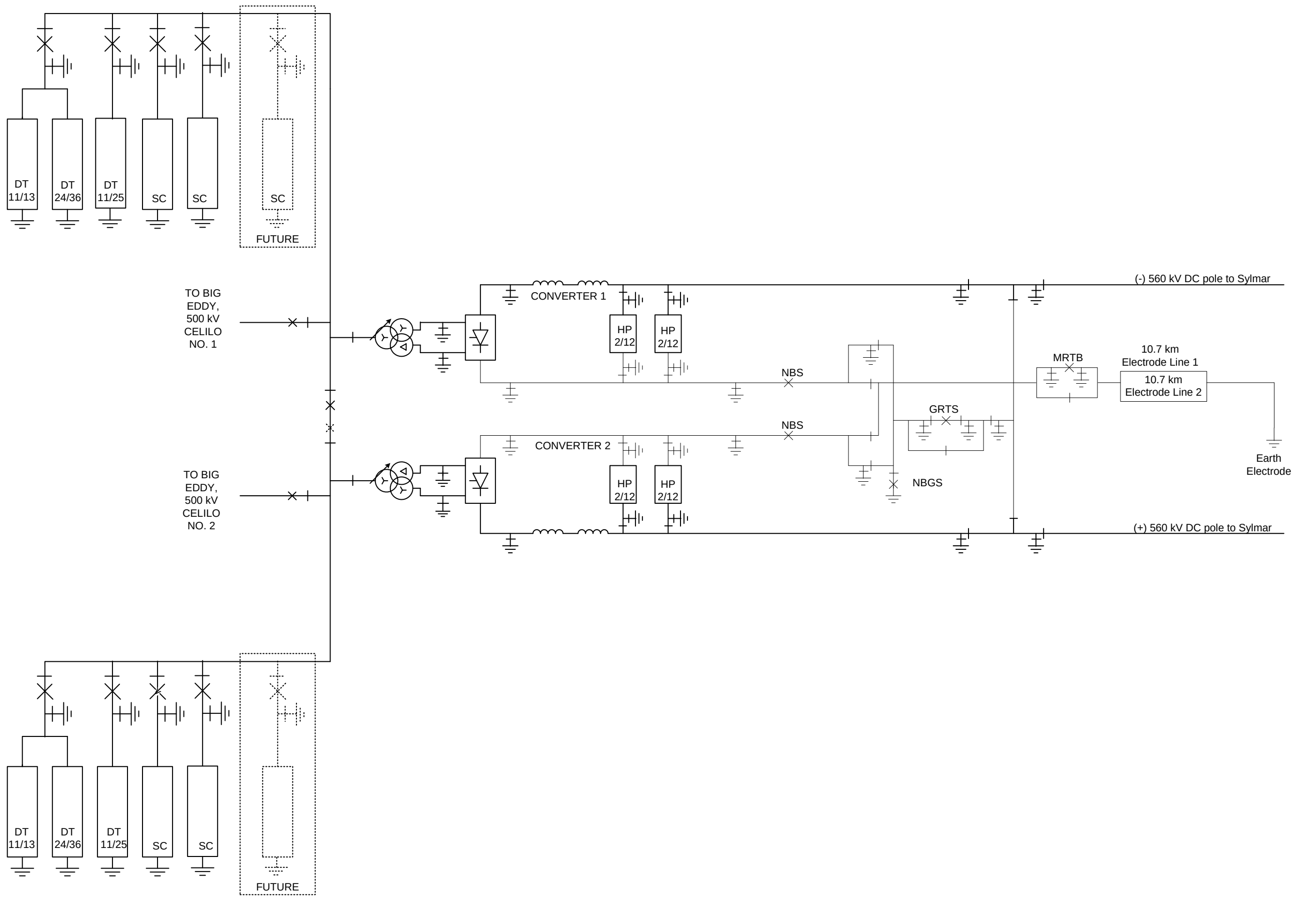


Figure 2 Celilo upgrade Single line overview.

The reactive power compensation of the Celilo Converter Station Upgrade is designed to balance the reactive power consumption of the converters with the reactive power generation from the reactive power of filter and shunt capacitor banks. In Phase 1 2210 MVAr in filters and shunt banks are installed to compensate for a maximum converter consumption of 1921 MVAr. This compensation is considering the balance with regard to a.c. voltage, allowed exchange with the connected a.c. network and hysteresis in order to refrain from hunting of circuit breakers. A typical example of how filter and shunt banks are connected throughout the power transmission from minimum power to rated power is shown in Figure 3 for normal bipolar operation. A reactive power control (RPC) is included to administrate the reactive power balance at the various operating conditions.

The a.c. filter configuration has been determined by taking into consideration the requirements on harmonic performance and the constraints on filter bank size, reactive power interchange with the network, and outage requirements.

The thyristor valves are of a quadruple valve design, i.e. four series connected single valves, mounted on top of each other in one mechanical unit. Three such structures are used per 12-pulse converter and are suspended from the ceilings of the existing valve halls. For Celilo each complete single valve unit consists of 90 series connected thyristors with intermediate reactors.

There are economic and space advantages of combining the Y and D units of the converter transformers into single phase three winding units and it was verified that such transformers can be designed, manufactured and transported to the Celilo site. They will have unit rating of 770 MVA and transport weight of 380 tonnes. They will be installed in the same positions as the existing transformer for Converters 1 and 2.

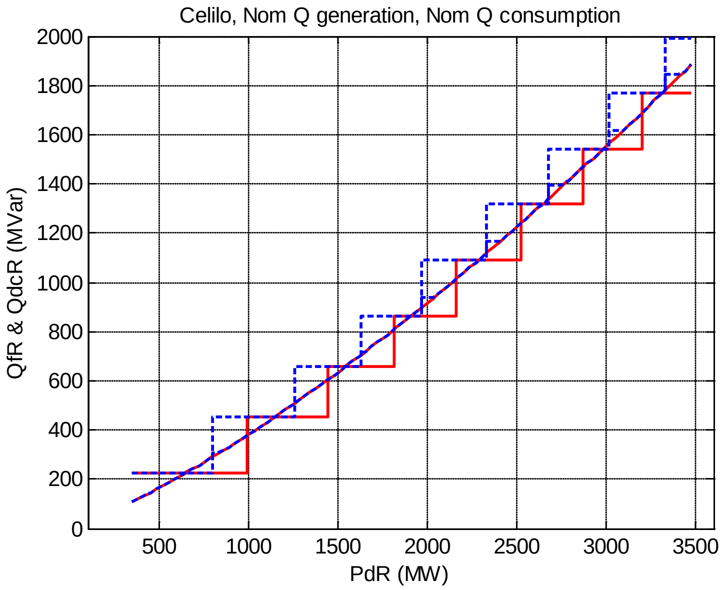


Figure 3 Celilo upgrade Reactive power control

The layout for the upgrade has been adapted as far as possible and practical to the existing layout and centering around the existing Converter 1 and 2 valve halls. The result will be placement of equipment and systems which will be familiar to those who are already acquainted to the Celilo station see overview in Figure 4.

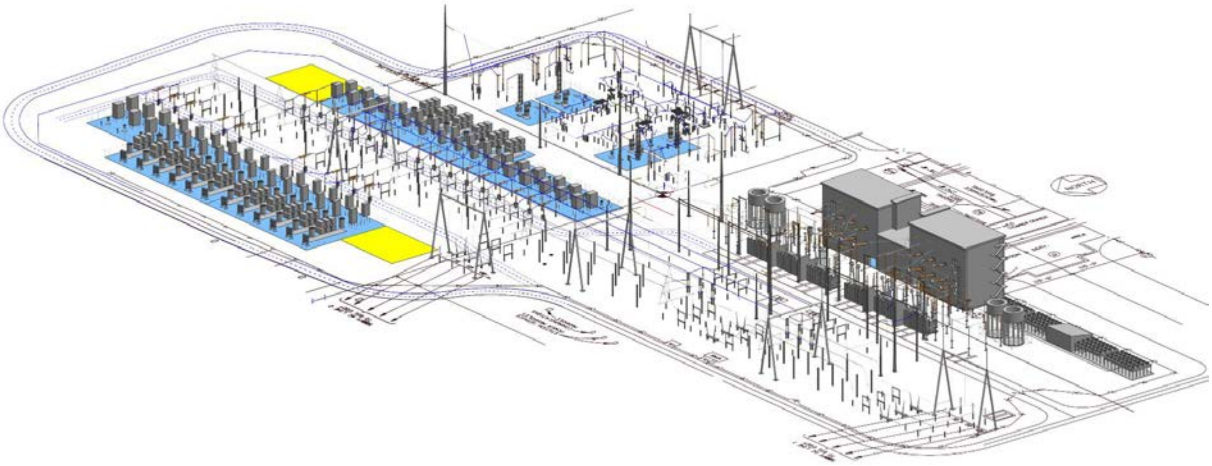

Figure 4 Celilo upgrade overview layout

For the control and protection system place will be arranged in the old degassing building. The system is fully computerized and built with state-of-the-art electronics, microprocessors and digital signal processors that are connected by high performance industry standard busses and fiber optic links. The system, which is called MACH and specially developed for HVDC and FACTS, includes redundant control and protection functions for all DC equipment. Within each converter unit, the main computers communicate with each other through a dedicated and duplicated LAN. The communication with the HMI is via a separate SCM LAN. The system is distributed, meaning that the main computers for the control and protection functions are placed in main computer cubicles while the I/O systems are placed in separate, distributed I/O cubicles.

Reliability, Availability and Maintainability (RAM) predictions per station, for the Celilo PDCI Upgrade, confirm that the specified target values will be met as defined in the table below for the maximum continuous power transfer capacity of 3820 MW.

- Forced Energy Unavailability (%) 0.70

- Energy Availability (%) 98
- Scheduled Energy Unavailability (%) 1.0
- Single pole forced outage rate per pole year 2.0
- Bipole forced outage rate (failure/year) 0.10

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