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# Feasibility of HVDC LCC Converter Station Upgrade to VSC

**B. MEHRABAN[1], B. ATTAWAY[1], R. ADAPA [2], P. WANG[3],
K. WALKER[3], N. DHALIWAL[4], R. KOLT[4]**
**[1]AEP, USA**
**[2] EPRI, USA**
**[3]Manitoba Hydro, Canada**
**[4]TransGrid Solutions Inc., Canada**

## SUMMARY

This paper investigates the feasibility of converting or upgrading an existing Line Commutated Converter (LCC) station to a Voltage Source Converter (VSC) station and what existing converter station equipment can be repurposed as part of the new VSC station.

Equipment that cannot be redeployed from an LCC into a VSC HVDC adaptation:

- Solid state conversion equipment—thyristor technology will not work with the VSC, which requires new IGBT technology.
- While existing LCC converter transformers may be used, due to the physical layout of present-day VSC valve halls and the placement of the phase reactors, the existing transformers would have to be relocated to accommodate a VSC configuration. Consideration must also be given to the age of the existing transformers and their suitability for a typical 40-year projected lifetime in a new HVDC system. LCC converter transformers with bushings connected through the valve hall cannot be used for a VSC conversion.
- For a similarly rated LCC system, the existing valve hall cannot be used due to the VSC physical layout requiring extra space for the phase reactors (whether inside or outside the building) and extra wall bushing connections.
- The control and protection system of an LCC is not suitable to be used for a VSC.

Existing LCC equipment that may be considered for reuse in a VSC conversion are:

| | |
|---|---|
| smoothing reactors | valve cooling |
| AC filters | auxiliary supplies |
| DC switchgear | DC measuring equipment |

bmehraban@aep.com

The redeployment of this equipment would depend on the VSC voltage rating. A new insulation coordination study would be required to determine the protection levels and whether certain existing equipment would be suitable, such as by-pass switches and some of the arresters.

The economic impact of the project was also considered for determining the best solution based on the following options:

1. Build a new green field station near the existing station, and then transfer over.
2. Build a new station near the existing station, but use some of the components of the original converter.
3. Demolish the existing station, and build a new station at the same location.

The shortest outage duration will be for option 1. The existing system will continue to transmit power while the new station is being built. Once the new station is ready, an outage of three-six months will be required to commission and integrate the new station into the system. This option will result in minimum amount of revenue loss.

For option 2, an additional several weeks are required to move the equipment from the old converter to the new site. This is in addition to the commissioning period as required in option 1. The actual duration of the outage will depend on exactly what equipment is being reused.

For option 3, the old system would have to be shut down completely from the time the removal of the existing equipment starts until the new system is in operation. Since the new building cannot be built until the old site has been cleared, the outage time will be longest of the three options. This duration is estimated to be at least five to six months to remove the existing facilities and some of 28-32 months to construct the new building and install the equipment.

**KEYWORDS**
Line Commutated Converter, Voltage Source Converter, Converter Transformer, Modular Multilevel Converter, Phase Reactor

bmehraban@aep.com

## 1. INTRODUCTION

The design of the first Line Commutated Converters (LCC) used mercury arc rectifiers in the HVDC conversion process. Thyristor valves replaced the mercury arc technology in the early 1970s. Innovations with higher current and voltage-rated thyristors, water-cooled and air-insulated valves utilizing both electrically-triggered and light-triggered thyristors contributed in the reduction of the components.

The Voltage Source Converter (VSC) technology was introduced in 1997 at the rating of 3 MW and 10 kV. Within 20 years VSC technology reached the rating of 1000 MW in the symmetrical monopole and 2000 MW in a bipolar system. Presently the Modular Multilevel Converter (MMC) in both half and full bridge configurations is the VSC technology of choice.

VSC technology provides many distinct advantages over the LCC. It is anticipated that the VSC will be the technology of choice for ratings up to 3000 MW in the near future. The LCC will certainly have its place for the very high ratings, in both voltage and power. Therefore one must consider the VSC option for the replacement of existing LCC facilities. Obviously the economics will play a major role in the decision making process, but the advantages of the VSC should be considered in the evaluation of the options [1].

The objective of this paper is to investigate the feasibility of converting or upgrading an existing LCC converter station to a VSC converter station, examine what existing converter station equipment can be repurposed in an LCC to VSC station rebuild.

## 2. MAIN CONVERTER EQUIPMENT

After describing the main components of an LCC station and of a VSC station, this paper will investigate what LCC components that may be reused in a VSC station as well as the economic impacts of the replacement in terms of outage duration, impact on transmission capability and outage cost.

For this discussion, assume that the LCC HVDC scheme is a bipolar system with each pole rated for 500 kV and 1000 MW. This is a typical bipolar LCC scheme that may be configured utilizing two series-connected 12-pulse converters per pole or a single 12-pulse converter per pole. The assessment can be extended to include a LCC back-to-back (BtB) system consisting of one 12-pulse converter rated at ~600 MW at 160 kV, which is a typical rating for many BtB stations.

### *A. Converter Valves*

The thyristor valves are the most important equipment in the modern day LCC used in HVDC transmission. The thyristor valve is a highly specialized piece of equipment and is second in cost only to the converter transformer.

Modern HVDC systems based on the LCC technology utilize water-cooled, air-insulated thyristor valves. The valves are constructed inside the valve hall. In most designs, the valves are suspended, however, the valves can be also floor mounted. The valves can be arranged either in double or quadruple valve structure. The choice is dependent on the rating, the valve hall clearances, as well as the transformer configuration.

All modern VSC valves use modular configuration where a number of submodules are connected in series to make the required voltage level. This design is based on the concept of modular, multilevel voltage-sourced converters. Each phase module is made up of "n" submodules (or cells) connected in series. In a half bridge configuration, each submodule is made up of two insulated gate bipolar transistors (IGBT)—or IGBT cells consisting of several IGBTs connected in series—two diodes and a capacitor connected, as shown in Figure 1.

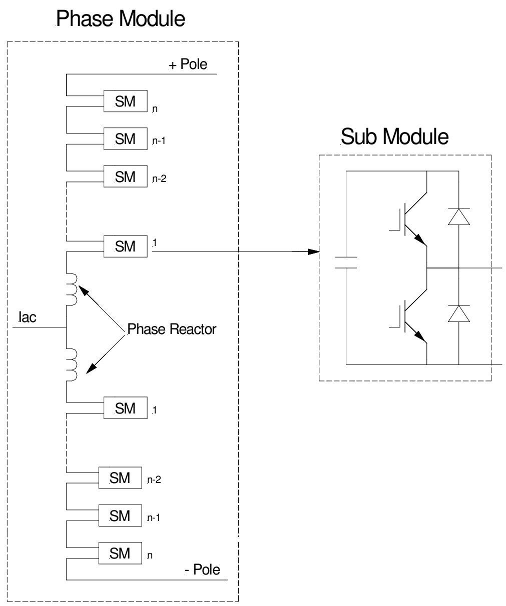


**Figure 1: Single Phase Module with Submodules**

The converters with half bridge configuration do not have the ability to extinguish dc line faults without a dc breaker or without disconnecting the converter from ac and dc sides. With the full bridge configuration dc line fault current can be extinguished by control action without the dc breaker and without disconnecting from ac or dc side. The actual valve is normally split into several sections depending on the rating and design of the valves. These sections are installed either floor mounted or suspended from the ceiling [2], [3], [4].

### *B. Converter Transformers*

The converter transformer is connected on the line side to the ac system and on the valve side to the converter valves. The rating and turns ratio and the tap range are selected and customized for each dc system. Considering the 12-pulse configuration of the LCC converter, two winding types are necessary for the valve side: a Wye winding and a Delta winding. The converter transformers for a VSC system are similar to the ones for an LCC system with the following exceptions:

- The VSC systems mostly use Wye/Delta transformers
- For symmetrical monopole configuration the transformer windings are not subjected to dc stresses.
- The harmonic current is relatively small but the harmonics are of a higher order.

A very common question in the industry is “can the converter transformers of an existing HVDC system, as defined above, be utilized if the LCC scheme is replaced with a VSC system with the same power rating?

In order to answer this question, one should compare how the VSC converter is realized. Usually transformers for a VSC are connected in a wye-delta configuration; however in some instances a wye-wye transformer configuration has been utilized. From an electrical point of view, the peak of the phase to ground valve winding voltage of the VSC must be at a lower value than the dc voltage.

Consider an LCC station with an original configuration of two series 12-pulse converters per pole, and assume that the converter transformers for such an LCC HVDC system are three-phase-two-winding configuration. Therefore, for each 12-pulse converter per pole there are two units. For a 500-kV pole, each 12-pulse converter would be rated for 250-kV dc and the six pulse unit is at 125-kV dc. In a typical situation, the peak phase voltage of the valve winding of these transformers will be lower than the 125-kV. In principle the valve winding voltage restriction is fulfilled. Note this will not be the optimal ac voltage for the VSC rated for 125-kV dc, but theoretically it will work.

However, on a per pole basis each one of the two winding transformers will have to be connected to a VSC converter rated at 125-kV dc which means four individual VSC valve halls are required. Obviously this is difficult to achieve considering that the pole for the LCC has only two valve halls. It is even more complicated because of the location of the phase reactors, which have to be placed either between the transformer and each converter arm or between each arm and the dc bus bars of each converter. The phase reactors can be placed inside or outside the valve hall; however, placing them outside the valve hall will increase the number of wall bushings. Space is also needed for the charging resistors and their bypass breakers either on the system side or the converter side of each transformer.

This configuration would also result in the need for additional dc switch gear and additional larger valve cooling units. So the limitation here is not the transformer electrical rating but the physical configuration. It should also be noted that there are operational restrictions for the series connected VSCs if half bridge technology is utilized. It is not possible to connect an energized transformer to a bypassed converter. This means if a bypassed converter is brought into service the whole pole needs to be blocked, and all series converters restarted together.

The problem is more pronounced in the single 12-pulse converter per pole configuration, which would also be the case for either a conventional LCC bipolar scheme or in a BtB arrangement. In most such schemes the transformers are single-phase-three-winding units with the wye and delta bushings protruding into the valve hall, where the wye and delta are configured. Connecting the valve winding bushings to two series-connected independent VSCs is not possible because the two VSC converters are in separate valve halls with their respective phase reactors. Similar to the previous scenario, extra space is needed for the phase reactors and the charging resistors. Therefore, LCC converter transformers with bushings connected through the valve hall could not be utilized for a VSC conversion.

### *C. Control and Protection*

For the purpose of high reliability, an LCC HVDC control and protection (C&P) system is designed based on a duplicate system of main and standby. The hierarchy of the system is typically, a station control level, pole level and the valve base electronics. The modes of operation and the control modes are system dependent.

All Voltage Source Converters operate on the same principle. The converter is connected to the ac system via a series inductance. The switching valve generates a fundamental frequency ac voltage from the dc voltage. The magnitude and phase (δ) of the fundamental frequency of this ac voltage on the valve side of the reactor can be controlled. The control of this voltage magnitude and phase is the essential controlling function of the VSC (refer to Figure 2).

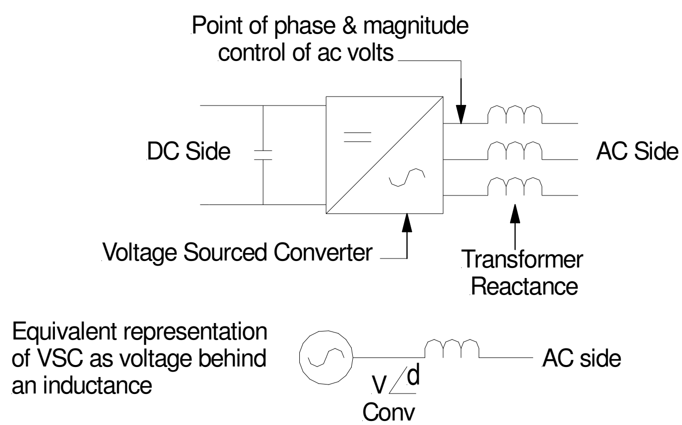


**Figure 2 : A VSC as a Voltage Source behind a Réactance**

However, the control strategy of the VSC is totally different from the LCC even if the LCC system presently operates using the latest digital-based control system. The function in a VSC module management system or valve base electronic (VBE/thyristor) is different from the LCC. The overall space requirements for the cubicles would be much the same as for an LCC converter. However, the control and protection system of an LCC is not suitable to be used in a VSC.

*D. Valve Hall*

In LCC schemes, the thyristor valves are usually arranged in stacks or tiers to form a structure of four valves physically configured one on top of each other. This arrangement is called a quadruple valve with three quadruple valves forming one 12-pulse bridge within the valve hall. Arrangements can be made as double valve in some circumstances. These types of structures require the valve hall to have significant height requirement for electrical clearances. Further, the width of the valve hall is influenced by the type of converter transformers used and their arrangement with respect to the valve hall. Actual dimensions are dependent on many factors, such as dc voltage, clearances derived from the insulation coordination, and transformer and valve structure arrangements.

However the layout of the VSC converter is different as the valve sections are mostly installed beside each other and not on top of each other like the LCC valve. The valve halls require more land area than an LCC valve of the same rating. For instance, a VSC valve hall rated at 320 kV and 500 MW for the Xiamen Project in China has valve hall dimensions of 46m x 35m x 12m (H) [5].

Due to the height requirements of the quadruple valve structure, most LCC valve halls are built as tall structures. The VSC valve physical design is lower but occupies a larger floor space, and its design is presently horizontally integrated. Therefore an LCC valve hall most likely will not be suitable to accommodate a VSC valve design of a similar rating. However it is possible to use an LCC valve hall for a VSC, if lower VSC ratings can be used.

## 3. SIMILAR EQUIPMENT for both LCC and VSC

### *A. Smoothing reactor*

In a long distance LCC HVDC scheme the smoothing reactor is normally connected in series with the dc converters and the dc line. In some systems, however, the smoothing reactor is split in two parts. One part is connected between the line and the converter high voltage side and the other on neutral side. In a back-to-back scheme, the smoothing reactor may be connected in the low voltage part of the circuit. In modern schemes, the dc smoothing reactor is air-insulated, naturally air-cooled, dry-type reactor [6].

As the change in real power transmitted is determined by the change in dc current, the effect of the smoothing reactor on the dynamic response of the system must be considered. In VSC systems the smoothing reactor also limits the rate of rise for the short circuit current for some faults. The size of the smoothing reactor used for VSC transmission is considerably smaller than one used in a LCC HVDC scheme, typically in the range of 20 to 50 mH [7]. Nevertheless, the LCC smoothing reactor can be used in the VSC system.

### *B. Valve Cooling*

The cooling system for a typical thyristor valve is based on the use of deionized water. The rating of the cooling pumps is dependent on the required water flow, as well as the sizing of the cooling pipes and the actual heat generated by the thyristor valves.

The losses for an LCC station (including ac and dc filters) are in the order of 0.6–0.75%. For a comparable rated VSC station (which typically doesn't have ac or dc filters) the losses are of the order of 0.85-–1%. The VSC valve losses are therefore significantly more than LCC valves. As a result, a valve cooling system of higher capacity (compared to LCC valve) is required.

Existing LCC cooling systems which have been upgraded with improved redundancy would have to be reviewed on a case-by-case basis.

### *C. AC Filters*

LCC converter technology requires the extensive use of harmonic filters to comply with utility emission standards, as well as for reactive compensation. Most VSC systems don't require ac filters, however some common filter arrangements can be redeployed for the VSC converter mainly for additional reactive power support. The ac filter requirement for VSC would be specified on a case by case basis.

### *D. DC Filters*

Since VSC converters do not require dc filters, the dc filter area from an LCC system could be used if more space is required in the dc yard for other related VSC equipment.

*E. DC Switchgear*

Some of the LCC dc switchgear can be redeployed for a VSC application. For instance, series connected LCC converters would allow all pole switchgear and by-pass equipment to be utilized.

If the existing transformers are used then the number of series converters per pole will be double that of the LCC system (one for wye and one for delta). This will require additional new dc switchgear to isolate each converter. For an existing LCC pole with two 12-pulse converters in series, two additional sets of dc switchgear will be required. The two sets of existing dc switchgear can be reused. Alternatively, the VSC converters can be considered as two groups each consisting of two converters that are put in and out of service together. In this case, the existing dc switchgear is sufficient for the new VSC converters.

For an LCC system with single 12-pulse converter per pole, two sets of dc switchgear per pole will still be required, as there will be no existing dc isolation switchgear. The alternative is to always operate the two VSC converters together without the possibility of bypassing a blocked VSC and operating with a single VSC on that pole. For existing BtB systems, there is no dc switchgear. A VSC conversion of a comparable rating may require two VSC valve halls and thus need additional dc switchgear to be purchased for operation with single VSC.

In terms of the lightning and switching impulse levels, the existing dc switchgear insulation levels would remain the same. Depending on the VSC voltage rating, some of the existing bypass switches may be utilized, and some of the arresters could also be redeployed. A new insulation coordination study would be required to determine the protection levels and whether and what existing equipment is suitable.

*F. DC Measuring Equipment*

The dc measuring equipment for an LCC converter would be basically the same for a comparable VSC converter. However, the lifetime of the existing equipment needs to be factored in, as well as the availability of spare parts and matching the response time and interfacing issues.

*G. Auxiliary Supplies*

The auxiliary supply requirements for a VSC converter would be almost the same as an LCC converter, so the existing chargers, batteries and station service could be used. The lifetime of the existing battery systems should be considered for their reuse in a VSC system since the typical lifespan of lead acid batteries is 15 to 20 years.

## 4. VSC ADDITIONAL EQUIPMENT

*A. Phase Reactors*

In the VSC converter, the three phase modules are connected in parallel on the dc side. Since the generated dc voltages cannot be exactly equal, balancing currents flow between the modules of different phases. These currents are limited by use of phase reactors.
In addition, the phase reactors limit balancing currents between upper and lower halves of the each phase module. The phase reactors also limit the rate of rise of fault currents. Phase reactors can be placed at the dc side or ac side of each arm.

*B. Charging Resistors*

When the VSC converter is first connected to the ac system, the capacitors in the submodules must be charged. Depending on the start-up concept of the scheme, the circuit breaker may be equipped with a closing resistor or a separate resistor and bypass switch is installed in series with the transformer either on the system or the converter side. The resistor reduces the charging current of the converter. This reduces the stresses on the free-wheeling diodes and limits the disturbance to the ac system.

When the converter is first connected to the ac system through the charging resistor, the capacitors in the converter valve charge via free-wheeling diodes. After a predetermined delay the main breaker contacts close and bypass the charging resistor. The charging time is dependent on system short-circuit power, closing resistor, transformer impedance, transformer secondary voltage and the dc circuit capacitance.

Once the dc voltage is high enough to charge the gate power units, the converter operation can be started under no-load conditions (i.e., no fundamental frequency current flowing into the ac system), the dc voltage can now be controlled at the operating level.

## 5. ECONOMIC EVALUATION

To determine the feasibility of using any existing LCC converter equipment (including a back-to-back scheme) for a VSC replacement, the economic impact must be considered. The following options are to be considered for determining the economic impact.

1. Build a new, green field station near the existing station, and then transfer over.
2. Build a new station near the existing station, but use some of the components of the original converter.
3. Demolish the existing station and build the new station on the same location.

The economic impact of replacing the LCC converter with a VSC converter will depend on which option is chosen for replacement. The shortest outage duration will be for option 1. The existing system will continue to transmit power while the new station is being built. Once the new station is ready, an outage of three-six months is required to commission and integrate the new station into the system. This option will result in minimum amount of revenue loss.

For option 2, an additional several weeks will be required to move the equipment from the old converter to the new converter. This time will be in addition to the commissioning period as required in option 1. For example, if the auxiliary equipment (battery banks, 600V supplies, etc.) are to be reused, the existing system would have to be shut down much earlier than if only smoothing reactor (etc.) is to be reused. The cost of buying new equipment versus loss of revenue resulting from additional outage should be taken into account in deciding if some components of the old system should be used.

For option 3, the old system would have to be shut down completely from the time the removal of the existing equipment starts until the new system is in operation. Since the new building cannot be built until the site has been cleared, the outage time will be the longest of the three options. This duration is estimated to be at least five to six months for removal of the existing facilities and additional time in the range of 28-32 months to construct the new building and install the equipment.

## 6. CONCLUSIONS

Equipment that cannot be redeployed from an LCC into a VSC HVDC renovation:

- Solid state conversion equipment—thyristor technology will not work with the VSC, which requires new IGBT technology.
- While existing LCC converter transformers maybe used, due to the physical layout of present-day VSC valve halls and the placement of the phase reactors the existing transformers would have to be relocated to accommodate a VSC configuration. Consideration must also be given to the age of the existing transformers and their suitability for a typical 40-year projected lifetime in a new HVDC system. LCC converter transformers with bushings connected through the valve hall cannot be used for a VSC conversion.
- For a similarly rated LCC system, the existing valve hall cannot be used due to the VSC physical layout requiring extra space for the phase reactors (whether inside or outside the building) and extra wall bushing connections.
- The control and protection system of an LCC is not suitable to be used for a VSC.

The above equipment comprises over 55% of the total cost of an HVDC system.

Existing LCC equipment that may be considered for reuse in a VSC conversion are:

| | |
|---|---|
| smoothing reactors | valve cooling |
| AC filters | auxiliary supplies |
| DC switchgear | DC measuring equipment |

The redeployment of this equipment would depend on the VSC voltage rating. A new insulation coordination study would be required to determine the protection levels and whether certain existing equipment would be suitable, such as by-pass switches and some of the arresters.

When considering the economic impact aspects, option 1 would be the best choice as long as there is suitable land available for a new station adjacent to the existing converter stations or reasonably nearby for connection to the dc transmission line.

If option 1 is not feasible due to land constraints, then option 3 would be the better choice over option 2 for the following reasons:

- Even though option 3 may have a longer duration to fully complete, the arranging of outage times and the greater risk of forced outages and problems with the removal of old and installation of new equipment may be a challenge.
- If the old equipment is mixed with the new converter station equipment, any warranty and availability/reliability requirements of the new equipment supplier will be

compromised since they will have issues with determination of the lifetime and accessibility of replacement parts for the older equipment.

There could be other factors which may influence the replacement options 2 and 3 such as the availability of generation. For example, coal generation maybe retired and staging of the replacement generation may coincide with the removal of LCC equipment and implementation of the VSC converter equipment.

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