HVDC TECHNOLOGY AND POWER QUALITY ISSUES IN SLOVENIAN TRANSMISSION SYSTEM – TECHNICAL STUDY

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ABSTRACT

Due to high electric energy demand in the Western Europe, the high voltage direct current (HVDC) connection between Slovenia and Italy is being discussed in Slovenia. The results of a recent study ordered by the Slovenian TSO are presented in the paper. The study focuses on the potential impact of the HVDC system on the power quality at the transmission system (TS) level – in particular it's impact on reactive power control and voltage profile regulation and the level of harmonic distortion. Main currently available technologies have been taken into account.

INTRODUCTION

As it is generally known, LCC technology of the DC transmission cannot contribute to the regulation of reactive power in the network; quite the contrary, in the operation of this technology, significant consumption of reactive power can happen. On the other hand, with VSC-MMC technology regulation of reactive power and voltage profile is possible (4 quadrant operation), but is limited with the operation diagram of the system. The extend of the regulation depends on the design and dimensions of converter stations. Voltage control is dependent on the impedance at the PCC - the short-circuit power at the point of connection and the R / X ratio. These aspects and their meaning for the Slovenian TS will be presented in the paper [1].

All power converters cause a certain level of voltage and current harmonic distortion and HVDC systems are no exception. With the latest technologies used in the converter stations, the so-called modular multi-level converters or MMC, level of harmonic distortion may be negligible, however with slightly older VSC technology (2- or multi-level configuration) and in particular with LCC technologies harmonic levels can be significant, and it is therefore necessary to install appropriate filters. Detailed device models and generic network models have been developed for the simulation purposes within the study, which will be presented in the paper.

In the paper, the impact of various HVDC technologies on the control of reactive power, voltage profile and harmonics level will be analysed.

HVDC AND REACTIVE POWER AND VOLTAGE CONTROL

The impact of various technologies of HVDC on the control of reactive power and voltage conditions was analysed by means of EMT simulations on accurate device models and generic network model. The simulation results are presented in detail below, but first the subchapter gives a brief general description of the need for reactive power for LCC and VSC technology.

Reactive Power Control with LCC and VSC Technology

A major drawback of the HVDC systems in the LCC technology is that converters are consuming a large amount of reactive power. The current on the AC side is always lagging the AC voltage, so regardless of the direction of the active component of the current, reactive power consumption remains, therefore, the LCC converter behaves in the same way as a parallel choke. Under ideal conditions, the absorbed reactive power is of at least 0.5 MVAr/MW, but it can of course be much higher if the inverter operates at higher (unusual) triggering angles or at a reduced DC voltage [1].

If the HVDC station is located near the power plant, a certain proportion of reactive power can be provided with the generator, however in most cases the reactive power that the inverter withdraws, cannot be provided in this way and therefore appropriate compensators of reactive power are require, connected to the AC terminals. Most of these are connected directly to a high voltage.

Since the consumption of reactive power depends on the transfer of the active power, compensators are usually designed in several stages (typically 4 on a converter) to ensure a certain level of flexibility of compensation and to prevent excess reactive power. Reactive power compensators are usually designed at least with inrush inductors, however in most cases as filters, which allows

the device to operate to some extend also as a harmonic filter.

Unlike the LCC technology, voltage converters or VSC technology does not lead to the consumption of reactive power during operation. Moreover, the VSC converter in any version (2- or 3-level, multi-level...) can be controlled in a manner to consume or generate reactive power according to pre-defined reference points. Therefore, VSC technology does not need any additional compensators of reactive power, except in cases where it is necessary to filter the harmonics of the output current. For this purpose, the tuned compensators of smaller dimensions are sufficient [1].

Simulation Results for Control of Reactive Power and Voltage Regulation with LCC Technology

In order to evaluate the impact of LCC technology on voltage profile and consumption of reactive power, we have simulated the following three examples:

- LCC is operated without the filters and at active power controlled to 0 MW;
- LCC is operated without filters at full nominal power (1 p.u.);
- LCC operates with filters at full nominal power.

The results for the above cases are in the same order shown in figures 1-3. In all the figures, the following quantities are shown (from left to right):

- Per-unit value of the voltage of the AC rectifier stations;
- Per-unit value of the voltage of the AC inverter station;
- Active component of power in MW at rectifier station;
- Reactive component of power in MVAr on the rectifier side of the device;
- Active component of power in MW on the inverter side of the device;
- Reactive component of power in MVAr on the inverter side of the device;

From the figure 1 we can see that operation of LCC HVDC systems with reference set to 0 MW consumes high levels of reactive power, i.e. about 350 MVAr on the rectifier and 370 MVAr at the inverter side. The voltage drop on both sides of the device is correspondingly high, as in the rectifier side (which is connected to the load of P = 500 MW and Q = 500 MVAr) drops to 0.91 p.u.

Figure 2 shows that the voltage profile during operation at rated power is even worse. At the rectifier side of the HVDC system voltage drops to less than 0.9 p.u. Notice, that due to the lower voltage, HVDC does not reach nominal 1000 MW, but only about 830 MW.

Figure 3 shows that if the appropriate reactive power compensators are connected, the voltage conditions are recovered and at the same time, the transfer of the active power is close to the nominal 1000 MW.

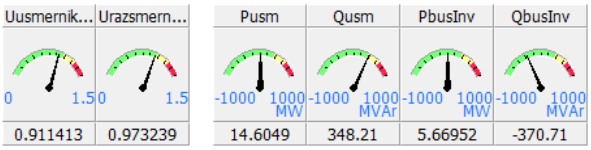

Figure 1: LCC without filters, active power 0 MW.

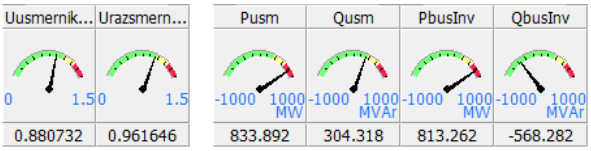

Figure 2: LCC without filters, at nominal power.

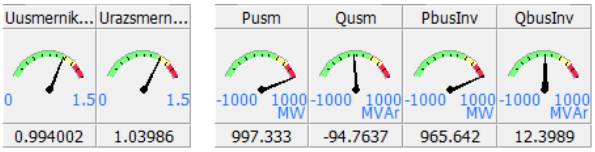

Figure 3: LCC with filters at nominal power.

Simulation Results for Control of Reactive Power and Voltage Regulation with VSC Technology

The simulation results are shown for stationary conditions and during the transients. It should be noted that the operation of the converter was idealized in terms of operational characteristics. Namely, in simulations VSC converter allows 4-quadrant operation without major restrictions, which in practice does not apply. The results are shown in figures 4-7. In all the figures, the following quantities are shown (from left to right):

- Active component of power in MW at rectifier station;
- Reactive component of power in MVAr on the rectifier side of the device;
- Active component of power in MW on the inverter side of the device;
- Reactive component of power in MVAr on the inverter side of the device;
- Per-unit value of the voltage of the AC rectifier stations;
- Per-unit value of the voltage of the AC inverter station;

Operation during Stationary Conditions

Figure 4 shows the operation of the HVDC in idle mode. The voltage on both sides of the converter is set to approximately 1.05 p.u. From the figures it can be seen that VSC converter does not withdraw reactive power during operation. On both sides of the HVDC system, the reactive power flow is app. 0 Mvar.

From figure 5 it is clear that during the operation of the HVDC at 1 p.u. power, voltage is slightly reduced at the rectifier side and increased by approximately 3 % at the inverter side, while the consumption of the reactive power is still very small.

With figures 6 and 7 we tried to show, to what extent we can influence the AC voltage of the converter at a specific SCR ratio. In the first figure, converter station on the rectifier side consumes 1000 MVAr of reactive power and at the inverter side, the reference reactive power is still set to 0 MVAr. It may be noted that in this case the AC voltage at the rectifier station is for a few percent (about 4%) lower than in figure 4, while the transfer of the active component of the power remains at the nominal value.
Similarly, we can also conclude from figure 7, which shows the operating point where 1,000 MVAr of reactive power is injected at the rectifier side. In this case, the voltage increases by a few percent (about 5 %) and the transfer of active power remains the same.

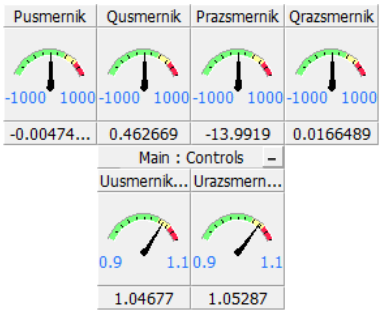

Figure 4: VSC in idle mode.

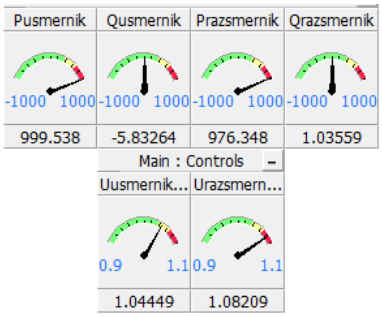

Figure 5: VSC at the rated power.

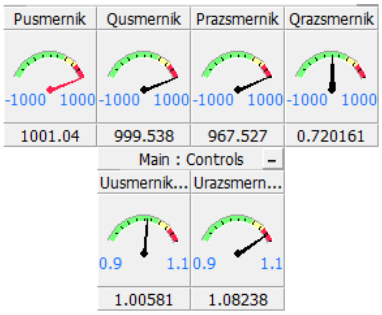

Figure 6: VSC at the rated active power transfer and consumption of 1000 Mvar at the rectifier side.

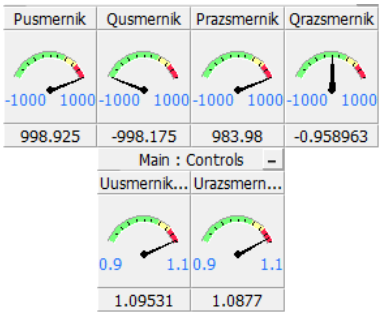

Figure 7: VSC at the rated active power transfer and injection of 1000 Mvar at the rectifier side.

Operation during Transient Conditions

Figure 8 shows recordings of several quantities during transients. From top to bottom, the following quantities are shown:

- per-unit AC voltage at the rectifier station and per-unit AC voltage at the inverter station;
- employment component of power in MW at the rectifier side of the device and the working components of the MW power inverter on the device;
- reactive component of power in MVAr on the rectifier side of the device and reactive component of power in MVAr on the inverter side of the device.

From the figure, the transition of quantities during step change of active power reference can be seen. Active power component reaches a new stable condition after a certain time (about 1000 MW), while there are no significant unwanted transients on the reactive component of the power and voltage.

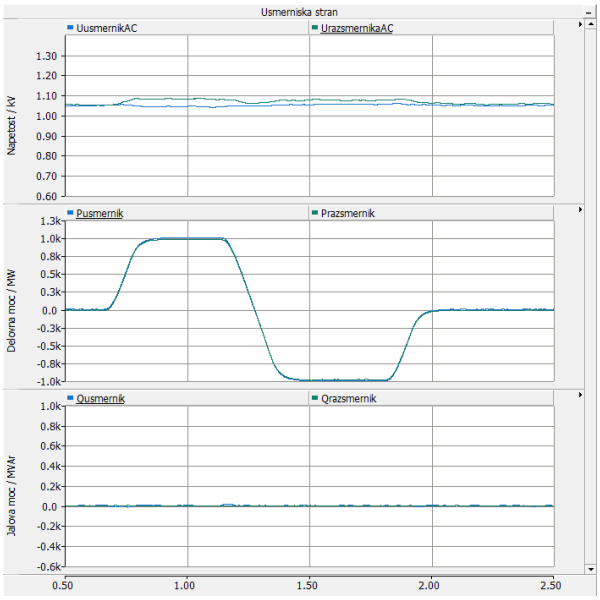

Figure 8: Step change of the active power reference in the following sequence: 0 p.u. - 1 p.u. - -1 p.u. - 0 p.u.

HVDC AND POWER QUALITY

All power converters cause a certain level of harmonic distortion of voltage and current in the network and HVDC systems are no exception.
This chapter first determines the spectrum of harmonics in the LCC current and the VSC-MMC technology current, and then it demonstrates the results of impedance frequency analysis.

Filters for LCC Converters

The basic building block of the LCC technology is a 6-pulse bridge. This configuration produces a very high level of harmonic distortion that acts as a stiff current source harmonics, with the injection of harmonic currents 6n ± 1, in the AC network.
Dimensioning of filters for these currents is quite expensive, so in most cases a 12-pulse bridge consisting of two 6-pulse bridges in series, with a phase shift of 30 °, are used. In such a topology the harmonics are still generated, only that with this configuration only harmonics of order 12n ± 1 will appear and they will have lower amplitudes (see figure 9).
Most filters are implemented as single- or double-tuned filters for 11th and 13th component in combination with a high-pass filters, which restrict the flow of harmonic of higher orders, i.e. 23, 25, 35, 37 ... Sometimes filters are installed also for lower harmonics, for example, . 3rd, 5th and 7th, if we are dealing with a 6-pulse topology.
The task of dimensioning of the corresponding high-voltage harmonic filters is complex, because in addition to providing an adequate low levels of harmonic distortion, it is also necessary to ensure that the filters will not cause unwanted resonance amplifications of harmonic components. Detailed knowledge and analysis of the impedance-frequency characteristics of the network is therefore essential [2, 3].

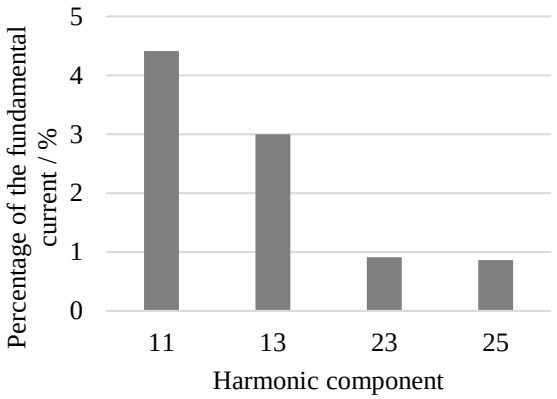

Figure 9: Spectrum of the characteristic current harmonics, secondary windign of the transformer.

Filters for VSC Converters

Even with VSC technology in a 2-level or 3-level configuration (with PWM), filtering of the output quantities is still required, but to a lesser extent than in the LCC technology.
However, with VSC converter the injected harmonic currents into the grid are usually at higher frequencies, so the filter elements can be smaller. Harmonics are in fact the result of the high-frequency switching of switches (PWM), which is for HVDC application typically running in the range of 1-2 kHz [2, 3].

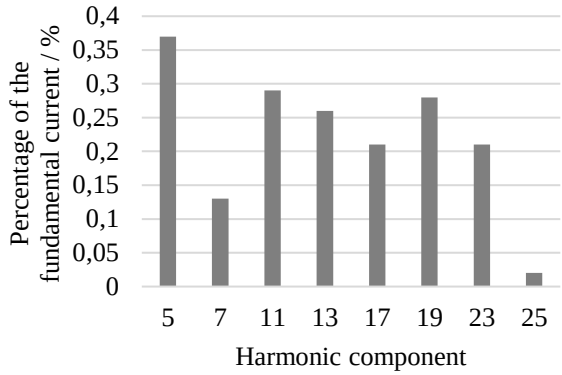

Figure 10: Spectrum of the characteristic current harmonics with VSC-MMC technology, secondary windign of the transformer.

Analysis of the Impedance-Frequency Characteristics

Impedance characteristics were calculated on a Slovenian network model. Looking at the impedance from the load side, values with high impedance are critical, since even a small harmonic load current may cause high harmonic voltage.
Figure 11 shows the impedance characteristic of the network for the status quo – without HVDC system. Two characteristics are shown - above one is for the 400 kV Divaca busbar, the lower one is for the 400 kV Bericevo busbar. From the characteristics, it can be seen that there is a more pronounced parallel resonant points in the area of critical harmonics. These areas are in the figure marked with the red colour. It must therefore be ensured that at frequencies within these areas no current harmonics will be generated and injected into the present busbar. In this way, no amplification of voltage harmonic will happen. When installing the HVDC system, it is necessary to analyse the impedance frequency characteristics, especially in the implementation of the LCC, where the filters significantly affect the impedance conditions.
Figure 12 shows the impedance characteristic of the network with HVDC system in operation, seen from the Bericevo and Divaci busbars, respectively. The characteristics show that compared to the existing situation they have significantly changed – especially characteristic in Divaca, which is the result of the filters on the buses. Critical resonance point from the area around the 5th harmonic moved slightly lower and critical resonance points from the area around 23rd and 25th harmonics moved slightly higher. The situation is therefore somewhat less problematic than the characteristics of the current

situation, although caution is still needed at the third harmonic frequency.

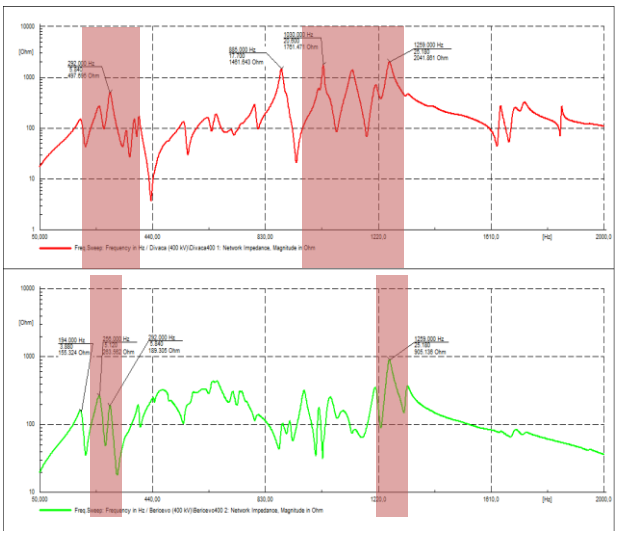

Figure 11: Impedance frequency characteristics in Divaca (above) and Bericevo (bellow), 400 kV busbar; current situation without HVDC system.

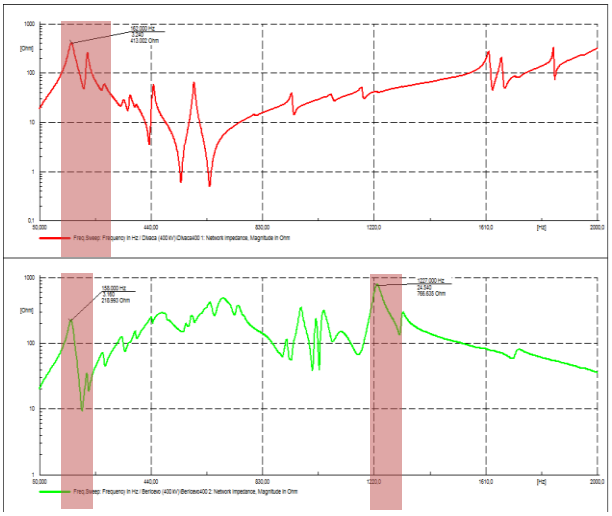

Figure 12: Figure 13: Impedance frequency characteristics in Divaca (above) and Bericevo (bellow), 400 kV busbar; possible future situation with HVDC system.

CONCLUSIONS

HVDC and Reactive Power and Voltage Control

Conclusions of the subchapter can be summed up in to the following points:

- LCC application in erecting of a HVDC transmission cannot contribute to the control of reactive power in the network; more likely may be encountered the opposite, with operation of this units high reactive power flows is produced. With well selected (suited to needs) compensators that reactive power can be compensated on the AC side of a converter station.
- Control of reactive power and voltage with VSC-MMC application is possible (4-quadrant operation) but limited with the operation characteristics of each system. The extent of the control range depends on the type and ratings of converter stations. In practice a 1000 MW unit may approach 400 MVAr capacitive or 750 MVAr inductive power.
- The extent of voltage regulation range depends on impedance conditions – short-circuit power at the network connection point and the R/X ratio.

HVDC and Power Quality

Conclusions of the subchapter can be summed up in to the following statements:

- The HVDC LCC system does not contribute significantly to the harmonic distortion, when suitably designed harmonic filters are installed.
- The HVDC VSC-MMC system does not contribute significantly to the harmonic voltage distortion and network currents (eventually without installed harmonic filters).
- Analysis of impedance - frequency characteristics has shown that the conditions of the current state (without HVDC) are relatively complex on both locations, which is why it is important to perform a thorough analysis of frequency characteristics before the erection, when the final configuration of the HVDC system will be established and known.
- The strongest influence on impedance - frequency characteristics is produced by harmonic filters of the LCC system.

REFERENCES

For a Conference citation:

[1] "Technical Feasibility Study of the HVDC Link Bericevo–Divaca–Salgareda (PCI Project HVDC 1000 MW Slovenia–Italy) ", ELES, 2016.

[2] "The Grid Code, Issue 5 Rev.1". National Grid Electricity Transmission., 2012.

[3] "System requirements concerning the connection of High Voltage Direct Current links to the Fingrid Oyj's AC grid". Guideline Power System Planning.