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TECHNICAL AND ECONOMIC COMPARISON OF HVDC CONVERTER TECHNOLOGIES

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Abstract- This study aims to find out what the most technically and economically feasible converter type for HVDC applications. For this purpose, the HVDC converter types applied in the Turkey and all over the world are examined in the framework of economic and technical. In this scope, two main converter technologies used in HVDC transmission such as The Line Commutated Converter (LCC) and The Voltage Source Converter in Modular Multilevel Converter topology (MMC-VSC) are presented in structural and functional aspects. Then, the advantages and disadvantages of both converters are compared in terms of economic and technical outlooks. For this comparison, in order to exhibit technical performances, two different HVDC back-to-back stations are modeled for both topologies in MATLAB/Simulink environment and the behaviors of both converter topologies are analyzed with respect to power transmissions, AC side short circuit faults, voltage deviations and harmonics. In addition, investment and operating costs for both types of converters are introduced. At the end of study, the results obtained from the simulations are presented and discussed in detail.

Keywords: High Voltage Direct Current, Line Commutated Converters, Voltage Source Converters, Modular Multilevel Converters, Asynchronous Parallel Connection.

I. INTRODUCTION

In each country's own electricity grid legislation, it is regulated that a network operation will be performed in accordance with the quality standards of electrical parameters. For example, the obligation to trade electricity with European countries is to comply with the requirements set by "European Network of Transmission System Operators for Electricity (ENTSO-E)". Likewise, each country has similar conditions for the quality of the electricity grid. Thus, the network parameters and quality of countries vary according to each other. In the electricity trade between countries, it is desirable that on the one hand, electrical disturbances do not affect another side. HVDC systems provide asynchronous parallel connection for international electric trade.

In addition, the back-to-back HVDC systems that allow asynchronous interconnection between adjacent networks that have different frequency level and prevent breakdowns between the networks due to fault isolation to the neighboring network. Also it is possible to eliminate electromechanical oscillations and increase grid stability by controlling power flow quickly and precisely using back-to-back HVDC systems [1].

On the other hand, HVDC transmission has typically 30-50% less transmission losses than alternating current (AC) overhead lines, moreover cable connections longer than 80 km are only possible in HVDC transmission [2]. At the end of 2017, 51 HVDC back-to-back stations are installed in the world [3].

II. HVDC CONVERTER TOPOLOGIES

The converters used in the HVDC system are divided into two groups as line commutated and self-commutated. Self-commutated converters are also divided into two groups as current source and voltage source. In recent years, modular multi-level converters, which are a type of voltage source converters, are become the forefront of new technology. One of the most important selection criteria for the converter type in HVDC is AC system's strength. AC system's strength is determined by its Effective Short Circuit Ratio (*ESCR*).

For strong AC networks, *ESCR* is greater than 3. For weak AC networks, ESCR is between 2 and 3. *ESCR* is less than 2 in very weak AC networks. The effective short circuit ratio is as the following:

$$ESCR = \frac{S_{SC} - Q_{filter}}{P_{HVDC}} \tag{1}$$

$$Q_{filter} \approx 0.5 P_{HVDC} \tag{2}$$

where, S_{SC} is the three-phase short circuit apparent power (MVA) of the AC system Q_{filter} is reactive power (MVAr) of all shunt filter capacitors connected at the converter station AC bus. These harmonic filters are especially used in LCC systems. P_{HVDC} is the rated DC power. Generally, the LCC need an effective short circuit ratio of at least 2 to operate [4]. That means for using LCC, it must be:

$$S_{SC} \geq 2.5 P_{HVDC} \qquad (3)$$

However, MMC-VSC converters can operate on both weak networks and strong networks.

A. Line Commutated Converter (LCC)

LCC HVDC was introduced in 1950 in the USSR and 1954 (Gotland) in Sweden. Mercury arc valves were used in both systems. The first application of thyristor valves was applied to the Eel River scheme in Canada in 1972. Because of the superior reliability of thyristor technology, the use of thyristors has led to a rapid increase in the installed capacity of HVDC systems. In recent years, more reliability improvements and compact designs with large-capacitance thyristors have contributed to significant advances in HVDC applications. LCC can be operated as rectifiers and inverters.

The thyristor- controlled converters allow for tuning the average output voltage and power flow. The voltage polarity is changed during the change in power flow direction. A thyristor is turn on by a gate signal and turn off during commutation to another one. Thyristors are not being able to turn off manually, like an IGBT. LCC converters generate harmonic currents at the AC side and also harmonic voltage at the DC side. That's why LCC systems need harmonic filters to eliminate harmonics. The loss of a LCC type HVDC converter station is about 0.8% [5].

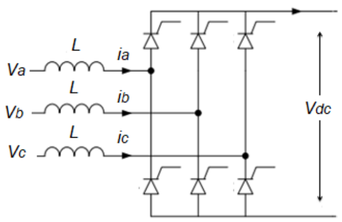

Figure 1. LCC principle scheme

B. Modular Multilevel Converter (MMC)

Voltage Source converter (VSC) systems using IGBT were first introduced in late 1990's. The VSC HVDC transmissions based on two- and three-level VSC HVDC systems were introduced.

VSC can perform independent control of active and reactive power flow. The power reversal depends on only the direction of current in MMC HVDC system. Developed at the end of 2010, MMC technology has provided to reduce converter losses and harmonics. Currently, loss of MMC based HVDC converter station is 1% which is so close to LCC based HVDC station [5].

Current studies on MMC topology in literature include AC and DC failures effect and fault-ride-through analyze on MMC system. In addition to control system structures in MMC, HVDC links are covered as Figure 2 [6-8]. The comparison results of LCC and MMC converters are shown in Table 1.

III. TECHNICAL PERFORMANCES LCC & MMC BASED HVDC BACK TO BACK STATIONS

Two different HVDC back-to-back stations, LCC and MMC have been modeled for both topologies in MATLAB/Simulink environment.

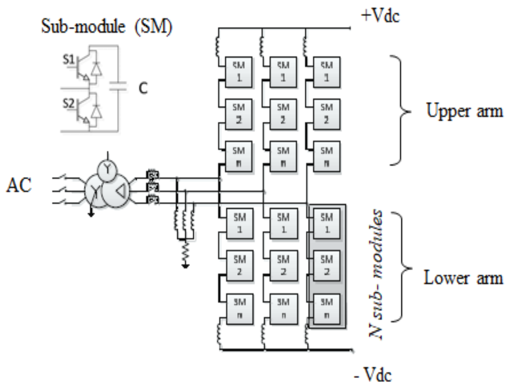

Figure 2. MMC principle scheme [9]

Table 1. Comparison LCC and MMC converters [10,11]

LCC Converter	MMC Converter
Thyristor switching based	IGBT switching based
Requires stronger AC systems	Efficient in weak /strong networks
Black start operation with addition equipment	Black start capability
Requires harmonic filters	Requires no harmonic filter
No independent power control	Independent power control
Needs large station area	Compact station area (nearly ¼ of LCC station)
Lower station losses (~0.8 %)	Higher station losses (~1%)
Reactive power demand is equal to nearly 50% of active power	No reactive power demand.
Max converter rating (by the end of 2017): 10.000 MW, ±1100 kV (Xinjiang-Anhui, China)	Max converter rating by the end of 2017: 4x1250 MW, ±420 kV (China-Chong, China)
The system is sensitive to voltage drops or transient AC failures because of commutation failures.	The system is reliable against any voltage drop or transient AC failure
Not useful for multi terminal HVDC system	Useful for multi terminal HVDC system
Operating cost is 13% less investment cost 0.5 % less	Investment and operating costs are slightly higher

The behaviors of both converter topologies have been analyzed with respect to power transmissions; AC side temporary phase to ground faults, voltage deviations and harmonics. The system parameters that are modeled in MATLAB/Simulink are indicated on the Table 2. LCC and MMC system models are shown in Figures 3 and 4.

Table 2. Parameters of MMC and LCC back to back systems

AC Systems	1	2	AC Systems	1	2
Voltage (kV)	400	400	Voltage (kV)	400	400
Frequency	50	50	Frequency	50	50
Scr (Psc/Pdc)	4	4	Scr (Psc/Pdc)	4	4
Primary voltage (kV)	400 (Yg)		Primary voltage (kV)	400 (Yg)	
Secondary voltage (kV)	300 (Y)		Secondary voltage (kV)	120 (Y)	
Power rating (MVA)	650		Secondary voltage (kV)	120 (D1)	
MMC			Power rating (MVA)	650	
			Harmonic Filter and Compensation		
Number of SMs per arm	36		Filters (MVAR)	270	
Number of IGBTs per SM	2		Capacitors (MVAR)	90	
IGBT resistance (mΩ)	1		LCC		
SM capacitor (mF)	1,8		Converter blocks	12 pulse	
Arm inductance (H)	0,0716		I rated(A)	2000	
Arm resistance(Ω)	0,225		γ (extinction angle) Inverter	18°	
Switching Frequency (Hz)	167,5		α (firing angle) Rectifier	18°	
DC Link			DC Link		
Capacitance (µF)	70		Smoothing Reactor (mH)	60	
Rated voltage (kV)	± 300		Rated voltage (kV)	300	

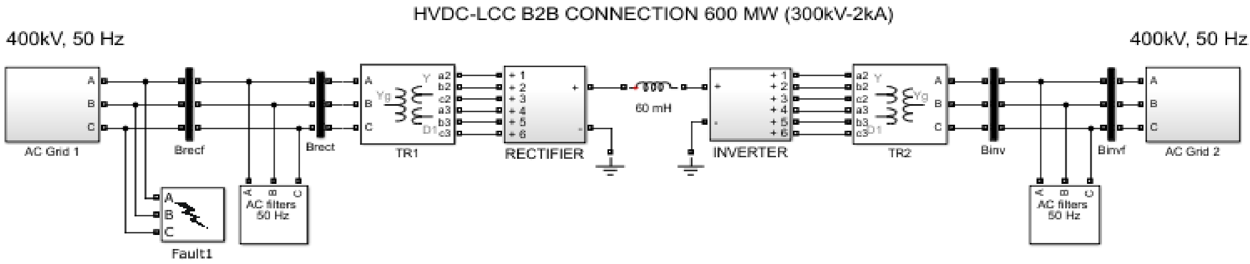

Figure 3. Simulink model of LCC based HVDC tie

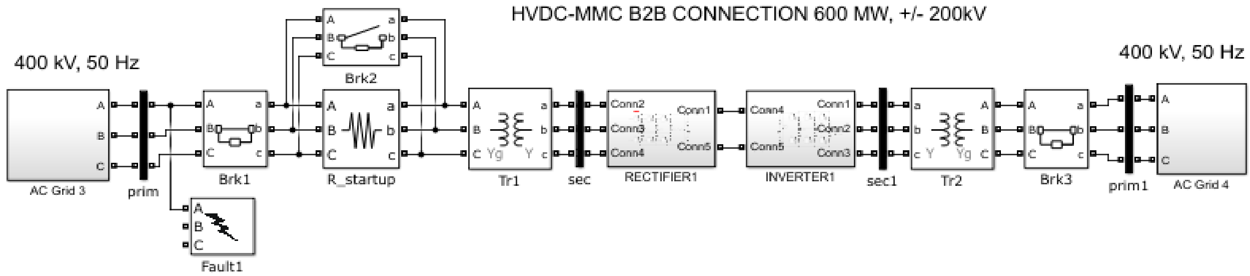

Figure 4. Simulink model of the MMC based HVDC tie

A. Fault Analysis

The fault is applied on the rectifier side on both converters in this simulation, and also the temporary fault simulated between phase-A and ground during 50 ms (t=2.5-2.55 sec).

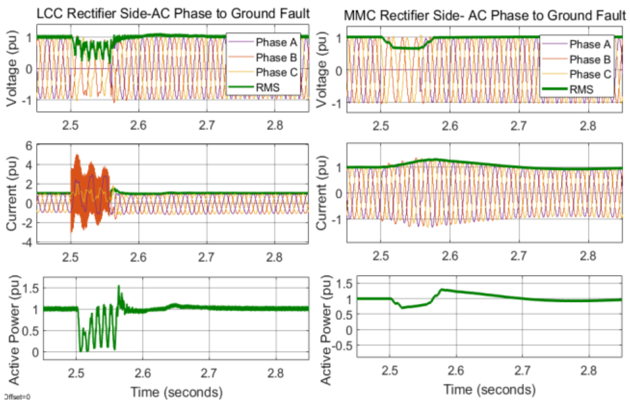

Figure 5. System response of LCC and MMC converters rectifier sides during A-G fault

During simulation of both the LCC and MMC model, Figure 5 shows the graphic subplots for the voltage, current and active power waveforms for LCC and MMC HVDC converters. During the fault period, it was observed that the voltage drop across the rectifier side of both systems is somewhat greater in the LCC system. However, the effect of the AC fault current on the MMC system is quite limited compared to the LCC system, which is reflected in the active power oscillations.

On the rectifier sides of both systems where the fault occurs; the pick-to-pick variation of active power oscillations is found to be 0.5 pu in the MMC system while it was found to be 2.5 pu in the LCC system. After the short circuit fault; as a result of the voltage drop, commutation failures which may cause the current not to completely commutate from one thyristor valve to another, so lead to a short-circuit, cause relatively large electrical disturbances that occur in the LCC system.

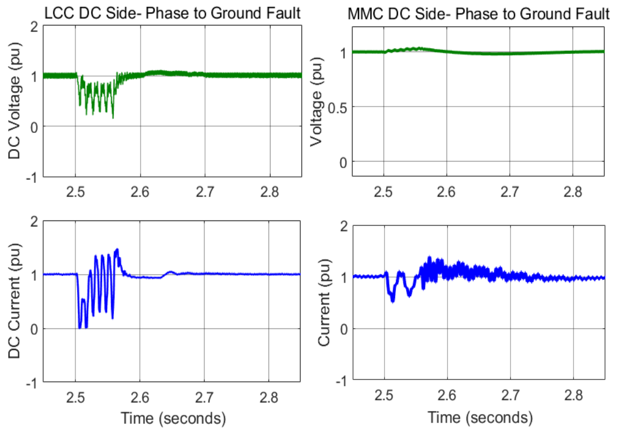

Figure 6. DC voltages and currents of LCC and MMC during A-G fault

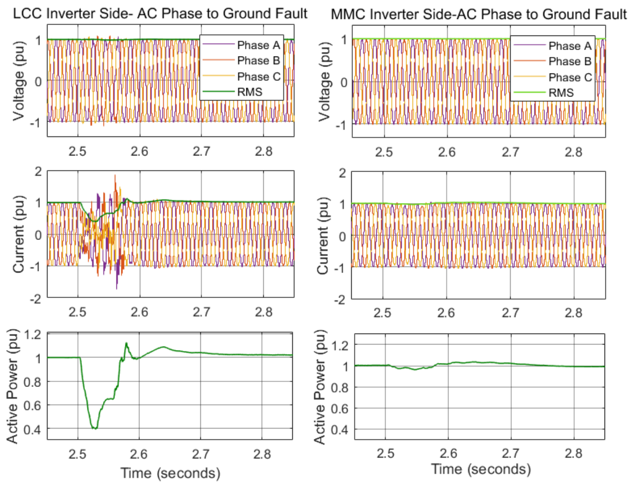

Figure 7. System response of LCC and MMC converters inverter sides during A-G fault

As seen in Figure 6, unlike the LCC converter, commutation failures do not occur in the MMC converter during an AC fault. In contrast to LCC, there will be very little change in DC voltage in MMC system. It is seen that the power transmitted by the MMC converter does not go below 50% even during the fault which depends on the voltage reduction at the AC terminals.

As seen in Figure 7 in the LCC system during the fault on the rectifier side, because of the imbalance of currents, the active power transfer on the inverter side is dropped to 0.4 pu. However, in the MMC system, effect of transient faults on the rectifier side is quite limited at the output of the inverter. Active power changes on inverter side are negligible when compared to LCC.

B. Voltage Deviation Analysis

In this analysis; on both systems, AC networks located on the rectifier side applied a voltage drop of 0.2 pu for 100 ms (t = 2.5-2.6 sec). The effect of this voltage change on the DC voltage and on inverter output is investigated.

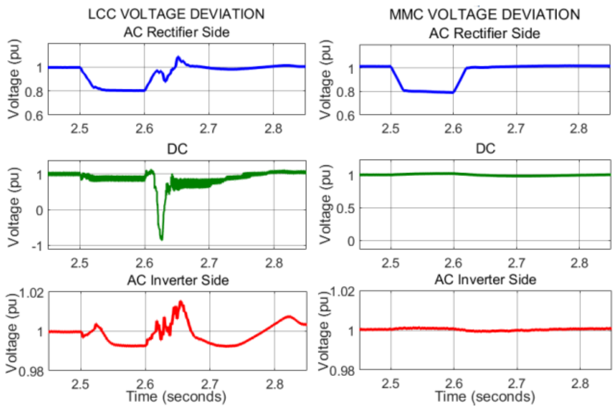

Figure 8. System response of LCC and MMC converters during voltage deviations

As seen in Figure 8, after the voltage drop in the AC grid, the DC voltage dropped below zero for a very short period of time due to the communication errors in the LCC system, but quickly recovered and reached 1 pu value again. Due to this voltage drop; nearly 1% oscillation of active power is occurred on inverter side. In the MMC system, active power and DC voltage changes on inverter side remained quite limited compared to the LCC system. In this study; DC fault is not simulated because it is very rare occurred in back-to-back and cable connected HVDC systems. DC faults are the weak side of the MMC system. When a DC fault occurs, the fault current is fed from AC connection and increases because of continuous conduction status of diode until the fault is cleared. However, phase reactors and DC smoothing reactors are effective in limiting the failure current. During this period, the voltage in the connected AC systems will decrease depending on the power of the AC system and the position of the failure.

C. Harmonic Analysis

Harmonics are measured in both systems. As seen in Figure 9, in the LCC system, total current harmonic distortion is reached to 8.23%, especially 11th and 13th harmonics have been effective in this distortion. After using harmonic filters; total current harmonic distortion is reduced to 1.97% by providing harmonic elimination.

As seen in Figure 10, in the MMC system; total current harmonic distortion has been 0.75%, total voltage harmonic distortion has been 0.19%. MMC systems do not require harmonic filters, unlike LCC systems, and harmonic distortion ratio is much less.

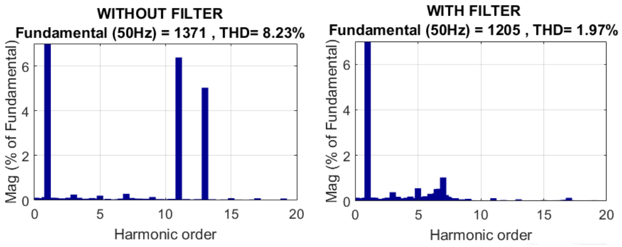

Figure 9. Current harmonic components in LCC system

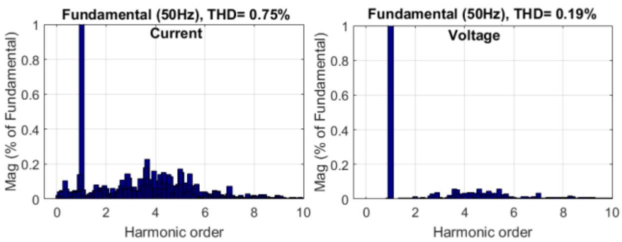

Figure 10. Current and voltage harmonic components in MMC system

IV. COST ANALYSIS

According to the study in the literature [12], Figure 11 shows the cost breakdown that is used for each type of converter and configuration, 2x500 and 1x1000 MW, 190 km cable connected HVDC system. As seen in Figure 11, according to the total investment cost analysis, HVDC cable connected LCC system is cheaper than the VSC (MMC based) system about 0.5%.

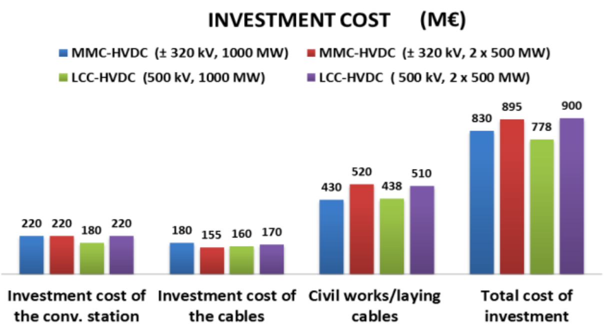

Figure 11. Investment costs of LCC and MMC converters [12]

In the literature [12], operating cost of LCC and VSC (MMC based) converter stations are analyzed. In this context, the cost analysis of 1000 km HVDC transmission line with 1500 MW capacity between the two countries in Europe has been done. However, in this study, only operating costs of the converter stations are mentioned. On the other hand, the conditions considered in the analysis are that the average spot market price of electricity is 65 €/MWh and the annual availability of the system is 8600 hours. From the perspective of station loss and operational -maintenance (O&M) costs as seen in Figure 12, LCC converter station is cheaper than VSC (MMC based) converter station about 13%.

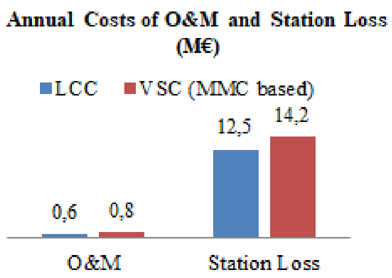

Figure 12. Station loss and O&M costs of both converters [12]

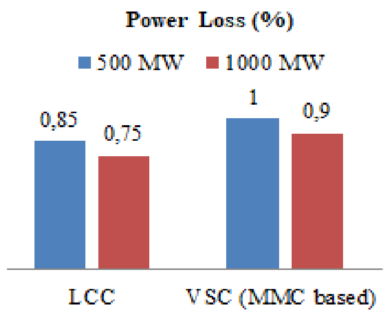

Figure 13. Power Loss (%) of both converters [12]

As can be seen from the Figure 13, above, investment costs are close to each other and the LCC system has a nearly 0.5% lower cost than MMC systems.

V. CONCLUSIONS

By the development of the energy trade, electricity trade between neighboring countries has gained importance. HVDC technology makes power flows between electrical grids without being affected by electrical disturbances. In this paper, LCC and MMC based HVDC systems are evaluated in terms of technical and economical comparison. LCC is the most common converter type used in HVDC projects. It can deliver up to almost all power capacity and is slightly cheaper than MMC. On the other hand, the LCC requires reactive power and is more vulnerable to commutation failures. Moreover, it generates harmonics during operation and requires filters to reduce harmonics. Simulation results are shown that MMC system is more reliable than LCC system on AC short-circuit faults and voltage fluctuations. Although DC short-circuit faults have a large effect on the stability of the MMC system, the problem can be overcome by using DC short-circuit breakers. The fast-dynamic response of MMC to reactive power demands has ability to operate even at lower short-circuit ratios, where LCC would not be able to operate.

Although MMC systems have many advantages, they may not be the most appropriate solution for every need. The economical aspect, grid conditions and operating features must be taken into consideration. HVDC technology will enable low-cost energy transmission from major power units such as the nuclear power plant in the future, as well as the asynchronous connection of neighboring electrical networks. In particular, the use of MMC technology is seen as the most suitable option thanks to the flexible control facilities for possible multi terminal HVDC connection between many countries in next future.

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BIOGRAPHIES

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