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Concept Design and Characteristics of 500 kV HVDC Transformer

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SUMMARY

In a High Voltage Direct Current (HVDC) system, the HVDC transformer serves several functions, such as act as a galvanic barrier between the AC and DC systems to prevent the DC potential to enter the AC system, voltage transformation between the AC supply and the DC system and a fairly large tap range with small steps to give necessary adjustments in supply voltage. The HVDC transformer is one of the most important components and the reliability and efficiency of the HVDC transformer has a major impact on the total cost of HVDC transmission over a long period of time. Therefore, the high reliable and efficient design of the HVDC transformer is one of the major concerns for transformer manufacturers.
In this paper, the study results for concept design of 500 kV HVDC transformer are described. The electrical field distributions between the line side widning and valve side winding are estimated by the Finite Element Method (FEM). And insultion materials arrangement is optimized by using Genetic Algorithm (GA). It was considered that three types of electrical stresses (AC, DC and polarity reversal condition) to prevent electrical breakdown. And in order to estimate the influence from harmonic current, stray losses under normal operation condition and HVDC system operation condition were calculated by FEM. These result was taken into account to design of 500 kV HVDC transformer. This design will increase the reliablity and efficiency of 500 kV HVDC transmission.

KEYWORDS

HVDC transformer, Dielectric stress, Harmonic current losses, Finite element method (FEM), Optimal design

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1. Introduction

The first commercial operated High Voltage Direct Current (HVDC) system was installed approximately 60 years ago. HVDC system has a lot of advantages of the large power, low-cost and high power quality for long-distance transmission as compared to HVAC system [1, 2]. There has been a steady increase in HVDC system in the world.
LSIS has undertaken HVDC projects based on accumulated technology for the AC power system. In 2012, LSIS develops 80 kV, 60 MW Jeju HVDC pilot system in Korea. Further research is being carried out to meet the demands of increasing power transmission. Figure 1, 2 is shown the schematic diagram and major facilities in 80 kV Jeju HVDC pilot system.
This paper describes the concept design and characteristics of 500 kV HVDC transformer. Dielectric stress and losses was estimated by the numerical analysis under HVDC system operating condition. And introduces a method for optimzing a parallel oil-barrier insulation structure of 500 kV HVDC transformer. For the optimization, Genetic Alorithm is used.

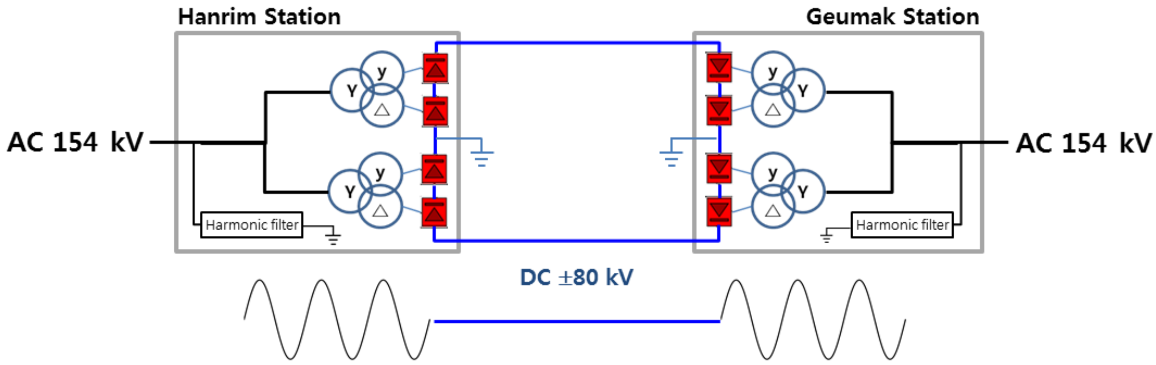


Fig. 1 Schematic diagram of 80 kV HVDC pilot system

Fig. 2 Major facilities in 80 kV HVDC pilot system

2. Special demands on HVDC transformer

2.1 Combined voltage stress with both AC and DC

The valve windings which are connected to the rectifier and converter circuit are subject to the combined load stress of AC and DC voltage. Added to this stress are transient voltage from outside caused by lightning impulse and switching operations. Insulation configuration of transformer is generally the composite insulation system combining solid insulation (barrier) and insulation oil.
AC voltage is shared according to dielectric constant and voltage concentrate in the insulation oil with low dielectric constant. On the other hand, DC voltage is shared according to resistivity and voltage concentrated in the barrier with high resistivity [3].

The HVDC transformer should have the insulating performance for these two conflicting properties. For this reason, insulation distance of HVDC transformer was larger than normal AC power transformer. Table 1 shows the test voltages required for 500 kV HVDC transformers in IEC 61378-2.

Table 1 Test voltage for 500 kV HVDC transformer

Test voltage	Line side winding	Valve side winding
Lightning impulse test	1050 kV	1425 kV
Switching impulse test	850 kV	1300 kV
AC separate source voltage withstand test	460 kV (1 min.)	620 kV (60 min.)
DC separate source-voltage withstand test	-	840 kV (120 min.)
Polarity reversal test	-	600 kV (-90 min., +90 min., -45 min.)

2.1.1 Optimization of insulation structure

Transformer design is primarily determined by minimizing the overall cost, including the cost of materials and losses. Minimization of HVDC transformer must take into account constraints which may be imposed on the transferred power, the impedance, the flux density, the overall height of the tank, etc.

The focus of design optimization is to minimize insulation distance and numbe rof barrier that can withstand all possible voltage stress conditions because transformer volume is normally affected on these. Minimized insulation distance and number of barrier give advantage of transformer volume reduction, which is cost efficient for transportation, installation footprint and easier manufacturing. In order to evaluate each candidate solution of insulation structure a proper analysing way, which is implemented on MATLAB with the aid of FEM is needed.

Genetic Algorithm (GA) is used for the optimization, and the analyses of each candidate solution structure are performed with Finite Element Analysis. GA is one of widely used optimization algorithms. The algorithm is strongly motivated from evolutionary process of nature. The optimization process is mainly composed of two steps of selection and reproduction with initial population. In the first step of selection, each chromosome is evaluated by a fitness function, and chromosomes which have chances to reproduce are chosen to be in the mating pool, following a certain selection rule. Part of those selected chromosomes evolves themselves by reproducing offspring and the other just survives to the next stage. Mutation could also happen in offspring at a certain possibility.

The optimization using GA is performed under the following circumstances.

-. Widths of barriers are fixed to 3 mm.
-. The initial population is randomly made.
-. The maximum distance of oil gap is 20 mm.
-. The population is 40.
-. Iterative calculation is done 40 times (generations).

The suggested algorithm produces parallel oil-barrier insulations having 5 % less insulation distance than inital insulation design in 500 kV HVDC transformer.

2.1.2 Electrical stress on steady state condition

An electric field distribution is dependent on the property of the insulation material such as oil and barrier. In AC condition, electric field distribution is determined by oil and barrier's permittivity ratio. And DC steady state condition, resistivity ratio of oil and barrier can be a

dominant parameter. The ratio of resistivity for oil and barrier may vary in the range 10 to 500 depending on several factors such as oil quality, moisture content, temperature, ageing.
The ratio of permittivity for oil and barrier is much smaller ratio of resistivity and close to two. This means that almost electrical stress is appied the barrier in the DC steady state condition .On the other hand electrical stress will be applied the insulation oil in the AC condition. Figure 3 shows winding and insulation construction of 500 kV HVDC transformer. And the electric field distribution pattern for DC and AC condition are shown in Figure 4. The difference in electrical field distribution patterns must be considered in insulation design of 500 kV HVDC transformer.

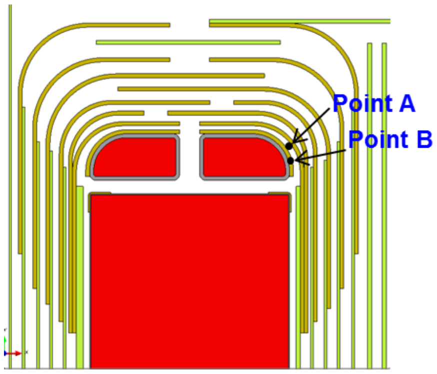
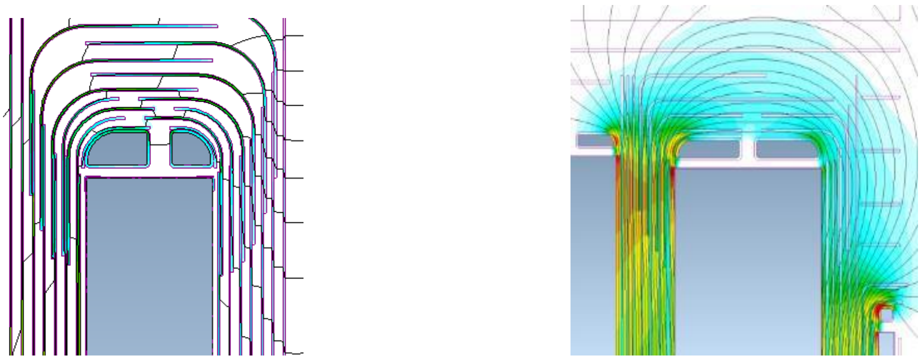


Fig. 3 Calculation model of HVDC transformer



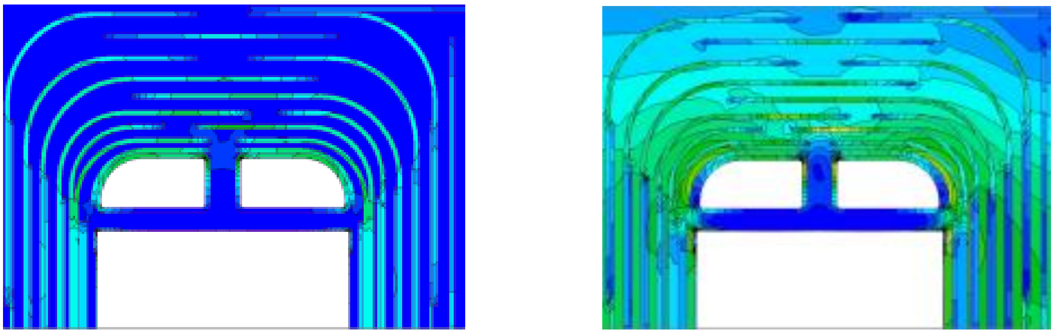
(a) DC condition (b) AC condition

Fig. 4 Electrical field distribution pattern in 500 kV HVDC Transformer

2.1.3 Electrical stress on transient condition

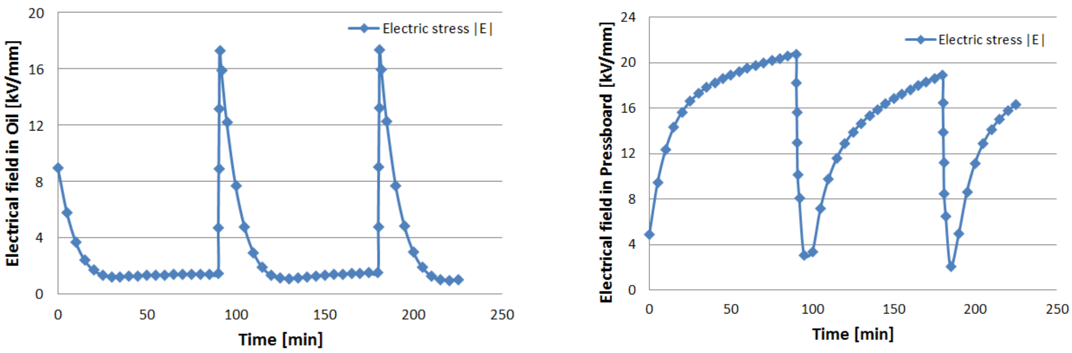
When the power direction changes in an HVDC system the current direction remains the same while the polarity of the voltage will be reversed. This phenomenon is called "Polarity Reversal". The transient performance may be affected by pre-stress conditions and by any stored space charge, particularly when polarity reversal occurs.
After a sudden changed in DC voltage, its distribution will be depending on capacitive and it will change into a resistive distribution as times goes. Therefore, the design of the insulation structure for a HVDC transformer is much more complex than for a conventional AC transformer which is not subjected to a DC voltage component. The test voltage waveform of polarity reversal has two polarity reversals. The sequence of test voltage waveform includes 90 minute at negative polarity followed by 90 minute at positive polarity and finally 45 minute at negative polarity.
Generally each reversal of the voltage from one polarity to the other shall be completed within 1 min. To get the accuracy and reduce the time of calculation, transient options should be considered such as calculating time step when calculating the polarity reversal condition.

The electrical stress distribution is shown Figure 5. Figure 6 (a) and (b) shows electrical stress distribution in oil duct and barrier in accordance with calculating time step, respectively. According to the figure 6, the electrical stress vary but the maximum value of electrical stress remains as same value while the test voltage of polarity reversal is applied. The stress rises to a value related to the capacitive distribution during the application of the initial voltage but then gradually falls as the space charge migrates from the oil to the pressboard insulation. It then increases again on each reversal of the applied voltage and it actually attains a much higher value than the stress appearing at the initial application of voltage. These enhanced stress level should be taken into account in insulation design.



(a) Stress distribution in oil duct @point A (b) Stress distribution in barrier @point B

Fig. 5 Polarity reversal stress distribution in 500 kV HVDC transformer



(a) Stress distribution in oil duct @point A (b) Stress distribution in barrier @point B

Fig. 6 Polarity reversal stress distribution according to the calculation time

2.2 DC bias current cause over saturation in core

The core material and stacking method is not different from those of conventional AC transformer. But effect of DC bias current should be considered in core of HVDC transformer. The cause of DC bias current is asymmetry of valve firing angle and inflow of DC current induced by the grounding system.

DC bias current in windings may cause significant half-cycle saturation. Under such a condition, the DC flux generated by the DC current offsets the AC flux in the core. DC bias current could increase the no-load losses and no-load noise depending on core design, core material, nominal magnetic flux density and DC field strength in the core. Figure 7 shows the no-load loss and noise level increase according to the DC bias current in the core. All curves have been normalized and show the relative no-load loss increase compared to that under AC excitation. As flux density in the core increases, the effect of the DC bias current on the core no-load loss is reduced. Also characteristics of noise level are similar tendency to that of no-load loss for DC bias current.

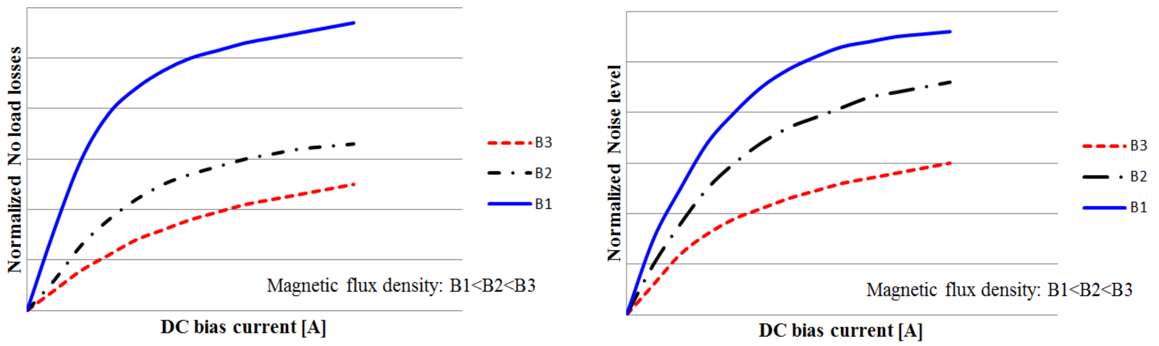


Fig. 7 Increase of no load loses and noise level under DC bias current

2-3 Harmonics current in the valve windings

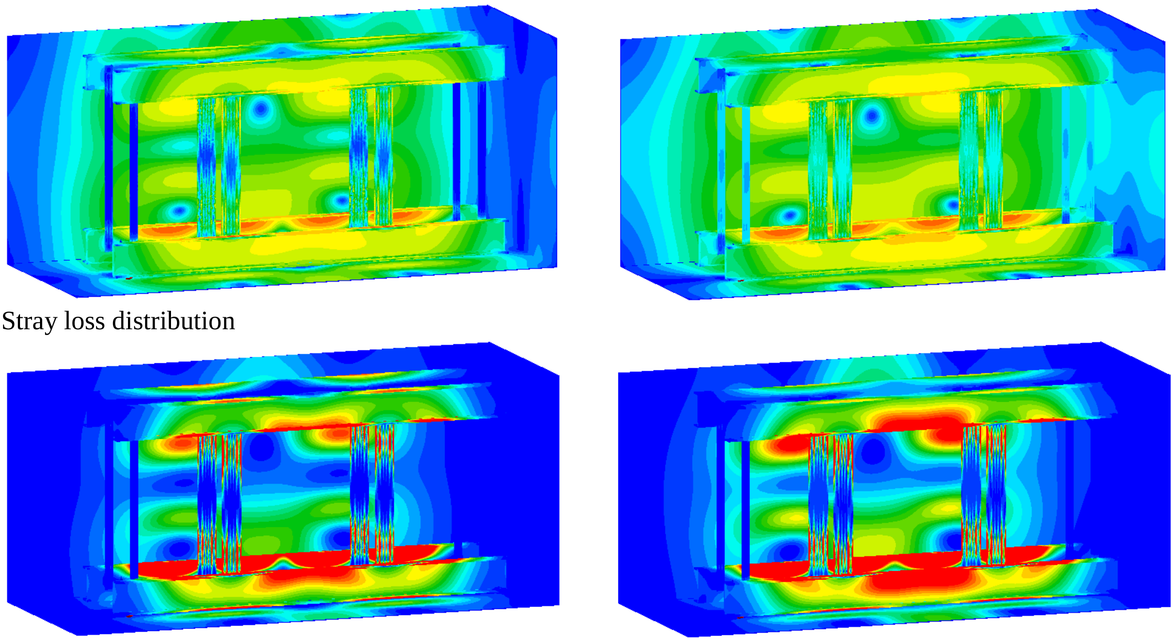
Normally for power transformers, the operating losses can be split into two parts of no-load loss and load losses. The no-load loss is a function of the applied AC voltage and core material. As the applied AC voltage in HVDC system operation is governed by the line side voltage and close to a sinusoidal shape, the no-load loss will remain the same as for a normal power transformer. The load losses depend on the load current. The load losses could be divided into two components from analysis point of view; one is resistive loss and the other stray loss. The resistive loss is component obtained as the product of the square of the load current and winding resistance. The leakage flux from the load current will create circulating currents in the windings and other metallic part exposed to the leakage flux. These currents increase the load losses called stray losses. Circulating currents depend on frequency of leakage flux. The HVDC transformer experiences harmonic currents ranging from 5th up to least the 49th of the supply frequency which will be present in the valve winding.

The level of the harmonics and their orders of magnitude are very dependent on the operating point of the HVDC system control. A peak value of harmonic current at each order in the HVDC transformer's valve winding is shown in Table 2. This value changes according to the switching angle and switching angle essentially depends on operation mode of the rectifier such as, the load value and the angle of valve control. In the Table 1, G and N means the switching angle and the number of a harmonic respectively.

The odd-numbered harmonics cause additional losses in the windings and other metallic structural parts. These loses are about two to three times higher in the HVDC transformer comparing to conventional AC transformer. Figure 8 shows the stray loss distribution on the metallic structural parts such as tank wall, yoke beam and tie plate. An estimate of the worst case has to be made to allow an evaluation of the additional losses and their effect on the hotspot in the winding and metallic structural part. Therefore the choices of copper wires must be very careful. Preferably continuous transposed conductors should be used. And the magnetic shunt or shield has been used to reduce losses of metallic structural parts.

Table 2 Harmonics value in valve winding current

N / G	N=5	N=7	N=11	N=13	N=17	N=19	N=23	N=25
G = 0	20 %	14.3%	9.1%	7.7%	5.9%	5.3%	4.35%	4%
G = 5	19.8 %	14.1%	8.7%	7.3%	5.4%	4.7%	3.7%	3.2%
G = 10	19.4 %	13.4%	7.8%	6.2%	4.0%	3.2%	2.0%	1.5%
G = 15	18.7 %	12.4%	6.3%	4.5%	2.1%	1.3%	0.2%	0.16%
G = 20	17.6 %	11.0%	4.5%	2.6%	0.35%	0.3%	0.83%	0.87%
G = 25	16.4 %	9.42%	2.6%	0.8%	0.86%	1.1%	0.83%	0.55%



(a) Regardless harmonics (b) Consideration of harmonics

Fig. 8 Polarity reversal stress distribution in 500 kV HVDC transformer

3. Design of 500 kV HVDC transformer

The HVDC transformer concept depends on system voltages in AC as well as DC side, throughput power, transport limitation, converter station layout, etc. Table 3 shows the specification of 500 kV HVDC transformer.

Generally, large HVDC transformers are single phase transformer. 500 kV HVDC transformer were designed. The core form has two wound limbs and two equal valve windings in parallel. And core material is grain oriented silicon steel. The stacking of core is not different from AC transformer. The electric filed analysis has been done to optimize insulting construction between line winding and valve winding and core. The harmonic current in the valve winding produces additional losses so that continuous transposed conductors (CTC) are used on winding and magnetic shunt on tank is applied.

The design results of 500 kV HVDC transformer is shown in Table 4. The efficiency was about 99.7%. No-load and load losses are about 174.1kW and 743.5kW, respectively. Figure 9 is designed configuration of 500 kV HVDC transformer.

Table 3 Specification of 500 kV HVDC transformer

Type	HVDC transformer
Number of phase	1 Phase
Rated voltage	345/221.56 kV
DC System voltage	± 500 kV
Rated frequency	60 Hz
Applicable standards	IEC 61378-2 / IEC 60076

Table 4 Design result of 500 kV HVDC transformer

Losses (@ Nominal tap position)	Load losses	743.5 kW
	No load loss	174.1 kW
Masses of active materials	Winding wire insulation	25.7 ton
	Electrical anisotropic steel	132.2 ton
	Total weight	157.9 ton

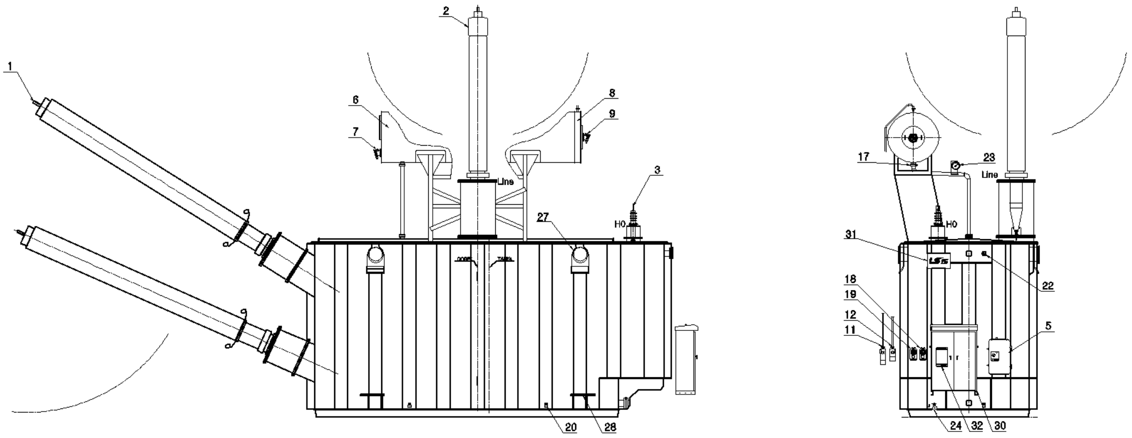


Fig. 9 Configuration of 500 kV HVDC transformer

4. Conclusions

The concept design for 500 kV HVDC transformer is obtained by using optimizing program for insulation structure. And the dielectric performance was verification under AC, DC and polarity reversal voltage by the FEM.

As the result, it was able to confirm that the sufficient dielectric strength and the suggested algorithm produce that insulation distance reduced 5 % than inital insulation design in 500 kV HVDC transformer. This design will increase the reliablity and efficiency of 500 kV HVDC transmission.

BIBLIOGRAPHY

[1] Arrillaga, J. High voltage direct current transmission, Peter Peregrinus Ltd. London, 1983.

[2] Kimbark, E. W. Direct current transmission, John Wiley and Sons, New York, 1971.

[3] Yoshida, et.al., “Insulation property verification of end of the converter transformer winding”, Annual Conference of IEEE Japan, No,5-216,5-217,1995.

[4] Eckholz, K.and Heinzig, P., “HVDC-transformers-a technical challenge,” PowerCon 2002, pp. 547-551,2002.

[5] Eckholz, “HVDC Transformers State of The Art,” Sientific Symposium, May 2001.

[6] W. Xu, T.G. Martinich and J.H. Sawada, “Harmonics from SVC Transformer Saturation with Direct Current Offset,” IEEE Transactions on Power Delivery, Vol 9, No. 3, pp. 1502-1509, April 1994.