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# **Economical Comparisons of Interconnection Technology** for Asynchronous AC Power Grids

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Abstract. There is growing interest in grid connections between different micro grids, countries, and the selection of interconnection method should be based on an economic analysis. This paper analyses the economics of VFT (Variable Frequency Transformer) and HVDC (High Voltage DC) and proposes an optimal grid interconnection method. The economic evaluation was conducted based on the new investment cost depending on the capacity of the facilities needed for the grid connection, and the feasibility study was carried out to find out which method is more advantageous economically.

## **1. Introduction**

Efforts are being made to improve economic benefits and reliability of power supply through grid interconnection, such as micro grid, interconnection between countries, and Northeast Asia super grid. Consequently, research on the grid connection type is actively being carried out. The characteristics of the systems, geographical location, reliability, and economic efficiency are considered in the selection of the grid connection system, among which economic analysis accounts for a large part. In this paper, feasibility study is carried out through economic evaluation of grid connection methods. The economic analysis was based on the investment cost of VFT and HVDC connection method based on the capacity - based connection system establishment, and the cost of the converter station and VFT station including the power conversion device were compared.

## 2. Grid connection method

HVAC, HVDC, and VFT are the most commonly used methods for interconnecting between two grids. Fig. 1 shows the three interconnection methods for power grids.

## 2.1. HVAC

HVAC is the mostly used interconnection method, and powered by a high AC voltage to transmit power to long distances, but it is necessary to readjust the protection equipment according to the new system configuration and to apply the same reliability evaluation standard as the concept that the power system is unified rather than simply power transmission. It is necessary to secure reserve power for maintaining stability in the entire interconnected system. In addition, the responsibility becomes the collective responsibility of the connected system. For AC grid connection, the rated voltage and frequency must be the same, but the power grid operating conditions is not suitable for other asynchronous grid connection. In this paper, it is judged unsuitable for the asynchronous grid connection and excluded from the economic evaluation.

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# 2.2. HVDC

High voltage DC transmission (HVDC), which converts AC power into DC power and converts it back to AC power, is widely used in grid connection due to its advantages. The advantages of the HVDC system in terms of grid connection are as follows.

- Low cost compared to AC transmission in long distance power transmission
- It does not affect the AC system and it can transmit a large amount of power
- It is possible to connect with other systems of different frequencies
- Can reduce power reserve ratio
- Various methods of connection are available depending on the characteristics of the system
- Minimize influence between systems
- Easy to increase transmission capacity

Disadvantages include the cost of power conversion equipment, the generation of switching harmonics, and the establishment of compensation facilities due to the additional supply of reactive power.

# 2.3. VFT

The grid connection method using a rotating transformer (VFT) can be applied to an interconnection between two systems having different frequencies without converting AC power into DC power. In common with HVDC, it can achieve high efficiency, low harmonic generation, and easy maintenance. The characteristics of VFT in comparison with HVDC are as follows.

- No harmonic generation
- There is no risk of sub-synchronous de-coupling
- Modular Design and scalable
- Low Impact on Adjacent Generators
- Compatible with nearby generators
- Stability of load input
- Active power response to accidents
- Black start capability



Figure 1. Power System Interconnection Diagram

# 3. Economical Evaluation of HVDC interconnection for Asynchronous Power grids

There are two types of HVDC connections: current-type LCC HVDC and voltage-type VSC HVDC. In this study, the cost is estimated based on the VSC HVDC which has advantages such as minimization of construction site, bidirectional power control without polarity change, and reducing harmonic effects. HVDC investment costs include stations containing AC-DC converters, stations containing DC-AC inverters, breakers, and the like.

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#### 3.1. Converter station

VSC Converter, a voltage converter, has a rating of between 300 and 350 MW. Therefore, the construction of large-capacity transmission lines requires the construction of a number of converter stations and typically results in a loss of 2% per unit. VSC converter stations mostly use switching valves with IGBT semiconductor power devices, and are driven with a switching frequency of about 2 kHz.) The configuration of the converter station includes valves, transformers, filters, etc. According to the data provided by ABB, investment cost of 0.15187 \$ / W is required. Based on the data, the formula, equation (1) for the cost of the converter station can be obtained. Table 1 gives the HVDC converter station cost according to transmission capacity through the formula.

$$C_{converter\ station} = 0.193 \times P^{1.0736} \tag{1}$$

where *C<sub>converter station</sub>* is the estimated cost, and P is the transmission capacity (MW)

Fabl	e 1	. ]	Investment	costs	based	on	the	transmission	capacity	of	the	converter	station
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Transmission capacity(MW)	300MW	600MW	900MW
Cconverter station(m\$)	88.103	185.430	286.570

#### 3.2. Circuit breaker

The circuit breaker is necessary to protect the equipment by opening and closing the line to prevent secondary accident when an abnormal voltage such as open / close surge and lightning flows in the transmission line. Since it is installed at the entrance and exit of the facility connecting the lines, two breakers are required per facility. In case of DC system such as HVDC, there is no interval for the current to reach zero for one period, resulting in a very large surge occurs when the circuit breaker is opened and closed. Therefore, DC circuit breakers are to be used and the economic evaluation of this paper is based on the cost of the solid-state circuit breaker (SSCB), which is the most economical DC breaker. The equation (2) for the DC breaker can be obtained, and Table 2 gives the breaker cost according to the rated voltage of SSCB.

$$C_{cb(dc)} = 0.0021V - 0.0142 \tag{2}$$

where  $C_{cd(dc)}$  is the estimated cost, and V is the rated voltage(kV).

 Rated Voltage(kV)
 12
 20
 150
 300

 Cost(m\$)
 0.0110
 0.02780
 0.3008
 0.6158

Table 2. Investment cost based on SSCB rated voltage

## 3.3. The total investment cost of the HVDC

In order to connect two systems in the HVDC, a converter station must be installed in accordance with the transmission capacity. Therefore, the economic feasibility of the HVDC was evaluated based on the establishment of 300, 600 and 900 MW HVDC station. There shall be one converter station and two DC breakers at the sending and receiving ends, respectively. In case of a reactive power compensation device, it is possible to compensate a certain amount at the converter station, and DC transmission does not generate reactive power, it is not included in the investment cost calculation. The circuit breaker is assumed to be based on 300kV considering that the voltage of the DC system is

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generally higher than the voltage of the AC system. Based on the above considerations, the investment cost of each HVDC plant is estimated and it can be obtained as follows. Table 3 lists the investment cost by capacity of the HVDC.

Transmission capacity(MW)	300	600	900
Converter station cost(m\$)	176.206	370.860	573.14
Circuit breaker cost(m\$)		2.4632	

Table 3. Investment cost o	of new HVDC conve	erter station facility (m \$)
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# 4. Economical Evaluation of VFT interconnection for Asynchronous Power grids

VFT station requires a station including a rotary transformer to be installed between two different systems, and a transformer for adjusting the rated voltage between the systems and two breakers per device are required.

## 4.1. Transformers

The transformer is a facility that can step up or down the transmission voltage. Depending on the rated capacity, the cost of the iron core and the winding greatly affects the transformer. The investment cost for the transformer can be calculated as shown in Table 4, and the formula for calculating the cost of the transformer can be obtained.

Table 4. Investment cost based on the rated	power of the transformer
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Rated Power(MVA)	900	722	630	400	300	200
$C_{trans}(m\$)$	6.9552	6.4446	5.8236	4.14	3.3534	2.4564
		C		0.7513		(2)

$$C_{trans} = 0.0459 \times P^{0.7513} \tag{3}$$

where  $C_{trans}$  is the estimated cost, and P is the transmission capacity (MW)

# 4.2. VFT

The cost information of the VFT was not published, and was equivalent to the DFIG price used in the wind turbines, and for DC motors required for control, 30% of the DFIG price of the same capacity applied. The investment cost of 5MW DFIG can be estimated at about \$ 515200 and assuming the cost is proportional to capacity, the investment cost of VFT can be shown in Table 5.

**Table 5.** Investment cost by capacity of new VFT equipment(m \$)

Transmission capacity(MW)	300	600	900
VFT cost(m\$)	40.1856	80.3712	120.5568

# 4.3. Circuit breakers

The cost of the circuit breaker can be calculated according to the rated voltage as shown in Table 6 and, the formula for the circuit breaker cost can be defined as equation (5).

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Rated Voltage(kV)	33	132	220	400
Cost(m\$)	0.08004	0.17112	0.25254	0.41814
	(4)			

Table 6. Investment cost based on rated voltage of circuit breaker

where  $C_{cd(ac)}$  is the estimated cost, and V is the rated voltage(kV).

#### 4.4. Total investment cost of VFT

The economic feasibility of the VFT was analysed based on the establishment of a transformer for AC connection and VFT station with capacities of 300MW, 600MW and 900MW between two asynchronous grids. There shall be one transformer at sending and receiving ends, and VFT stations at between grids, and two AC breakers per unit. Based on the above considerations, the investment cost of each VFT plant is estimated and it can be obtained as follows. Table 7 lists the investment cost by capacity of VFT.

Table 7.	Investment	cost of new	VFT	station	facility	(m \$	\$)	
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Transmission capacity(MW)	300	600	900
VFT cost	40.1856	80.3712	120.5586
Transformer cost	6.666	11.222	15.218
Circuit breaker cost		1.5152	

## 5. Economical Comparison for VFT and HVDC

Economical evaluation of the establishment HVDC and VFT was compared and analysed. Figure 2 shows a graph of the cost of the investment according to the capacity of each type when the connected station is establishment, and Table 8 lists the total cost of the investment by capacity. As can be seen in the graph, VFT is economical in terms of equipment costs when compared to HVDC. Also, the cost increase of HVDC is greater than that of VFT as the power capacity increases.



Figure 2. Investment Cost by Capacity

	HVDC	VFT
300MW	178.6692	39.0932
600MW	373.3232	74.5612
900MW	575.6032	109.4692

Table 8. Investment cost by capacity of connection method

## 6. Conclusion

HVDC has been mainly used for various grid connections according to its advantages, but there are several problems, such as high frequency harmonics, the cost of power conversion device and station, and DC breakers. On the other hand, VFT is an inexpensive solution relatively, and based on the wellestablished AC technology. Also, VFT has no harmonic generation due to the rotating device. In this paper, the economic evaluation of VFT and HVDC for interconnection of the asynchronous power grids is presented, and VFT is verified that it has the same performances and better economy rather than HVDC as the higher power capacity.

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