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Proposing a Rule for VSC-HVDC Optimal Placement to Improve Transient Stability of Power System

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ABSTRACT

Transient stability indicates the system's ability to dampen the rotor oscillations of synchronous generators after severe faults. The transient instability causes considerable damage to the generator and reduces the production capacity in the network. In this paper, at first, using the simulation and replacement of individual transmission lines, the behaviour of synchronous generators against severe faults and the impact of replacing conventional AC transmission lines with VSC-HVDC (Voltage Source Converter-High Voltage Direct Current) systems are investigated. The critical fault time (CCT) is considered as the stability indicator. In the second step, AC transmission lines are replaced by VSC-HVDC lines to investigate the amount of stability improvement by different placement. Ultimately, to avoid many simulations, a criterion is proposed for optimal placement of the HVDC system in the power grid. This criterion finds the most critical generator in the system and the most efficient AC transmission line replacement by HVDC. The results show the proposed criterion can reduce the computational burden with appropriate accuracy and also the using of HVDC systems is effective in improving the transient stability of power systems. Also, a suitable criterion for locating and replacing the HVDC system has been proposed.

1. Introduction

Transient stability of the power network means the system's ability to maintain the rotor angle in limited range after a severe disturbance. Transient stability is also known as the ability of the power system to maintain synchronism, when it is affected by disturbances like network faults, loss of production, or large load shedding. The transient stability is affected by the nonlinear characteristics of the power system components. One of the famous indicators for evaluating the transient stability conditions is the CCT [1] so that increasing this indicator equals a more secure margin.

In the literature, several methods have been introduced to improve transient stability using different tools. Steam valve control [2], braking resistance [3], and excitation system [4] are some of them. In [5], a resistive solid-state fault current limiter (R-type SSFCL) is proposed to improve the transient stability of the DFIG-based wind generator system. A series dynamic braking resistor (SDBR) and an LR-type solid-state fault current limiter

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(SSFCL-LR) are also considered to compare their performance with the proposed R-type SSFCL. The simulation results show that the R-type SSFCL is more effective in improving the transient stability of the system. Also, the use of FACTS (Flexible Alternating Current Transmission System) devices [6], Flywheel Energy Storage System [7] and High voltage direct current (HVDC) system are other ways to improve transient stability [8]. On top, there are some works which summarizes different stability improvement techniques [9, 10]. Another important subject is finding the location of stability improvement equipment, for example in [11], optimal location of the shunt FACTS controllers is performed. The main focus of this paper is on the using HVDC system on the transient stability and also providing a method to choose the most suitable place to replace the HVDC system. So, more detail about HVDC is presented.

1.1. HVDC systems

The HVDC transmission system is a technology-based on high-capacity power electronics, transmitting power through DC lines. Generally, HVDC systems can be divided into two categories: LCC (Line Commutated Converter) system and VSC (Voltage Source Converter) system. The VSC-HVDC system has many potential advantages over LCC systems in the stability point of view; some of the most important of points are mentioned below:

1- Completely independent control of active and reactive power without the need for additional compensating equipment. This operation is carried out using PWM (Pulse Width Modulation) technology. Consequently, when the active power is transmitted in the DC lines, it is possible to control the reactive power and the voltage magnitude in the AC network [12].

2- VSC-HVDC increases the possibility of using pulse techniques, which has a significant impact on system control [12].

3- VSC converters work without dependence on the voltage source, so the faults in the AC network will not affect the DC side. However, disturbances and faults in the AC system cause the voltage drop, which inherently reduces the DC transmission power [13]. Therefore, the use of the VSC type of HVDC system can be more effective in improving the transient stability of the power network compare with LCC type.

1.2. Stability Improvement by HVDC

In [14], the effect of HVDC connections based on the embedded voltage source converter (VSC-HVDC) on the transient stability of AC networks is investigated. It is shown that an HVDC junction can ensure the synchronization of different AC regions, even if no AC transmission line connects them. Reference [15] provides an overview of the effects of VSC-HVDC control and operation on power system stability. In the next step, the structure, control setting and modelling of the VSC-HVDC are briefly reviewed to provide a basis for further discussion of system dynamics. In [16], the transient stability of the VSC-HVDC transmission line is investigated by injecting power on the line, and according to the results, it is observed that the transient stability is improved. In reference [13], a reactive power control strategy is proposed for multi-terminal VSC-HVDC systems to improve transient stability. The estimated frequency is operated as a reference to control the complementary reactive power at each converter station. Similar results have been obtained by controlling reactive power. Reference [17] presents a suitable location for substation construction to connect VSC-HVDC between Belgium and the United Kingdom from the perspective of stability considerations. In another work, after submitting the model of a two terminal DC power system and an AC/DC system (an AC line parallel with a DC line) consisting of voltage converters, an optimal HVDC controller is presented for both modes [18]. In Reference [19], the control of real power by HVDC converter and the effect of transient reactive power on stability are studied. An algorithm based on Lyapunov's direct method is used to dampen power system oscillations. Reference [20] introduced a method for controlling the reactive power injection of the VDC-HVDC multistage system to improve the transient stability. In this paper, a complementary reactive power signal is provided for each converter. Finally, reference [21] is similar to the previous work, except that the control method is based on active power. In this method, each VSC is controlled using the global frequency measurement compared with the local measuring. Simulation studies have been tested on modified Cigre Nordic network with a multi-terminal DC system. In references [22], by controlling the active and reactive power in the HVDC, the transient stability has been improved, but these references did not propose any idea for the location of HVDC implementation. As economical point of view, a comparison of different stability improvement equipment is presented in Table 1 from CIGRE Working Group B4 [23]. In should notice that HVDC compare to TCSC and SVC shows a better performance for transient stability improvement [24].

Table 1. Cost of different transient stability improvement equipment

Equipment	Cost Range (USD/kW)
TCSC	\$50 - \$150
SVC	\$50 - \$150
STATCOM	\$100 - \$300
SSSC	\$150 - \$300
UPFC	\$200 - \$400
HVDC	\$100 - \$250

Although with comparison to TCSC and SVS, HVDC is more expensive, HVDC transmission systems are particularly economical in several scenarios [23].

1. Long-distance overhead transmission: increasing the AC power loss compare to DC loss (typically over 600 km).
2. Long-Distance underground cables: increasing the AC capacitive reactive power and voltage stability problems (typically over 50 km).
3. Interconnecting different frequency grids: connecting a 50 Hz power grid to a 60 Hz power system.
4. Under sea interconnections: in this case, using a l

ong-distance cable reach to scenario 2.

In this paper, the optimal location of HVDC lines in the power system is studied to improve transient stability. For this purpose, after finding the critical generator, the most effective connected line in stability improvement of the selected generator is determined. From economic aspects, we only consider replacing existing AC line with new HVDC system and other financial aspect of HVDC is out of scope of this paper. The results show the proposed criteria can determine the most convenient location of HVDC system without extensive simulations requirement. To consider the real application of the proposed method, The HVDC control system is considered with full details.

2. HVDC modeling and its controllers

According to the [22], it is observed that controlling both active and reactive powers exert a more beneficial effect on transient stability compared to their one-to-one control. Therefore, in this paper, the control system is designed to controls both active and reactive powers. The studied VSC-HVDC system configuration is shown in Figure (1). In this system, two different controllers are employed for the generator and the network sides. One terminal of the transmission line which is connected to the generator bus is named generator side, and the other side of the transmission line, is named network side. The VSC-HVDC system has been replaced with the lines that are in the vicinity of the generators to be more effective in improving the transient stability of the generators .The power (active and reactive) of HVDC and the terminal voltage are controlled in the generator side and network side, respectively. The HVDC is connected to the high voltage bus of the unit transformer.

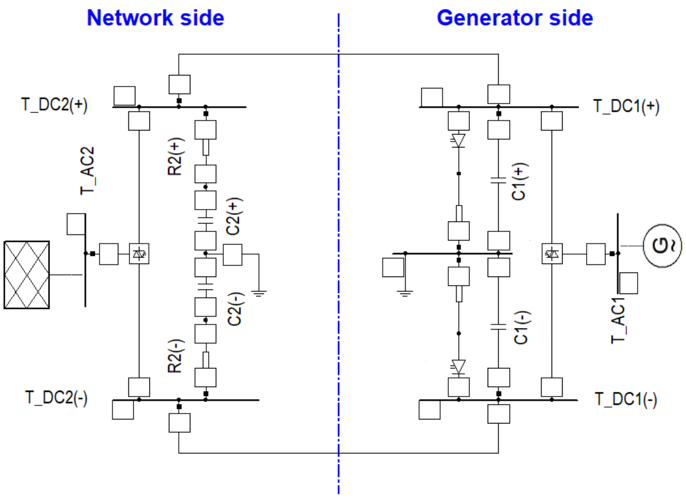


Fig. 1. Single-line diagram of VSC-HVDC system

2.1. Generator side controlling

The generator side converter is the voltage source converter. The main controller can conduct active current and reactive current to control the DC voltage and reactive power, respectively. The controller block is shown in the Figure (2). In this figure, the control logic of active current, reactive current, and current limiter are highlighted in red, green, and blue colors, respectively.

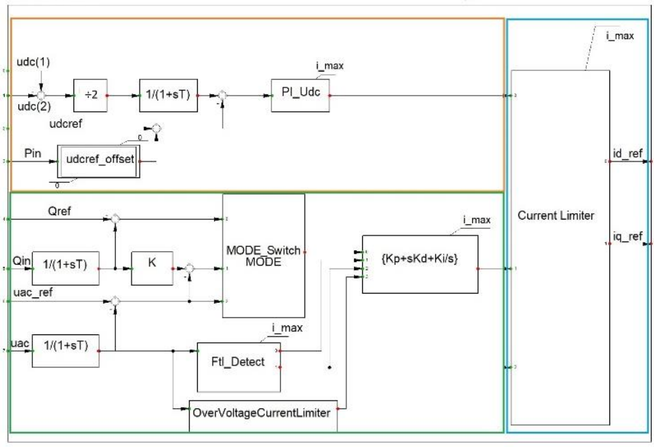


Fig. 2. HVDC generator side controller

During normal operation, the current limiter prioritizes the active current (id) and limits the reactive current (iq). However, during the fault condition and up to 500 milliseconds, the reactive current is given priority, and the active current is limited. The used parameters in this controller are provided in Table (1).

Table 1. Parameters of the generator side controller

Variable	amount	unit	Description
U_{max}	1.15	p.u.	Maximum allowable internal voltage
x	0.1487	p.u.	Series reactor impedance
T_{rudc}	0.001	s	Constant time DC voltage filter
Droop	0.05	p.u.	Voltage drop controller gain
K_u	12	-	PID controller gain
K_{iu}	100	1/s	PID controller integral constant
K_{du}	0	1/s	Fixed PID controller derivative
fltMODE	1	-	Filter values (0 or 1)
K_flt	2	-	Reactive current gain
K_d	10	-	PI controller gain for DC
T_d	0.1	s	Time constant of PI controller integral for DC
$I_q$fmax	1	p.u.	Maximum reactive current at fault time
U_t	0.1	p.u.	Voltage error
MODE	1	-	1 or 2
I_max	1.1	p.u.	Maximum allowable current

The current controller takes the reference current from the main controller and calculates the modulation index which transmitted to the converter. The current controller is shown in Figure (3), and the values of related parameters are demonstrated in Table (2).

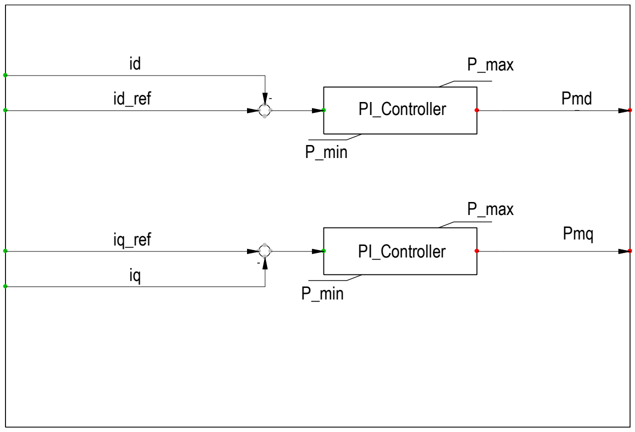


Fig. 3. HVDC current controller - generator side

Table 2. Values of current controller

Variable	amount	unit	Description
K_{pm}	1.000	p.u.	Proportional interest
T_{pm}	0.002	s	Integral time
P_min	-3	p.u.	Minimum pm value
P_max	3	p.u.	Maximum pm value

The chopper controller has positive and negative DC voltage as input signals. If the voltage exceeds a specific limit, the DC valves activate the chopper resistance and block these valves again if the voltage drops below the specified threshold. Chopper resistors are required in the fault condition to prevent power transmitting from the DC circuit to the AC network. As a result, the DC circuit is charged. This phenomenon can damage the IGBT of the converter. So, the DC chopper must limit the voltage to an appropriate value.

2.2. Network side controlling

The primary task of this control is to adjust the voltage and frequency of the network side. This adjustment is performed through the input signal Pm (modulation index) and f_0 (frequency) of the PWM converter. The modulation index is controlled by two PI controllers plus a feed-forward path using the measured DC voltage. The controller structure is shown in Figure (4), and the related parameters are given in Table (3).

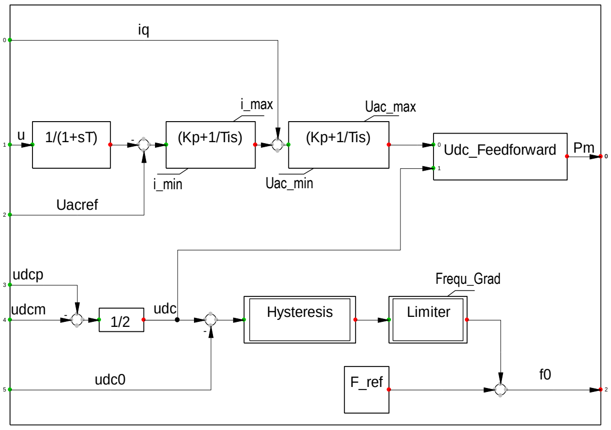


Fig. 4. HVDC network side controller

The first PI controller receives the AC voltage error as the input signal, and the output is the reactive current reference. This reference signal is compared to the measured reactive current. The output of the second PI controller is the reference AC voltage. In the "Udc Feed-forward" block, the reference AC voltage is divided by the measured DC voltage and multiplied by a constant that depends on the adjustment method. The controller considers an internal limitation of reactive current. This restriction is only activated by the fault occurrence time. Reactive current feedback (iq) reduces the voltage across the converter [25].

Table 3. Values of the main controller variables on the network side

Variable	amount	unit	Description
Kuac	2	p.u.	Proportional gain of voltage controller
Tuac	0.2	s	Voltage controller integral timer constant
Kiac	2	p.u.	Proportional gain of the flow controller
Tiac	0.02	s	Voltage controller integral timer constant
F_ref	1	p.u.	Reference frequency
Tfilter_U	0.005	s	Fixed time filter
UdcHigh	99	p.u.	Maximum allowable DC voltage
UdcLow	0	p.u.	Minimum allowable DC voltage
PlusFrequ	0.03	p.u.	Frequency value
i_min	-0.7	p.u.	Minimum allowable current
Uac_min	-0.1	p.u.	Minimum allowable AC voltage
i_max	0.7	p.u.	Maximum allowable current
Uac_max	1.1	p.u.	Maximum allowable AC voltage
Frequ_Grad	1	1/s	Frequency drop

3. Optimal placement of VSC-HVDC in the power grid

The purpose of this section is to find optimal location of the HVDC system to maximizing the transient stability improvement. In other words, the answered question is which existing AC line is the best choose to replacement with HVDC to maximize CCT. As a result, the existing tower and conductors can be reused for HVDC system and therefore installation cost reduces significantly.

3.1. Generator selection index

For finding the location of HVDC, the first step is finding the critical generator. By proposing a new index, the effectiveness of the system generators is sorted to find the most effective generator in the instability. Therefore, the terminal of this generator is extremely attractive candidate for HVDC line connection. This index is extracted from two fundamental rules. First, based on the equal-area criterion (EAC), a generator with more power loading and transient reactance (X'd) is more likely to unstable. The second rule is extracted from the swing equation (1) [1].

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = \mathrm{P_m} - \mathrm{P_e} \qquad (1)$$

Where H is the inertia constant of the generator, δ is the rotor angle, ω_s is the synchronous speed, and $\mathrm{P_m}$ and $\mathrm{P_e}$ are the machine mechanical and electrical powers, respectively. So, the generator with less inertia (H), and consequently less kinetic energy, is more exposed to instability. As a result, the selection index of the generator is proposed as Equation (2).

$$\mathrm{I}_g = Average\ CCT\ improvement(\%) \qquad (2)$$

To calculate this coefficient, for each generator, each of the transmission lines connected to the generator bus is replaced with a HVDC system, and the CCT improvement percentage is obtained for each mode. Finally, according to the number of transmission lines connected to the generator bus, the average CCT improvement percentage is calculated for each generator. As a result, any generator that has a higher coefficient, the transmission lines connected to the bus of that generator are a more suitable option for replacement. Based on the Equation (2), the probability of fault occurrence considered equal for all scenarios. The fault is considered on the busbars and the maximum CCT increasing shows the most potential for stability improvement. To evaluate the most critical condition for transient stability, the severe condition is considered with the following features:

- three-phase fault with zero impedance
- nearest fault location: busbar of the generator
- generator peak loading condition

3.2. Line selection index

The most advantageous parameter of replacing HVDC with AC line is reactive power control and its voltage increase in post-fault conditions [22]. As follows, a line that carries less reactive power in the post-fault conditions is more attractive to replace with an HVDC line. Between different time snapshots, the first time after fault clearing time is the most critical point. In this paper, the line selection index for replacement with HVDC lines is provided by the authors. the proposed criterion for selecting the transmission line is the amount of reactive power passing through the AC line after the fault, as Equation (3).

$$\mathrm{I}_l = Q_{line}|_{t=t_{clear}+\Delta t} \qquad (3)$$

Where Q is the reactive power crossing the desired line, t is the time, t_{clear} is the fault clearing time, and Δt is a time difference to overcome clearance transients (some milliseconds). In the following section, the mentioned theory will be evaluated by simulations.

4. Simulation and results

The IEEE-39 bus system (see Figure 5) was selected as the test system using Power Factory ® software. The fault is assumed to be transient, so the post-fault configure of the power system is similar to the pre-fault condition. The fault is considered three-phase which occurs on the high voltage side of the generator bus, due to high impact on the generator stability. For stability improvement, the HVDC is replaced with the existing AC lines connected to the faulty bus. To evaluate the HVDC effectiveness, the CCT of the nearest generator is selected as the stability index. Finally, the VSC-HVDC system introduced in the previous sections is placed in the network to investigate its transient stability. This placement is allowed in the form of a two-terminal (between the generator high voltage bus and one of the network substations) or a three-terminal (between the generator high voltage bus and two network substations). for calculating the stability improvement, the CCT deference is calculated in base case (before HVDC installation with existing AC line) and after HVDC replacing.

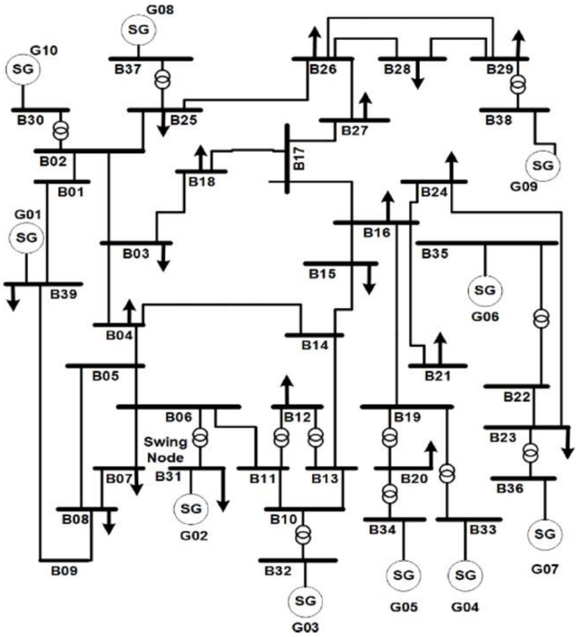


Fig 5. IEEE 39-bus standard system (New England)

4.1. Two-terminal HVDC installation

In this section, the VSC-HVDC line is replaced by one of the AC lines between the generator high voltage bus and one of the network substations. The VSC-HVDC systems are replaced in the generator bus to be more effective in improving the transient stability of the generator by controlling the active and reactive power. For example, the effect of HVDC line construction on the stability of generator No.8 is investigated.

First, in the network without the HVDC system, a three-phase fault is applied on the high voltage bus of generator No. 8 (i.e., bus No. 37). The fault is applied in second one and cleared after 170 milliseconds. To investigate the effect of HVDC on the system stability, according to Figure (6), the line 25-26 has been replaced with the HVDC line.

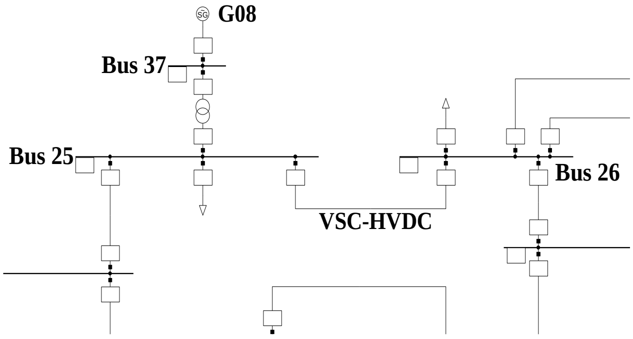
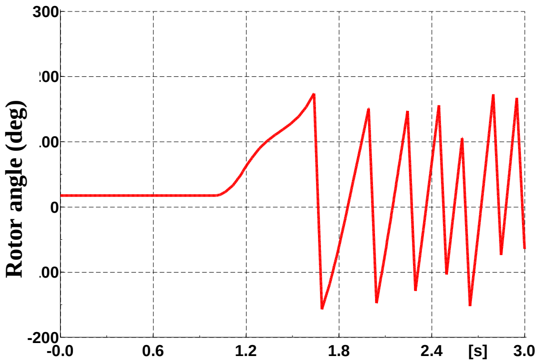
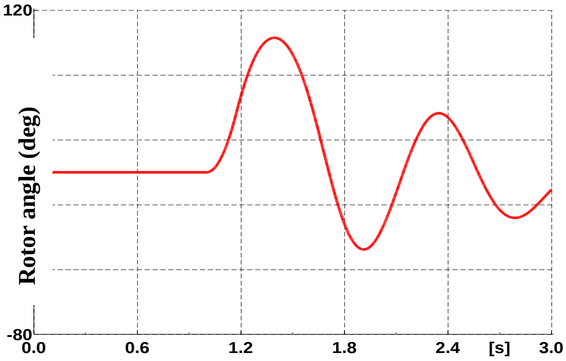


Fig 6. Replacement of line 25-26 with HVDC line

Other power system configuration and fault conditions are kept the same as before. Figure (7) shows the rotor angle curve of generator No. 8 in this scenario; (a) before HVDC installation which the rotor angle increases continuously, and the generator loses its stability, and (b) which with the presence of the HVDC system, the generator remains stable.



(a) without HVDC



(b) with HVDC

Fig 7. Effect of HVDC on the Rotor angle (degree) of Generator No.8

The transient stability evaluation has been done for all generators (except for generators No.1 and No.10) and all lines connected to the generators. Table (4) shows the CCT, the percentage of CCT increasing after using the HVDC system, and Ig index for each generator. Generator No.1 equivalent to the Canadian network connection. Also, Generator No. 10 loading is low (less than 20%). Generators No. 4 and 5 have a single connection to the network (i.e., line 16-19). Therefore, to prevent islanding condition after replacing the HVDC system, an AC line between buses 19 and 23 has been added to the network.

According to the results of Table (4), the use of HVDC line has improved CCT minimum 13%, maximum 80%, and averagely 30%. For generators No. 4 and 5, if the no AC line is added between buses 19 and 23, after establishing the HVDC system, the stability of these two isolated generators is significantly increased so that the CCT become 1450 and 1500 milliseconds for generator No. 4 and No. 5, respectively.

Table 4. Comparison of CCT increasing for two-terminal HVDC system placement

Generator #	Fault location Bus #	Network condition	CCT [ms]	CCT improvement (compared to	Ig index[%]
2	31	without HVDC (Base case)	680	-	37%
		HVDC Replacement in line 5-6	870	28%	
		HVDC Replacement in line 6-7	1000	47%	
		HVDC Replacement in line 6-11	930	36%	
3	32	without HVDC (Base case)	600	-	27.5 %
		HVDC Replacement in line 10-11	750	25%	
		HVDC Replacement in line 10-13	780	30%	
4	33	without HVDC addition of an AC line between bus 19 and 23 (base case)	220	-	13%
		HVDC Replacement in line 16-19	250	13%	
5	34	without HVDC addition of an AC line between bus 19 and 23 (base case)	220	-	18%
		HVDC Replacement in line 16-19	260	18%	
6	35	without HVDC (base case)	800	-	19%
		HVDC Replacement in line 21-22	900	13%	
		HVDC Replacement in line 22-23	1000	25%	
7	36	without HVDC (Base case)	600	-	32.5 %
		HVDC Replacement in line 22-23	750	25%	
		HVDC Replacement in line 23-24	840	40%	
8	37	without HVDC (Base case)	160	-	16%
		HVDC Replacement in line 2-25	180	13%	
		HVDC Replacement in line 25-26	190	19%	
9	38	without HVDC (Base case)	200	-	77.5 %
		HVDC Replacement in line 26-29	350	75%	
		HVDC Replacement in line 28-29	360	80%	

4.2. Three-terminal HVDC installation

In this section, VSC-HVDC lines are replaced by two AC lines. For this study, simulations are performed for two sample generators with the highest and lowest CCT before HVDC installation, i.e., generators No. 8 and 9. Table 5 shows the CCT results for single-line and double-line HVDC placement of these generators.

Table 5. Comparison of CCT increasing for three-terminal HVDC system placement

Generator #	Fault location Bus #	Network condition	CCT [ms]	CCT improvement
8	37	without HVDC (Base case)	160	-
		HVDC Replacement in line 2-25	180	13%
		HVDC Replacement in line 25-26	190	19%
		HVDC Replacement in lines 2-25 and 25-26 together	270	69%
9	38	without HVDC (Base case)	200	-
		HVDC Replacement in line 26-29	350	75%
		HVDC Replacement in line 24-29	360	80%
		HVDC Replacement in lines 26-29 and 24-29 together	550	175%

Figure (8) shows the HVDC replaced with lines 26-29 and 24-29 of the network

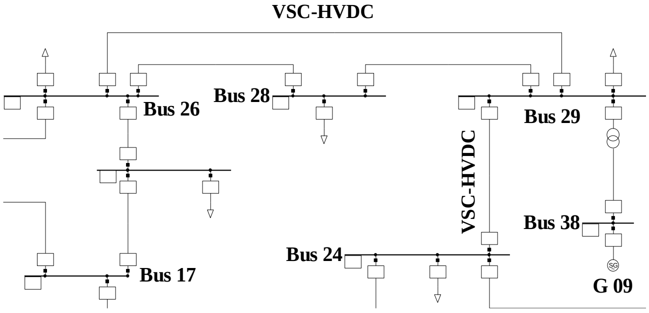


Fig 8. Replacement of lines 26-29 and 24-29 with HVDC line

Figure (9) shows a comparison of rotor angle variations for different scenarios of Generator No.9. The fault is applied in second one and cleared after 200 milliseconds. According to this Figure, the use of VSC-HVDC improves system stability, especially in the form of three-terminal type (dash yellow curve).

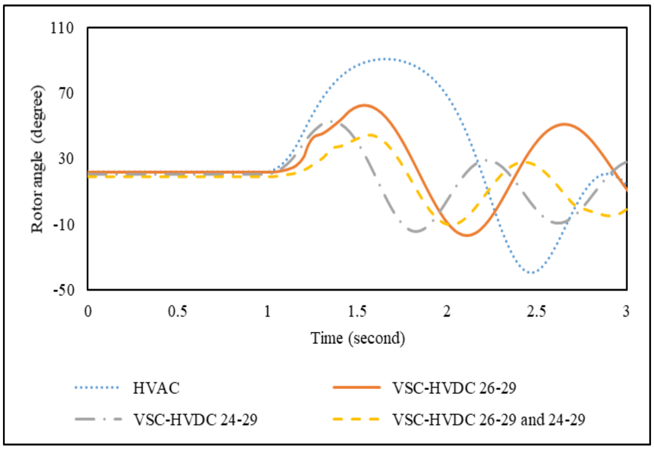


Fig 9. Rotor angle of Generator No. 9 for Table (6) scenarios

4.3. Optimal placement of VSC-HVDC system

In order to improve the transient stability of generators, VSC-HVDC systems are connected to the generator bus. For choosing the most suitable generator and transmission line to replace with a VSC-HVDC system, two steps should follow, as shown in flowchart of Figure (10):

1-Identifying the critical machine by the generator selection index (Ig introduced in section 3.1) .

2-Identifying the effective line by the line selection index (I_l introduced in section 3.2).

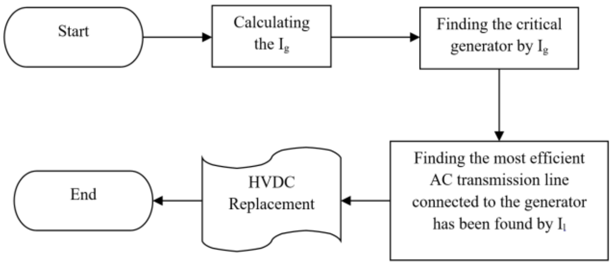


Fig 10. Flowchart of optimal placement of VSC-HVDC system

In this part, the presented criteria in section 3 are evaluated with simulation studies. The results for all generators and corresponding lines are shown in Table (6). According to the results, generator number 9 has the highest Ig coefficient among other generators and maximum CCT improvement. The minimum passing reactive power of this generator pass from line 28-29 and also has a better CCT improvement percentage. Therefore, replacing this line with the HVDC system is the best option.

Table 6. Comparison between proposed criteria and simulation results

Generator #	Ig index [%]	connected Lines	I_l index [MVAR]	CCT improvement [%]
9	77.5	28-29	140	80
		26-29	162	75
2	37	6-7	50	47
		6-11	110	36
		5-6	170	28
7	32.5	23-24	120	40
		22-23	275	25
3	27.5	10-13	44	30
		10-11	120	25
6	19	22-23	270	25
		21-22	305	13
5	18	16-19	560	18
8	16	25-26	270	19
		2-25	870	13
4	13	16-19	60	13

4.4. Comparison with previous works

This article can be comparable to literature works from three points of view, as follow:

1- A large-scale power network has been used in this paper with more simulation studies to evaluate the results, compared to references [17, 18, 19, 20, 21] that use a small test system.

2- This paper reaches to better stability improvement results. For example, in the best case of the reference [21], the CCT is improved 17% (53 milliseconds).While, we can increase the CCT about 80% (160 milliseconds).

3- In all above-mentioned references, optimal placement of HVDC has not been proposed and its location is considered as an assumption. In contrast, this paper introduces a conceptual criterion for HVDC location in power system from transient stability perspective. This is the most s advantage of this paper over other works.

4- In this article, also, an effective controller is proposed, which has a high impact on the stability of the generator.

5. Conclusion

In this paper, the effect of the VSC-HVDC transmission system on transient stability was investigated. The used HVDC control system contains two different logics for controlling the network and the generator sides. By performing various simulations in different scenarios, the effect of the HVDC was investigated as two- and three-terminal systems. In the most encouraging results, the HVDC system increased the CCT up to 80% and 175% in single-line and two-line HVDC replacement cases, respectively. Also, in this paper, a novel criterion for optimal placement of the HVDC system is proposed by Ig and I_l indexes. The comparison between proposed indexes and the obtained results from simulations cases showed that these indices can used for optimal HVDC location with appropriate approximations.

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