Inertia Emulation Control of VSC-HVDC Transmission System

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The increasing penetration of power electronics interfaced renewable generation (e.g. offshore wind) has been leading to a reduction in conventional synchronous-machine based generation. Most converter-interfaced energy sources do not contribute to the overall power system inertia; and therefore cannot support the system during system transients and disturbances. It is therefore desirable that voltage-source-converter (VSC) based high voltage direct current (HVDC) interfaces, which play an important role in delivery of renewable power to AC systems, could contribute a virtual inertia and provide AC grid frequency support.

In this paper, an inertia emulation control (IEC) system is proposed that allows VSC-HVDC system to perform an inertial response in a similar fashion to synchronous machines (SM), by exercising the electro-static energy stored in DC shunt capacitors of the HVDC system. The proposed IEC scheme has been implemented in simulations and its performance is evaluated using Matlab/Simulink.

Inertia emulation, shunt Capacitor, HVDC, VSC, Power systems, Stability

1 Introduction

Increasing energy consumption and concerns over environmental issues associated with fossil-fuelled power generation have been leading to an intensive focus on renewable energy development. It is anticipated that there will be an approximate boost of 26.6 GW in aggregate generation capacity over the period from 2009/10 winter peak to 2016/17 winter peak in the Great Britain, 11.7 GW of which will be contributed by wind power [1].

For the majority of power electronics interfaced renewable power generations (e.g. wind power, photovoltaic, tidal), power converters decouple the electrical power from the mechanical system (they possess a characteristic of $dP/d\delta=0$) and inherently plays the role of power sources without “inertia”, just like a vehicle travelling down a hill without engine braking. Ref. [2] and [3] suggests that doubly fed induction generator (DFIG) and full converter wind turbine generator (FCWTG) has minimal inertia as seen by the system respectively. Therefore, increasing wind power penetration could reduce the system inertia and affect frequency response by its conventional control mechanisms. Ref. [4] shows that there has been a considerably declining trend of effective inertia on the eastern interconnector in the United States over a period of more than 10 years, based on measured frequency transients relating to a number of system disturbances that were experienced over the period of analysis. Consequently, power system frequency control may be

eroded and costly, fast-acting, synchronous spinning reserve and/or other enhanced frequency response measures (for example, using relatively more frequency-responsive types of prime movers for synchronous generators) may be required. There is a clear desire for renewable power generations to be able to contribute to system inertia and frequency response through enabling its control system to mimic synchronous machine response.

On the other hand, in terms of renewable power transmission, the VSC-HVDC converter stations, which integrate offshore wind farms with the onshore grids, do not contribute inertia to the connected power system. Even there is supporting kinetic energy stored in large rotating electrical machines available at the other end of the HVDC system, the VSC stations inherently decouples the available kinetic energy from one AC system to another. Ref. [5] proposes a coordination control strategy for wind farms with line-commutated-converter (LCC) based HVDC to participate in inertial response. However, as [2] and [3] confirm that DFIG and FCWTG are inertia-less wind power generators by their conventional control, regarding to disturbance ride-through capability, it is not favorable to dictate “weak” wind farm power systems to quickly draw on the kinetic power primarily stored in the turbine blades, which may arise severe problems for the wind farm (e.g. the risk for the wind turbine blades to stall [6]).

To address these issues, an inertia emulation control (IEC) system for VSC-HVDC is proposed in this paper. The proposed IEC utilizes the electro-static energy stored in the

HVDC DC shunt capacitors in order to damp AC-side low-frequency oscillations at the point of common coupling (PCC) following large network disturbances. Provision of the IEC is achievable with minimum violation to the basic “power transmission” function of HVDC. The performance of the proposed IEC scheme is evaluated under a temporary loss of main event.

2 Synchronous machine inertia

Figure 1 Interaction between interconnected synchronous machines

In Figure 1, there are two synchronous machines (SM) interconnected by highly inductive transmission line with reactance of X . J_1 and J_2 represent moment of inertias of the synchronous machines SM_1 (generating mode) and SM_2 (motoring mode). Assuming that both machines operate at steady state, the active power transfer from SM_1 to SM_2 is given by equation (1):

$$P = \frac{E_1 E_2 \sin(\delta)}{X} \quad (1)$$

$$\frac{d\delta}{dt} = \omega_r - \omega_s \quad (2)$$

A transient increase in the input mechanical torque T_{M1} supplied by prime mover to SM_1 will cause its mechanical rotor angle advancing relative to that of SM_2 , resulting in rotor angular speed ω_r acceleration according to swing equations in Figure 1. Consequently, the voltage angle between two emfs E_1 and E_2 will increase based on equation (2), leading to a transient rise in active power transfer from SM_1 to SM_2 . The increased power transfer brings the motor SM_2 an increased electrical torque T_{E2} , which further interacts with SM_2 's mechanical torque T_{M2} to accelerate its rotor angular speed ω_2 .

This interacting cycle between SM_1 and SM_2 is accomplished almost instantly, but propagated backward and forward oscillations with impaired momentums typically take a few power cycles to settle. The speed deviation rates of SM_1 and SM_2 are determined by the individual moment of inertia J_1 and J_2 of all rotating masses attached to the shaft [7], shown in Figure 1.

In a larger interconnected power system, all electrical machines are electrically synchronized, and any power mismatch or disturbance creates power oscillations among all the machines, which will be ultimately shared by the

mechanical inertia of the rotating machines attached to that system. Ref. [7] defines a fictitious “inertial center” for a large-scale power system, that has an mean angular speed $\bar{\omega}$ for all electrical machines in a power system, and derives the following equation:

$$\frac{d\bar{\omega}}{dt} = -\frac{\Delta P}{2\Sigma H} \quad (3)$$

Equation (3) indicates that for a certain power imbalance ΔP between generation and load, the aggregate inertia ΣH of a power system determines the mean rate of angular speed deviation. Apparently, higher aggregate inertia confirms an overall stability of the power system by restricting machine angular speed deviations when subject to any disturbance. Ref. [8] investigates the effect of various individual SM inertia constants on the transient stability of the other machine, and conducts a comprehensive understanding on SM inertia mechanisms.

Back to the VSC-HVDC transmission system, the considerable energy storage capability of DC shunt capacitors can be exploited to allow the HVDC converter to respond to low frequency oscillations in a similar manner as SM with mechanical inertia. In next sections, the characteristic of the shunt capacitors, the selection for the capacitance to facilitate the proposed IEC will be demonstrated.

3 Conventional VSC-HVDC vector control

A. Inner current controller

The conventional control system for a VSC-HVDC is well documented in [9]. A synchronous d - q reference frame rotating at the system angular frequency ω facilitates the VSC control functionality by transforming three-phase voltages and currents at PCC to d - q vectors v_d and v_q , i_d and i_q through Park Transformation [10] in equations (4) and (5):

$$v_{dq} = v_d + jv_q = \frac{2}{3} j e^{-j\omega t} (v_a + e^{j\frac{2}{3}\pi} v_b + e^{-j\frac{2}{3}\pi} v_c) \quad (4)$$

$$i_{dq} = i_d + ji_q = \frac{2}{3} j e^{-j\omega t} (i_a + e^{j\frac{2}{3}\pi} i_b + e^{-j\frac{2}{3}\pi} i_c) \quad (5)$$

At steady state, as d -axis reference frame is aligned with one of three voltage phases at PCC, v_d represents three-phase voltage magnitude, while v_q is equal to zero. In order to control the current vector i_d and i_q through the converter PCC, converter voltage vectors v_{d_conv} and v_{q_conv} are continuously updated by equation (6) to generate required switching pulses for the required voltage waveforms at converter side, as shown in Figure 2.

$$\begin{bmatrix} v_{d_conv} \\ v_{q_conv} \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega L \begin{bmatrix} i_q \\ -i_d \end{bmatrix} + \begin{bmatrix} v_d \\ 0 \end{bmatrix} \quad (6)$$

Figure 2 VSC-HVDC configuration (* represents reference)

B. Outer controllers

The outer controllers of VSC-HVDC can provide several different control modes for VSC stations depending on specific operating requirement. Two straightforward modes are independent PCC active (P) and reactive power (Q) control, which function based on the following equations:

$$P = \frac{2}{3} v_d i_d \quad (7)$$

$$Q = \frac{2}{3} v_d i_q \quad (8)$$

The active power flow in the DC system must be balanced, so that one of VSC station equipped with DC voltage controller has to control the DC voltage by adjusting PCC current vector reference i_d^* . The AC voltage at the PCC is regulated by the AC voltage controller to modulate the reactive power at the PCC. For example, to transmit offshore wind power to onshore AC grid, the VSC rectifier at wind farm side should apply an active power controller varying with wind generation to maximize power transfer and an AC voltage controller, while the VSC inverter at AC grid side can utilize a DC voltage controller and AC voltage controller, as shown in Figure 2.

Four types of outer controllers in the VSC station control system: active power controller, reactive power controller, AC voltage controller and DC voltage controller are illustrated in Figure 3.

Figure 3 HVDC outer controllers (a) first: active power; second: DC voltage. (b) first: reactive power; second: AC voltage.

4 HVDC inertia emulation control

This section proposes an inertia emulation control (IEC) for the HVDC VSC stations. If DC shunt capacitors, is sufficiently large, the stored energy is available for provision of considerable damping support to the AC grid using inertia emulation. The additional energy can be obtained dynamically by varying HVDC DC link voltage using DC voltage controller in order to suppress the power oscillations. This can be achieved with DC shunt capacitors to release or absorb the excessive energy to the AC grid, without violating the normal HVDC operationability.

A. Machine inertia constant vs Capacitor time constant

In physics, “inertia” is defined as amount of resistance to change in velocity. For an SM, all the rotating masses attached to the shaft is quantified by an inertia time constant H in seconds, which corresponds to the period that it takes to accelerate from zero to rated speed ω using full rated power S_M , is given:

$$H = \frac{W_K}{S_M} = \frac{\frac{1}{2} J \omega^2}{S_M} \quad (9)$$

Where W_K represents kinetic energy stored in the rotating mass of the electrical machine, and J refers to the moment of inertia.

Capacitor driven applications are used in industry for many purposes such as power quality improvement, including static synchronous compensator for reactive power compensation, active power filtering and voltage imbalance correction [11]). With a controlled VSC, the size of the DC capacitors is characterized by a capacitor time constant τ , which similarly refers to the period needed to charge the capacitor from zero to rated voltage V_{dc} using rated power supply S_{VSC} , given in equation (10):

$$\tau = \frac{W_E}{S_{VSC}} = \frac{\frac{1}{2}CV_{dc}^2}{S_{VSC}} \quad (10)$$

Where W_E represents the electro-static energy stored in the capacitor, and C is the capacitance.

From energy point of view in equation (8) and equation (9), DC capacitors possess the inertia nature of electrical machines, as long as the energy stored in the capacitor can be temporarily exercised by the VSC.

B. Shunt capacitance and emulated inertia constant

In terms of the relation between machine speed deviation and power mismatch, the well-know equation of machine motion is given in equation (11):

$$\frac{2H}{f} \cdot \frac{df}{dt} = P_M - P_E = \Delta P_1 \quad (p.u.) \quad (11)$$

Where H is the inertia time constant, P_M is the mechanical power, P_E is the electrical power and ΔP_1 is the kinetic power stored or released in the machine rotating mass.

In order to facilitate the IEC design, similarly with the equation (11) of electrical machine motion, DC shunt capacitors placed in the HVDC network, also has an equation on apparent power variation in line with DC voltage variation:

$$\frac{NCV_{dc}}{S_{VSC}} \cdot \frac{dV_{dc}}{dt} = P_{in} - P_{out} = \Delta P_2 \quad (p.u.) \quad (12)$$

Where N represents the number of shunt capacitors in total (in the example of Figure 2, there are 4 capacitors in total for three-level neutral-point clamped VSCs, therefore $N=4$), P_{in} is the power input to all the capacitors and P_{out} is the power output, and ΔP_2 is the electro-static power stored or released in all the capacitors.

From equation (12), it can be seen that if the DC network voltage V_{dc} is effectively allowed to vary, there will be extra power dynamically changed in all the capacitors. Due to the low resistance of the DC cables, the DC voltage difference between the rectifier and inverter is tiny (normally a few kilovolts). For this reason, the DC voltages at the rectifier and inverter are regarded as an identical value, which is controlled by the DC voltage controller by the inverter control, shown in red in Figure 2.

To assign the HVDC system a virtual inertia, the “virtual” machine power variation ΔP_1 based on the specific requirement on inertia design in equation (13), should be equal to the shunt capacitor power variation ΔP_2 , giving equation (13):

$$\frac{2H}{f} \cdot \frac{df}{dt} = \frac{NCV_{dc}}{S_{VSC}} \cdot \frac{dV_{dc}}{dt} \quad (13)$$

The dt terms on both sides of equation (13) are omitted, and integrations for df and dV_{dc} are processed on both side. This gives equation (14) and (15):

$$\int \frac{2H}{f} \cdot df = \int \frac{NCV_{dc}}{S_{VSC}} \cdot dV_{dc} \quad (14)$$

$$2H \cdot \ln(f) = \frac{NCV_{dc}^2}{2S_{VSC}} \quad (15)$$

Therefore, the equation (15) is transformed to another format in equation (16), which is the basic principle of the IEC design:

$$H_{VSC} = \frac{NCV_{dc}^2}{4S_{VSC} \ln(f)} \quad (16)$$

Equation (16) demonstrates the HVDC converter inertia is determined by the number and capacitance of DC shunt capacitors, the nominal DC voltage and the converter rated power. Another way to say, for a given capacitance, the DC voltage level of the HVDC system should have a direct but non-linear correlation with the grid frequency, in order to achieve inertia emulation.

Equation (16) eliminates both of differential terms in equation (11) on system frequency deviation rate and equation (12) on DC voltage variation rate. This avoids of processing the differential property of frequency at the inverter PCC. The benefit will be demonstrated in the section C.

C. VSC Inertia emulation control loop

As demonstrated in the section B, in order to assign an specific inertial response to the VSC-HVDC system, equation (16) is transformed to another format to link the system frequency f_{grid} at the inverter PCC, with the DC voltage reference V_{dc}^* , shown in equation (17):

$$V_{dc}^* = \sqrt{\frac{4H_{VSC}S_{VSC} \ln(f)}{NC}} \quad (17)$$

The inertia emulation loop is designed in the VSC-HVDC inverter control system, shown in Figure 4:

Figure 4 Inertia emulation control loop

The real-time frequency, which is estimated by the phase-locked loop (PLL), acts as the input to be processed by log calculation, a specific gain, and square root calculation, based on equation (14). The calculated DC voltage reference is limited within upper and lower constraints in case the DC voltage exceeds the cable and capacitor rating or violates the converter functionality. The DC voltage controller in the inverter control shown in Figure 2 and Figure 3 will fast act to adjust the DC voltage level to the reference.

The IEC loop avoids of processing a differential term of grid frequency which may be problematic for converter op-

eration (e.g the differential term of a PID controller may cause a large output “kick” in response of a sudden input change [12]). The performance of the HVDC IEC is evaluated in next section.

5 Simulation evaluation

As shown in Figure 1, a back-to-back VSC-HVDC system is simulated in Matlab using SimPowerSystems. The parameters are listed in Table 1. As the effect of emulated inertia by the HVDC system is apparent in a low-inertia power system, the test power system is configured as one a synchronous generator with IEEE benchmark parameters [7] listed in Table 2, one passive load and 2000-MVA equivalent large power system, as shown in right hand side of Figure 2. The large power system will be disconnected for a short period to simulate a temporary loss of main event.

Table 1 Parameters for the VSC-HVDC system

Item	Value
Rated VSC power S_{VSC}	270 MW
Rated AC voltage V_{Rec}	100 kV
Rated AC voltage V_{Inv}	100 kV
Nominal DC voltage V_{dc}	± 100 kV
Reactor inductance L_v	0.15 pu
Reactor resistance R_v	0.005 pu
DC capacitor C_{dc}	105.6 mF
Switching frequency f_{sw}	1350 Hz

Table 2 Parameters for the synchronous generator and passive load

Item	Value
Rated MVA S_g	270 MW
Terminal Voltage V_g	18 kV
Load angle $\cos \delta_g$	0.75
x_d, x_d', x_d''	1.700, 0.256, 0.185
x_q, x_q', x_l	1.620, 0.245, 0.147
τ_d, τ_d', τ_q	4.800, 0.0437, 0.141
Governor delay τ_{gov}	0.1 s
Governor delay τ_{gov}	0.1 s
Load active power	550 MW
Load reactive power	100 MVar

The synchronous generator connects to the common 230kV transmission network by an 18kV-230kV step-up transformer, while the HVDC system connects the network by a 100kV-230kV step-up transformer. The large power system and passive load are directly coupled with the transmission network.

Based on equation (16), the emulated inertia constant $H_{VSC}=1$ s of the HVDC system, with rated apparent power of $S_{VSC}=270$ MW and the nominal DC voltage of $V_{dc}=\pm 100$ kV requires the capacitance of $C=105.6$ mF for each four capacitors, shown in red in Figure 2. This capacitance may be

relatively large for energy storage, compared with the typical capacitance value of VSC-HVDC shunt capacitors. However, in order to show apparently the effect of the proposed IEC, this large capacitance is adopted (a smaller capacitance will consequently emulate a smaller inertia constant).

Both of the VSC-HVDC and the synchronous generator feed the passive load an active power of 400 MW in total, while the large power system feeds an active power of 150 MW to the load. At $t=1$ s, a loss of main event is initiated by a temporary disconnection of the large power system for 200ms. The power oscillations in the network with and without the HVDC IEC are compared in Figure 5 through-out Figure 7.

Figure 5 Comparison on SM rotor speed

Figure 6 Comparison on inverter output active power

Figure 7 Comparison on DC voltage and Capacitor net power

It can be observed in Figure 5 that both SM rotor speed and the frequency at the inverter PCC vary less with the proposed IEC of the HVDC system than those with the con-

ventional control. As it is expected, the generator rotor with the HVDC IEC experiences variations with smaller amplitudes, and the frequency with the IEC drops less and restores faster than the frequency without. As the HVDC inertia with the IEC contributes the emulated inertia $H=1s$, this extra inertia effectively restricts the SM rotor speed deviation and frequency decrease.

The simulation results on SM rotor speed and the inverter PCC frequency imply that though the IEC, the emulated "inertia" by the VSC system is able to interact with the SM and act to counter-balance the momentum (trend) of rotor speed and frequency deviations.

During the temporary loss of main from $t=1s$ to $t=1.2s$, there is a power shortage in the islanded power system, and the SM rotor suffers a sudden stall in the speed to release the kinetic power from the rotor. The amount of released kinetic power is critical for system stability as the SM may fall out of step (lose synchronization with the large power system). The inverter active power responses with and without the IEC are shown in the first diagram of Figure 6.

The inverter with conventional control has its active power output slightly drop and restore to the original value around $P_{vsc}=195$ MW. This phenomenon is coincident with the former discussion in section 1 that HVDC inverter does not contribute any inertia and just like a vehicle travelling down a hill without engine breaking in any event (except severe AC voltage depression), passively responding to the power islanding disturbance.

With the IEC, at the initiation of the loss of main event, the HVDC inverter quickly output an excessive active power, similarly as the generator release the kinetic energy stored in its rotating masses. This partition of inverter power output sources solely from the DC shunt capacitors by the IEC to vary the DC voltage level, without affecting the rectifier transfer active power, shown in the second diagram of Figure 6.

The correlation between DC voltage and net power stored in the DC capacitors is illustrated in Figure 7, which shows the post transients after the temporary loss of main. During the period from $t=1.3s$ to $2s$, with the positive trend of DC voltage deviation, the stored apparent power flowing into the capacitors is releasing, and vice versus. It is also observed from Figure 8 that by varying less than 0.2 kV of the DC voltage, approximate 40 MVA of capacitor instantaneous power can be employed by the IEC in response to the loss of main event, with the calculated capacitance of 105.6 mF.

6 Conclusion

To cope with the increasingly reduced power system inertia due to the fast development of renewable power generation and transmission, this paper proposes a novel inertia emulation control (IEC) for VSC-HVDC transmission sys-

tem that may enable the HVDC system to provide damping support to AC networks similarly as conventional power plants with mechanical inertia. It has been shown that the emulated inertia H_{vsc} of the HVDC, with fixed rated apparent power S_{vsc} and DC voltage V_{dc} is solely determined by the capacitance of DC shunt capacitors. The proposed IEC essentially functions by varying the DC voltage to dynamically control the electro-static energy in the capacitors.

The performance of the proposed IEC is evaluated using simulations, and comparisons are made with respect to the conventional VSC-HVDC control. Simulation results show that VSC-HVDC system with the IEC provides an excellent damping effect on the temporary power-islanding event in terms of restricting the SM rotor speed variation and grid frequency dropping in an inertia-less power system. Future work needs to be taken is to examine the feasibility of the IEC implementation in practice, considering the limitations of the converter power rating and capacitor size.

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