Study of the Inertia Support Potential From HVDC Cables in Power Systems With High Renewable Energy Source Penetration

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ABSTRACT Stimulated from the de-carbonization targets which was set up by governments worldwide, more and more conventional generation has been decommissioned. Lack of power system inertia support has gradually emerged as a major challenge for system operators around the world. It is especially the case for weak power systems with higher renewable energy source penetration. Existing research in providing inertial support relies on the installation of super capacitors onto the existing high voltage direct current (HVDC) systems. This technique imposes additional cost and reliability concerns. This article proposed a novel strategy which unlocked the potential from HVDC cables to provide inertia support. A comprehensive feasibility study has been performed on a prototype system in which the dynamic frequency response is analyzed. The results showed that for a feasible control strategy, the released energy from HVDC cables is sufficient to replace the vast majority of synchronous machines within a typical power system. This demonstrated the feasibility of utilizing existing HVDC cables for inertia support which significantly reduces the economic costs and improves the power system transient stability.

INDEX TERMS HVDC cables, high renewable energy source penetration, inertia support potential.

I. INTRODUCTION

The energy system worldwide is transforming rapidly towards the trends of decarbonization and decentralization, which influenced how we generate, transmit and consume electricity every day. Major countries have set up achievable targets for decarbonization. The UK government has committed to strengthen its objective from ‘80\% reduction in CO\textsubscript{2} from 1990 levels’ to ‘net zero’ with a completion date in 2050. This requires the electricity system to operate at zero-carbon emission [1] by 2050. China is at the beginning of an energy transition with the aim of building a sustainable energy system for the future. With the key milestones set up at 2030 and 2060, China has planned to develop a ‘clean, low carbon, safe and efficient energy system’ in the coming decades. In the US Greenhouse Gas (GHG) reduction goals are achieved through the Renewable Portfolio Standard (RPS), which has been enacted by 29 states [2]. For instance, California increased its RPS target to 60\% by 2030 and mandated a 100\% clean target by 2015 [3]. The EU planned to significantly reduce its dependency on energy imports, as well as to invest on disruptive innovations for decarbonization [4]. All these ambitious targets require large scale commissioning of renewable energy sources such as wind or photovoltaic (PV).

Replacing synchronous generators with wind turbines or PVs reduces the inertia of power systems. Traditional grids rely on synchronous generators to provide bulk system inertia and participate in frequency regulations. When fault occurs, the kinetic energy stored within the synchronous generators (known as inertia) is released to compensate the imbalance between generation and demand. This prevents the frequency to fall (or rise) rapidly beyond its statutory limit. With the increased level of renewable energy source (RES) penetration, synchronous generators are gradually decommissioned,
which results in reduced fault levels and lower system inertia. The ability of power system to cope with large or small disturbance is thereby weakened. Various research work has been focused on improving the grid inertia level through super capacitors and advanced control methods.

In this article, a novel method which utilizes existing HVDC cables to provide inertia support is proposed. The key concept is to alter the energy stored within HVDC cables to maintain the system frequency when disturbance initiated. Acting as an energy storage device or capacitor bank, HVDC cable can replace synchronous machines to provide inertia support (shown in Figure 1). Utilizing the capacitance effect, cables release energy when frequency drops while absorbing energy when it rises.

To evaluate the maximum energy stored within the HVDC cable and the characteristics when releasing it, a distributed parameter physical simulation model is built. Since the stored energy is proportional to the terminal voltage squared, reducing the cable terminal voltage can release energy into the power system while increasing it will result the opposite. The inertia support mimic synchronous machine is achieved through transient process when altering the terminal voltages on HVDC cables. Assuming the maximum output can be reached, the amount of HVDC cables required to replace the traditional synchronous motor in a typical power grid is determined. This assessment demonstrated the potential energy stored within HVDC cables under normal operational conditions.

Then a cost calculation has been carried out to compare the above mentioned three methods for inertia support (super capacitors and HVDC cables). The distinction of HVDC cables on both cost and reliability is verified.

To perform this on actual power system, a scaled-down system prototype consists of 10 machines and 2 zones was established according to the National Grid published data [5] on Great Britain electricity network. The wind power penetration rate is varied from 10% to 70% (with 10% step) by changing the type of generator in the model, which accounts for the decarbonization process in the coming decades. Under the ideal condition that the cable voltage drops fast enough, the simulation is carried out in the system with and without the equivalent inertia support from the cable, and the characteristics of the frequency transient change are analyzed. It is concluded that for a feasible control strategy, the released energy from HVDC cables is enough to replace the clear majority of synchronous machines within a typical power system.

Operational experience shown the main constraint for integrating more RES is lack of system inertia. Techniques proposed in this article solve this critical issue with low cost and high reliability. This article reports disruptive innovation for decarbonizing power system and facilitates net zero targets set by the twenty-sixth session of the Conference of the Parties (COP 26) to the UNFCCC (United Nations Framework Convention on Climate Change) MMC. It has the potential to produce significant social and economic benefits. The feasibility of utilizing existing HVDC cables for inertia support which significantly reduces the economic costs and improves the system reliabilities. It will increase the stability of power systems with higher renewable energy source penetration. It is believed that the findings of this study are close related to the scope of the journal and will gain great credits from a large number of audiences.

II. EXISTING INERTIA SUPPORT METHODS FOR GRIDS

Inertia plays a key role in handling frequency disturbances within power systems. The power grid is evolving to integrate more and more RES, mainly wind and solar, which do not consist mechanical inertia. In the context of large-scale connection of RES, the low inertia features weakened the robustness of the power system and its ability to recover frequency from disturbances [6]. Intensive research work has been focused on improving the system inertia levels with various proposals. According to their mechanisms, the existing inertia support methods can be divided into two catalogues: rotating machines and power electronics devices.

A. INERTIA SUPPORT BASED ON ROTATING MACHINE

As a conventional generator, the traditional thermal power unit can supply electricity to the grid as well as provide inertia support. To achieve the same, large-scale energy storage equipment is widely utilized [7], with mechanical energy storage capacities of up to 100 MW from compressed air energy storage (CAES) devices [8], [9] and pumped-hydro (PHS) plants [10]. Like thermal units, the energy stored in the CAES and PHS can be used to drive synchronous generators for providing inertia support. In addition to these, synchronous compensator (SC) [11]–[13], as a rotating equipment, can store kinetic energy when spinning. Although a SC does not generate active power, it is able to release rotational kinetic energy to support system inertia in the event of sudden loss of generation. The existing methods to support power system inertia are summarized in Table 1.

B. INERTIA SUPPORT BASED ON VIRTUAL SYNCHRONOUS MACHINE

Virtual Synchronous Machines (VSM) are mainly used for the centralized grid connection of large-scale new energy
The key advantages of this methodology are listed below:

- the control algorithm can be designed to damp the frequency disturbances when power system is subject to contingencies.

Although the existing methods provide inertia support in some extent, they require significant investment on hardware and equipment which is not cost effective. Other key disadvantage is the needs of large amount of power electronic devices and super capacitors whose reliability is not adequate. In contrast of this, an innovative technique is brought into consideration to utilize the energy stored within the HVDC cables for inertia support. This method does not introduce additional equipment which resolve both the economic and reliability issues. It is also able to boost its inertia support capacity in the future with large-scale HVDC cables being laid.

### D. INERTIA SUPPORT BASED ON HVDC CABLES

High voltage direct current (HVDC) transmission is a common method of transmitting large amounts of renewable energy generation over long distances. However, as HVDC transmission does not have an inherent inertial response, it can pose a significant challenge to the frequency control of the connected grid. In VSC-based HVDC transmission, there are two possible sources of energy, one being the inherent energy storage capacity of the modular multilevel converter (MMC) [25], [26], and the second is the energy stored by the capacitive effect of the HVDC line itself [27].

The first type of approach proposes an integrated inertia control method for different MMC-HVDC systems: a coordinated control that integrates the capacitive energy of the MMC-HVDC sub-module and the overspeed reserve capacity of the wind turbine when the frequency drops significantly. The second type of method is the focus of this paper. Reference [27] uses a full or half bridge converter based MMC to extract energy from the HVDC cable to provide additional active power to the AC system. The literature argues that the increased costs are disproportionate to the benefits reaped when the dc voltage drop is kept small (around 10%).

To keep the active power constant, the cable current will increase accordingly when operating at reduced voltage.

### C. INERTIA SUPPORT BASED ON SUPER CAPACITOR

A large portion of existing work was focused on installing parallel capacitors on the grid-side of the voltage source converter based high voltage direct current transmission (VSC-HVDC) station to provide inertia support [22]–[24]. Virtual inertia control using capacitor bank to mimic synchronous machine meets the essential needs for frequency regulation. The key advantages of this methodology are listed below:

- the specified capacitance is capable to represent the inertia constant H of a typical synchronous machine;
- the control algorithm does not malfunction under high df/dr noise;

### TABLE 1. Methods to support grid inertia.

| Inertia       | Equipment | H/S | Rated capacity | Geographical constraints | Additional regulatory | Black start |
|---------------|-----------|-----|----------------|--------------------------|-----------------------|-------------|
| Kinetic inertia | SC       | 2-3 | MVA            | -                        | √                     | ×           |
|                | CAES      | 3-4 | MW             | Space                    | √                     | √           |
|                | PHV       | 2-4 | MW             | Topography               | √                     | √           |
| RES units      |           |     |                |                          | √                     | ×           |
| Virtual inertia | VSC-HVDC |    | MW             |                          | √                     | √           |
| Energy storage |           |     |                |                          | √                     | ×           |
| Controllable load |         |     |                |                          | √                     | ×           |
| RES units      |           |     |                |                          | √                     | ×           |
Nevertheless, a large margin is usually left for the power flow in practice (the actual power flow may be only 30% of the nominal value). This means that, provided safety requirements are met, the level of system inertia can be predicted before a fault and the power flow can be strategically controlled in advance, leaving some room for step-down operation. Thus, this paper argues that the energy storage potential of HVDC cables should be exploited to an even greater extent. Calculations and simulations have shown that the enormous amount of energy released is enough to replace most synchronous machines within a typical power system when the cable is operated with more voltage derating.

III. METHODOLOGY
A. CAPACITANCE EFFECT OF HVDC CABLE
The capacitance of a HVDC cable is an intrinsic parameter which determined only by its structure, rather than factors such as the operating conditions etc. When commissioning a new cable with no load, it is energized with HV which is equivalent to a charging process of a capacitor. The charging current decreases continuously and after 5RC (where the time constant RC of the charging process is determined by the structure of the charging circuit), the charging process is completed when the terminal voltage reached its rated value and the current reduced to 0. Thereafter it enters the steady state with no-load condition. The terminal voltage of cable is constant and the energy produced by the charging current is stored within the cable, like store within a capacitor bank. When a major disturbance in the system causes the frequency to drop below the threshold or the fluctuation rate exceeds a certain reference value, the control action triggered to reduce the terminal voltage of cable steeply, therefore the energy stored by the capacitive effect of the cable will be released rapidly to provide considerable inertia support for the power system.

To study the transient response of HVDC cables under system failures or disturbances, it is necessary to establish a detailed Multiphysics model of the cable.

To better represent its transient procedure, instead of calculating from lumped parameters, a distributed parameter model is used. A 2D Finite Element Analysis (FEA) model (shown in Figure 2) is built in COMSOL Multiphysics to determine the HVDC cable’s key parameters, such as characteristic impedance, capacitance etc.

B. FEASIBILITY ANALYSIS OF INERTIA SUPPORT FROM HVDC CABLES
1) ENERGY STORAGE OF 10KM DC CABLE
A 10 km-long cross-linked polyethylene (XLPE) Insulated DC high-voltage cable is selected as an example. The energy released from the cable and feeds back to the AC network when the terminal voltage dropped from 400 kV to 132kV. Instantaneous power for inertia support is computed as:

\[ W_c = \frac{1}{2}C(U_1^2 - U_2^2) \]

\[ = \frac{1}{2} \times 98.142 \times 10^{-12} \times 10 \times 10^3 \times (400^2 - 132^2) \times 10^6 \]
\[ = 69963 \text{ (J)} \]  

In (1) the distribution capacitance value \( C = 98.142 \text{ pF/m}. \)

To compare the energy released from the capacitors with synchronous generators, typical values are calculated for both cases.

The inertia, usually expressed as \( J \) with a unit ‘kg·m²’, is a standard physics term defined in various international standards. In engineering, the inertia of motor is usually expressed as ‘GD²’. The relationship between these two is:

\[ J = \frac{1}{4}GD^2 \]  

For synchronous generators, since pole pairs \( p \) can vary, the angular velocity \( \omega \) (rad·s⁻¹) refers to electrical angular velocity is different from the rotor’s mechanical angular velocity \( \Omega \) (rad·s⁻¹). The relationship among mechanical angular velocity \( \Omega \), electrical angular velocity \( \omega \), and stator current frequency \( f \) (Hz, s⁻¹) is shown as:

\[ \omega = p\Omega \]  
\[ f = \frac{np}{60} \]  
\[ \omega = 2\pi f \]  

System frequency \( f \) is either 60 Hz (for US and part of Japan) or 50 Hz (for the rest of the world). The number of polar pair \( p \) varies with different types of synchronous generators. For example, salient pole machines are widely used for hydraulic turbines while cylindrical rotor is dominating steam turbines. To achieve the same electrical angular speed, a quad-pole hydro machine only needs \( n_N = 750 \text{ r/min} \) while a cylindrical steam rotor needs a rotor speed of \( n_N = 3000 \text{ r/min} \).

When the rotor rotates at the rated mechanical angular speed \( \Omega_0 \) (synchronous speed), its rotational kinetic energy (unit: J) can be calculated as:

\[ W_k = \frac{1}{2}J\Omega^2 \]  
\[ J = \frac{2W_k}{\Omega^2} \]
The kinetic energy stored in the rotor of a synchronous generator is expressed as

\[
J \frac{d\Omega}{dt} = \Delta T \tag{8}
\]

At the same time:

\[
\Omega = \frac{\omega}{p} \tag{9}
\]

Take the QF-15-2 steam generator as an example, when the system frequency drops from 50 Hz to 49.8 Hz, the energy released by the its rotor is calculated as following:

\[
J = \frac{1}{4} GD^2 = \frac{1}{4} \times 2100 = 525(\text{kg} \cdot \text{m}^2) \tag{10}
\]

\[
W_k = \frac{1}{2} J \left( \Omega_1^2 - \Omega_2^2 \right) = \frac{1}{2} J \left[ \left( \frac{2\pi f_1}{p} \right)^2 - \left( \frac{2\pi f_1}{p} \right)^2 \right]
\]

\[
= 4375 \times \left[ \left( \frac{2\pi \times 50}{1} \right)^2 - \left( \frac{2\pi \times 49.8}{1} \right)^2 \right]
\]

\[= 206847 (\text{J}) \tag{11}
\]

Comparing (1) and (11), the energy released by reducing a 10 km 400 kV cable’s terminal voltage to 132 kV is approximately 34% of the energy released from a 100 MW synchronous generator when the system frequency reduces by 0.2 Hz.

2) **CALCULATION OF EQUIVALENT INERTIA OF DC CABLE**

The kinetic energy stored in the rotor of a synchronous generator is expressed as

\[
W_k = \int \frac{1}{p^2} J_s \omega d\omega = \frac{1}{2p^2} J_s \omega^2 \tag{12}
\]

Inertial time constant is:

\[
H = \frac{J_s \omega^2}{2S_n} \tag{13}
\]

Energy stored within a HVDC cable is:

\[
W_c = \int C u d\omega \tag{14}
\]

\[
W_c = \int \frac{C u d\omega}{\omega d\omega} p^2 = \int J_{\text{vir}, \text{Cable}} \omega p^2 d\omega \tag{15}
\]

The virtual inertia of the cable can be expressed as:

\[
J_{\text{vir}, \text{Cable}} = \frac{C u \omega}{p^2} \tag{16}
\]

It can be rewritten as (17) in the similar form as the rotational inertia of a synchronous motor.

\[
J_{\text{vir}, \text{Cable}} = \frac{\omega \Delta u}{\omega \Delta \omega} = \frac{p^2 C u \Delta u}{\omega \Delta \omega} \tag{17}
\]

Substituting \( W_k \) (6) and \( W_c \) (14) into (17) to get (18).

\[
J_{\text{vir}, \text{Cable}} = J_s \frac{W_c \Delta W_c / W_c}{2W_k \Delta \omega / \omega} = J_s \frac{k_{\text{Cable}} W_c}{2W_k \Delta \omega / \omega} \tag{18}
\]

where \( k_{\text{Cable}} \) represents ratio between the rate of change of \( W_c \) and the rate of change of the angular velocity of the generator. As shown in (19), \( k_{\text{Cable}} \) is only related to the step-down speed of the voltage, which is dependent to the control circuit but independent to the cable’s intrinsic parameters such as its type or length etc.

\[
k_{\text{Cable}} = \frac{\Delta W_c / W_c}{\Delta \omega / \omega} \tag{19}
\]

Therefore, the equivalent inertia time constant of the HVDC cable is:

\[
H_{\text{Cable}} = \frac{J_{\text{vir}, \text{Cable}} \omega^2}{2S_n} = \frac{J_s k_{\text{Cable}} W_c}{4W_k} \frac{\omega^2}{S_n} \tag{20}
\]

As shown in (20), \( k_{\text{Cable}} \) is the key parameter to measure the HVDC cable’s inertia support capability. It links the speed of voltage variation with the rate of change of the system frequency (RoCoF), and is the key parameter to optimize when designing the control circuits for HVDC cables’ inertial support.

**C. BASIC REQUIREMENTS FOR STEP-DOWN CONTROL CIRCUIT**

The derivation presented in Section 3.1 has provided the theoretical demonstration on providing inertia support for power system through rapid reduction on the terminal voltage of a HVDC cable. HVDC cables are widely utilized in modern power networks, especially for the transmission of offshore wind power. Therefore, through appropriate control circuit to reduce the operating voltage of cables when a frequency dip in the system occurs, the energy stored in cables can be fully utilized for integrated inertia control.

To make full use of the energy stored in DC cables, the cable operating voltage is required to decrease rapidly when the frequency change reaches a certain threshold, thus releasing energy rapidly for inertia support.

The design of step-down control circuit can be inspired from the reduced voltage operation of HVDC transmission projects. By considering the existing control methods in HVDC transmission projects, the simplest and most feasible method is to reduce the operating voltage by increasing the trigger angle \( \alpha \) of the rectifier. Since the DC voltages on the rectifier and inverter side of the converter station is cosine related to its corresponding trigger angle, the control system can increase the \( \alpha \) angle to reduce the DC voltage. This method allows for fast and easy voltage reduction operation.
The above analysis verifies the advantages of HVDC cables in providing system inertia support in an efficient and extensive manner. The actual step-down rate can meet the requirements and therefore the technical solution to provide inertia support for high percentage renewable energy power systems using high voltage DC cables is initially calculated to be feasible. Initially, the basic requirements to be met by the control circuit are presented.

A reduction in the DC side voltage will lead to a reduction in the output AC voltage of the converter, resulting in the converter absorbing a large amount of reactive power from the connected grid, which has an impact on the safe and stable operation of the AC-DC system, so the grid usually does not want the HVDC line to operate at reduced voltage. However, in special cases the reduced voltage operation will provide a large amount of inertial support for the system and the sacrifices made are worthwhile and need to be measured in the specific case. The control scheme of how to correlate the frequency change with the voltage derating rate is subject to further refinement.

IV. ANALYSIS OF INERTIA SUPPORT EFFECT OF HVDC CABLE IN 10-MACHINE 2-AREA TEST SYSTEM

A. 10-MACHINE 2-AREA TEST SYSTEM

This article selects the GB power system as a prototype for inertia analysis. Typical parameters are set up based on the released information from National Grid ESO. The demand and generation of the whole system is assumed to be 60 GW. A loss of 1800 MW generation instantaneously (approximately the largest loss of GB system, 3% of the system capacity) is set as a contingency to study the frequency response. To simplify the simulation, a 10-machine 2-area test system is built to shrink the GB system to its 1/400 (150 MW), within which the renewable generation gradually rises from 10% to 70%. A sudden increase of load (4.5 MW, representing 1800 MW loss in real system) is set as a contingency to study the transient stability. Due to the fact that the RoCoF issue is mainly caused by the high percentage rate of wind generations [28], wind power generation is built within the test simulation to reflect this.

Figure 3 is the single line diagram of our test system. The synchronous generator and DFIG together is 150 MW (representing 60 GW in GB System). The total number of synchronous generators or wind farms is 10 units, each with a capacity of 15 MW. The combination of unit types is variable and here we have considered a total of seven different scenarios. The percentage of wind generation varies from 10% to 70%, with a 10% step. The model shown in Figure 4 is built within Matlab/SimPowerSystems.

The DFIG wind turbine is feeding into the 230 kV transmission network via a 575 V/230 kV generator transformer. The rated power of a single DFIG generator is 15 MW, and the inertia time constant is 0.56 s under conventional control. On the grid side, a 15 MW steam generator with automatic generation control (AGC) and turbine governor is modelled. The electrical part of the motor is represented by a six-order state model. Synchronous generators operate in parallel and are connected to the grid via 18 kV/230 kV generator transformers. Both DFIG turbines and synchronous generators are connected to a 150 MW static load via a 10 km HVDC cable. Wind percentage gradually increases to 70% of the total generation. The proposed 10-machine 2-area test system can evaluate the transient stability characteristics especially when HVDC cables are used for inertia support.

B. TRANSIENT STABILITY SIMULATION OF 10-MACHINE 2-AREA TEST SYSTEM

The transient stability of the proposed model is studied with and without the inertia support provided by the HVDC cables.

1) ANALYSIS OF THE CHARACTERISTICS OF FREQUENCY TRANSIENT WITHOUT SUPPORT

The static load is increased by 2% by adding a 3 MW load at t = 30 s. The inertia time constant of the synchronous motor is $H_{\text{Fossil}} = 3.7$ before the equivalent inertia support of the cable is added and the inertia time constant of the DFIG generator is $H_{\text{DFIG}} = 0.56s$. As shown in Figure 5, after the same magnitude of disturbances, the transient stability gets worse with more wind penetration rates. The frequency fluctuation is described with two key parameters: the maximum frequency drop and the time to return to the new steady state.

2) ANALYSIS OF THE CHARACTERISTICS OF FREQUENCY TRANSIENT CHANGES WITH THE EQUIVALENT INERTIA SUPPORT OF HVDC CABLE

As explained before, the terminal voltage of the HVDC cable is reduced rapidly to release the energy for inertia support. Keeping the rest of the simulation same, but vary the voltage depletion rate, the transient stability is analyzed below.

As shown in Figure 6, a 3 MW load is added at t = 20 s, resulting in an instantaneous 2% increase in static load. With the same magnitude of disturbances, the transient stability worsened with more wind integrated. Comparing the results with simulation without the inertia support, it is observed that increasing the equivalent inertia of the cable achieves a significant reduction of the frequency fluctuation and thereby its system stability is improved.
C. RESULTS AND DISCUSSIONS

To further analyze the effectiveness, Figure 7 describes the frequency recovery after the same magnitude of disturbances with and without the inertia support from the HVDC cable. A clear improvement on the frequency dip (with less frequency drop and lower change rate) is observed with the inertial support.

The system without the equivalent inertia support of the cable reaches a frequency dip of 49.62 Hz at 4.47 s after the disturbance. The frequency dip with the inertial support from HVDC cable is 49.67 Hz, occurring at 5.44 s after the disturbance. Without inertia support, the maximum and average RoCoF is 1.04 Hz/s and 0.85 Hz/s respectively, while adding the support reduces them by 35% to 0.77 Hz/s and 0.62 Hz/s respectively. It is concluded that the inertia support from the HVDC cable results in a slower frequency change and improved stability than the system without support. The maximum RoCoF after the disturbance is inversely proportional to the system inertia level. The lower the grid inertia, the higher the RoCoF, and the more embedded generations to be tripped by the relay protections, which then results even deeper frequency drop. This positive feedback loop endangers the system security and could end up with a frequency collapse. The proposed method using HVDC cable to provide inertia support reduces the risk of frequency collapse when subject to high percentage of wind generations.

The reduction in the DC operating voltage of the cable leads to a reduction in the power transmitted by the DC system, an increase in system line losses and a reduction in the operating efficiency. To make better use of the energy stored in the HVDC cable, future work should focus on further study into this transient process, which can start with different step-down methods and investigate and compare the effects of different step-down waveforms on the system transient process when the step-down speed requirements are met.

D. TECHNICAL AND ECONOMIC CONSIDERATIONS OF INERTIA SUPPORT METHODS

1) OVERVIEW OF GRID INERTIA IN A TYPICAL NET-ZERO POWER SYSTEM

Up to now, 28 countries around the world have committed to decarbonize their energy system, among which the United Kingdom is pioneering the race for reducing carbon emission.
In June 2019, the UK’s revised Climate Change Act came into force, which sets up a clear path to ‘net zero’ by 2050. The UK power system is decarbonizing fast (longest operational record with zero carbon emission in the world), and its installed capacity of offshore wind is highest in the world. These make the power system in the Great Britain a typical example to study system inertia issues. This article selects the data from National Grid UK for analysis.

A large generation or demand loss can result the system frequency to change at a rapid manner. Most embedded generation within the modern power system have a protection relays to prevent them from generating while being isolated, also known as ‘loss of main’ protection. The current typical setting of this type of relay is between 0.125 Hz/s and 1 Hz/s, which means if the system frequency changed faster than this rate, the embedded generation within the whole system starts to trip themselves as a cascade event. For instance, the GB system have as high as 2 GW embedded generation when the demand is low and wind/solar generation is high. This indicates that a potential cascade tripping of 2 GW could further danger the system security after the first disturbance with frequency variation >0.125 Hz/s. This is commonly known as Rate of Change of Frequency (RoCoF) issues.

The amount of kinetic energy that can be utilized for inertia support is restricted by the operational frequency limits. According to the latest data released by National Grid, the estimated value of the power system inertia of Great Britain is approximately 200GVA·s. This is a combination of the inertia from generators >15MW and demand side contribution. The majority of system inertia is provided by synchronous generators, including hydro turbine, combined cycle gas-turbines (CCGT) and nuclear power units. In addition, pumped storage hydro units also provide considerable inertia support when spinning.

Traditionally, the UK has mainly used fossil fuels such as coal, oil and gas to generate electricity. However, traditional power sources are facing challenges with fossil fuel shortage, the decommissioning of nuclear power plants, and increasingly strict environmental regulations [29]. The energy structure of the UK power system in 2020 is shown in Figure 8. In order to achieve ‘net zero’ target, coal and gas turbines are gradually de-commissioned and replaced by renewable energy sources. From 2010 to 2020, the proportion of fossil fuels has been halved from 80% to 40%. The proportion of coal-fired power has been reduced to 2% and the proportion of clean energy such as wind, solar, hydro, and bioenergy is approaching the proportion of fossil energy sources such as coal oil and gas. This marks the end of the UK’s power sector’s reliance on coal power and its progression into the non-fossil energy era.

2) CONFIGURATION AND COST OF INERTIA SUPPORT PROVIDED BY SUPER CAPACITORS

New energy source such as solar power and wind power is developing rapidly. However, when frequency drops caused by power shortages, RoCoF protection trips, resulting in the removal of the turbine and further increases in power shortages. The inertia support method based on energy storage represented by super capacitors has received extensive attention.

It was proposed to configure a super capacitor for each wind turbine to provide extended inertia for the double-fed induction generator (DFIG) [30]. A 1.5MW DFIG is accompanied with a 1150 V×110 F super capacitor energy storage device. According to the literature [31], the cost of lithium ion supercapacitors is approximately $250–$1,000/kWh. For the super capacitor configuration in this example, where $C = 110$F and $V_{dc} = 1150$V, the stored energy is

$$V_{dc0} = \sqrt{\frac{V_{dcmax}^2 + V_{dcmin}^2}{2}}$$

is optimized to equally split the charging and discharging energy storage capability.

The energy stored within a set of lithium ion supercapacitors is approximately 20 kWh calculated by $V_{dcmax} = 1300$V and $V_{dcmin} = 977$V. The average cost of the capacitors is approximately $12,500. The rated voltage of a single lithium ion capacitor unit is ranged 2.2–3.8 V and its capacitance is ranged 1400–2500 F [32]. A single supercapacitor unit with a rated voltage of 3 V and a capacitance of 2500 F is selected for inertia support. To achieve the same nominal voltage (1150 V) of the DFIG, 384 units need to be connected in series. The capacitance of 384 series connected capacitors is 6.5 F, to increase this to desired level (110 F), 17 series capacitor branches connected in parallel to build the capacitor bank (384×17). The maximum discharge current limits the power extraction and absorption of the capacitor bank to 73.4 kW.

The practical Rate of Change of Frequency (RoCoF) limit in future GB power system is estimated to be 0.5 Hz/s [33]. Therefore, 4 GW of power needs to be provided within 1 second to meet the requirement of system frequency balance. If the missing inertia of 100 GVA·s in net zero system is supplied only by supercapacitor banks as described above, around 27,500 such banks are needed. This makes the one-time investment approximately $350 million, excluding the cost of supplement devices, operation and maintenance throughout their whole life.

FIGURE 8. The UK’s 2020 electricity generation by source.
At present, the total length of HVDC cables in UK transmission and distribution network is approximately 1355 km. With more and more offshore wind farms being commissioned, RenewableUK estimated that more than 9300 km DC cables will be laid in the short future [34]. On top of this, it is planned to build more interconnectors between UK and continent of Europe to accommodate more renewables for both sides. As shown in Figure 9, the length of HVDC cables is around 2,190 kilometers with most of them run at 600 kV full load.

\[
\frac{50^2 - 49.8^2}{50^2} \times 100\% = 0.8\% \tag{21}
\]

As (20), for a frequency deviation of ±0.2 Hz, only 0.8% of the stored kinetic energy can be transferred before the frequency limit is exceeded. At present in the GB power system, the capacity of fossil fuel synchronous generators is approximately 22.8 GW, in which 100 GVA·s kinetic energy is stored. During the frequency variation, 0.8 GVA·s (0.8 GJ) is released from the rotors for inertia support. So, decarbonize the existing fossil fuel generators will result a reduction of 22.8 GW synchronous generation. On the other hand, the total length of the cable is approximately 13,000 km and its reduced voltage operation can potentially provide the equivalent of a third of this total. It is thereby practical to conclude that, the HVDC cables are sufficient to provide the amount of inertia needed during the decommissioning of 7.6 GW fossil fuel synchronous generators.

The main idea of this method is to fully utilize the energy released from the HVDC cables during the voltage deple-
tion process. No additional energy storage device is required which means zero construction investment, low main-
tenance cost and low operational cost. The reduced installation of power electronics devices and supercapacitors can also reduce its complexity as well as improve the reliability.

3) CONFIGURATION AND COST OF INERTIA SUPPORT PROVIDED BY HVDC CABLES

At present the total length of HVDC cables in UK trans-
misssion and distribution network is approximately 1355 km. With more and more offshore wind farms being commissioned, RenewableUK estimated that more than 9300 km DC cables will be laid in the short future [34]. On top of this, it is planned to build more interconnectors between UK and continent of Europe to accommodate more renewables for both sides. As shown in Figure 9, the length of HVDC cables is around 2,190 kilometers with most of them run at 600 kV full load.

\[
\frac{50^2 - 49.8^2}{50^2} \times 100\% = 0.8\% \tag{21}
\]

As (20), for a frequency deviation of ±0.2 Hz, only 0.8% of the stored kinetic energy can be transferred before the frequency limit is exceeded. At present in the GB power system, the capacity of fossil fuel synchronous generators is approximately 22.8 GW, in which 100 GVA·s kinetic energy is stored. During the frequency variation, 0.8 GVA·s (0.8 GJ) is released from the rotors for inertia support. So, decarbonize the existing fossil fuel generators will result a reduction of 22.8 GW synchronous generation. On the other hand, the total length of the cable is approximately 13,000 km and its reduced voltage operation can potentially provide the equivalent of a third of this total. It is thereby practical to conclude that, the HVDC cables are sufficient to provide the amount of inertia needed during the decommissioning of 7.6 GW fossil fuel synchronous generators.

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4) TECHNICAL AND ECONOMIC COMPARISON

With the increased percentage of renewable energy sources, system inertia continues to fall due to the decommissioning of synchronous generators. To maintain the system security during the operational time scale, the system inertia must be kept above its threshold. As discussed in the previous section, two methods can provide inertia support:

- through supercapacitors
- through HVDC cables

Their feasibilities of both technical and commercial aspects are compared and analysed in Table 2.

From commercial point of view, technologies using super-
capacitor banks to provide inertia support incur excessive investment, which involve construction cost, operation and maintenance cost, auxiliary cost etc. O&M cost is calculated as a percentage of the initial construction cost, which is assumed to be 10% in this paper. For reliability analysis, assume the failure rate of individual supercapacitor is identi-
cal as: \( \lambda_{SC} \). The failure rate of a multi-element supercapacitor bank is calculated from (22), where the equivalent failure rate of 384*17 supercapacitor bank is \( \lambda_{b} = 17 \times 384 \times \lambda_{SC} = 6528 \lambda_{SC} \). This implies that the combination of large number

### TABLE 2. Technical and economic comparison of two support grid inertia methods.

| Technical factors | Supercapacitors | HVDC cables |
|------------------|----------------|-------------|
| Failure rate     | \( \lambda_{SC} \) | \( \lambda_{b} \) |
| Modelling complexity | Inability to model accurately, especially for ageing mechanisms | Modelling methods are more mature and accurate |
| Relay protection configuration | Requires recalculation and reconfiguration | Continuation of existing configuration |
| Surge withstand capability | Unable to withstand overvoltage and overcurrent | High tolerance to overvoltage and overcurrent |

| Economic factors | Supercapacitors | HVDC cables |
|------------------|----------------|-------------|
| One-time investment | $350 million | No extra investment |
| Investment in complementary equipment | $350 million | No complementary equipment |
| O&M costs | $35 million | No O&M costs for inertia support |
of components leads to significant increase in the fault rate.

$$\lambda = \lambda_1 + \lambda_2 + n \cdots + \lambda_n$$  \hspace{1cm} (22)

The proposed technique releases energy stored from existing HVDC cables to provide inertia support like the rotating synchronous machines. It takes away the needs to construct new devices, which save costs and increase system reliability significantly. Moreover, due to its own nature the HVDC cable can withstand overcurrent and overvoltage into a certain extent. With the rapid growth of the offshore wind in Europe and around the world, the laying of submarine cables continues to increase, and the energy stored within HVDC cables which can be used for inertia support is increasing fast. It is therefore practical to support a large portion of power system inertia by wisely utilizing the HVDC cables around the world.

V. CONCLUSION

The lack of system inertia is currently the most urgent challenge when decarbonizing the power systems. Traditional inertia support methods require the installation of new equipment or components, which not only introduces reliability issues but also increase the cost. For example, supercapacitor banks which provide inertia support require enormous investment ($700 million) in its installation, auxiliary, operation and maintenance. It is proposed that by utilizing existing HVDC cables, same level of inertia support can be achieved through controlling the terminal voltage. This reduces the complexity, maintained the reliability and reduced the cost for inertia support.

Based on this consideration, this article studies the effectiveness of using HVDC cables to provide inertia support in power systems with high renewable energy penetration. A feasibility study has been carried out, and it is demonstrated that by releasing the energy stored within the HVDC cables, sufficient inertia support can be provided. A simulation is performed on a 10-machine 2-area platform which represents the GB power system to study the dynamic stability. By comparing the results with and without the inertia support, a clear improvement on the frequency dip (with less frequency drop and lower change rate) is identified for the proposed method. It is also found that the RoCoF is reduced by 35% with the proposed inertia support strategy from HVDC cables. It is concluded that with the tailored control, the cascade trips of embedded generations and frequency collapse can be avoided with the proposed method.

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