Active Power Control of PV-Battery Connected MMC-HVDC System for FRT Support

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Received: 3 August 2020; Accepted: 5 October 2020; Published: 15 October 2020

Featured Application: Proposed technique replaces the dynamic braking resistor to control the excess energy in the PV-Battery connected HVDC link during the fault at the point of common coupling of AC grids and improves power levelling during the solar radiation and temperature fluctuation.

Abstract: Modular multilevel converter (MMC)-based VSC system has become attractive around the world for renewable energy integration. Instead of a dynamic braking resistor, this work proposes an active power reduction technique for PV systems to support the fault ride through (FRT) of the MMC-HVDC system. In addition, it develops a battery control strategy to improve transient performance during solar radiation and temperature change due to partial shading of the PV panels. Besides, a control technique for the battery to regulate the surplus energy in the HVDC transmission network is developed. Furthermore, the proposed control scheme optimally integrates solar energy using the modified incremental conductance method. A feedforward controller was employed to create a standalone AC grid. The complete system has been implemented in real-time digital simulation (RTDS). The results confirm the efficacy of active power reduction technique to protect the HVDC link voltage and battery control strategy for the improvement of transient performance during the irradiance and temperature changes. Besides, it improves the low voltage ride-through capability during balanced and unbalanced disturbances at the point of common coupling.

Keywords: MMC detailed model; modified incremental conductance method; PV; active power reduction; battery; balanced fault; unbalanced fault

1. Introduction

Electricity consumption is increasing day by day due to everlasting demand from the rising world population. Therefore, different countries are taking the initiative towards an alternative source. Renewable energy has become competitive over the years and able to compete with conventional energy [1–3]. Among renewable energy sources, PV has played a dominant role in the energy market. The 21st century has seen PV installation from a few megawatts to several hundred megawatts in countries like Spain and Germany. As the cost of PV panel is dramatically falling and efficiency is increasing, solar energy might become a significant source of energy for electricity generation. As with other renewable energy, a suitable place for PV panels to be located is deserts where the efficiency is the highest and the land is not utilized for forestry, agriculture, and rural and urban development. Hence, it requires a transmission line for the transportation of a large amount of power from the sites with a high amount of sunlight to the load center. Besides, insulators of the overhead line in the desert areas are prone to salt contamination, which makes the cable transmission more suitable.
Due to the advancement in the semiconductor switch and converter design over the decades, the HVDC transmission system has become attractive for renewable energy integration. Besides, the VSC-HVDC system has the ability of asynchronous interconnections, no issue of sub-synchronous resonances, reactive charging current and skin effect, ability to resist the AC fault propagation, real and reactive power controllability, and power reversal capability without changing voltage polarity [4,5]. Low loss and modular characteristics have made the modular multilevel converter (MMC) attractive for remotely located renewable energy interconnection over the HVDC line [6–8]. Due to a large number of submodules, MMC produces almost ideal sine wave voltage. It significantly reduces harmonic pollution at the point of common coupling and minimizes the cost of filtering. Like AC system, MMC-HVDC system also suffers a stability problem due to faults at the point of common coupling of AC grids if proper action is not taken.

Series-connected resistor-based bridge type fault current limiter has been discussed for a two-level VSC-HVDC system to mitigate different kinds of faults in [9,10]. However, this approach keeps a large number of semiconductor switches turned on at normal operating conditions, resulting in continuous conduction loss. The unbalanced fault analysis has been carried out for offshore energy-connected HVDC systems [11,12]. However, the detailed model was not considered, and no experimental result was presented in [11,12]. As the fault at the point of common coupling reduces the converter capability to deliver power, HVDC link voltage could go beyond its threshold. Fast communication-based centralized control, power reduction, power-sharing, and coordination among the converter stations have been discussed in [13–16]. Nevertheless, it requires a large bandwidth for communication and a reliable system. The active current is reduced from the wind turbine by controlling the electrical torque, which in turns reduces the overall electrical power injection [17–19]. However, response time is slow and not appropriate to mitigate the fast energy build up in the HVDC link during a fault in the AC side. The wind power is also reduced by detecting the grid frequency over the high bandwidth communication link during the fault [18]. The offshore wind farm output power could be reduced by decreasing the modulation index of the converter, which results in a significant reduction of power but a maintained converter-rated current [20]. Any communication failure could destabilize the whole HVDC grids, which in turn has made the dynamic braking resistor (DBR)-based local control more effective to deal with excess energy in the HVDC [18,21,22].

Although DBR (DC chopper) is suitable for wind energy-connected VSC-HVDC system due to the slow response of the wind generator, the PV system can rapidly change the output to control the energy flow in the HVDC link because the photovoltaic system has no inertia and power electronics converter response is fast [23]. Work related to voltage and frequency regulation, reactive power support to AC grid, and active power curtailment during the high frequency of AC grids of PV inverter have been reported in [6–8]. Usually, active power curtailment is one of the desirable features of a PV inverter for its utility with high PV penetration [24–29]. PV inverter curtails its output based on frequency rise from the threshold. Similarly, it could inject more energy during the frequency drop if it is operated below the maximum power point [25–28]. A fuzzy logic controller was employed to control the frequency of the PV–battery–diesel microgrid [27], where battery-free operation has been suggested if the PV system operates below the maximum power point. Droop control-based frequency regulation for PV-connected AC system has been discussed in [30] without taking variable solar radiation and temperature into consideration. Without providing inverter control details, primary frequency response has been addressed for a PV inverter-connected PV simulator system in [24]. An adaptive droop-based frequency and voltage regulation was presented in [30]. A utility size practical exhibition of a PV plant for supporting primary and secondary frequency regulation using active power curtailment has been discussed in [31]. The common feature for all works mentioned in [24–31] is the manipulation of PV power based on grid frequency command. However, frequency usually remains constant for MMC supported standalone AC grid for renewable energy integration. Hence, other features of the HVDC system need to be explored for active power reduction during the
fault. Unlike PV integrated AC grids, fault ride through improvement for PV-integrated VSC-HVDC system employing active power reduction has not been properly explored [23].

A flywheel energy storage is a fast and high power density device and presents high performance, which could be used for excess energy control during the fault. A flywheel energy storage-based fault ride through support has been discussed in [32–34], where excess energy is stored in the form of kinetic energy depending on the rotating mass and speed. On the other hand, the supercapacitor is also a short-duration energy storage device with high power density and fast response. It has similar potential for fault ride through support of VSC-HVDC link during AC side fault [35,36]. Besides fault ride through improvement, both systems could be used for power levelling purpose during normal condition. However, both systems are expensive and suffer high energy loss over a longer period. Therefore, it has limited use in the field except for research purposes. In contrast, the cost of a battery-based energy storage system has been going down over the years [37]. Besides, the battery has high energy density and can retain charge over a longer duration. Therefore, many utilities are now utilizing battery-based energy storage system for power levelling, frequency and voltage regulation, and fault ride-through improvement. Usually, transient fault demands a faster response from the energy storage system. The battery is a high energy density but low power density device that means it needs to be oversized to support the transient fault response. Although oversizing increases the cost for energy storage, it increases the energy delivering capacity for a longer duration to mitigate the energy shortage caused by solar radiation, temperature and wind speed change.

Papers reported in the literature [38,39] have placed capacitance on the high voltage AC side for AC grid-forming and included its dynamics in the control loop. It results in reactive power consumption and increases filtering cost, where MMC generates a small number of harmonics.

In almost all of these articles mentioned above for referencing, non-real-time software like Matlab Simulink and PSCAD/EMTDC were used to model and prepare results against different kinds of fault.

In PV systems, the two most widely used MPPT controllers are perturb & observe method (P&O) [40–42] and incremental conductance (IC) method [43–45] for tracking the maximum power point due to the variation of irradiance and temperature. Although IC is computationally expensive, it tracks the maximum power point (MPP) more rapidly than the P&O method. However, real-time implementation of IC creates problems as the algorithm contains the PV voltage difference in the denominator, which usually does not change during a sudden change in irradiance.

In this work, the MMC detailed model-based PV-battery connected HVDC network is formed. Active power reduction-based control strategy for PV is developed to replace the dynamic braking resistor and improve the fault ride-through capability during the AC side balanced and unbalanced fault. Furthermore, a control strategy is made for the battery to regulate the excess energy in the MMC-HVDC system and mitigate the energy shortage of PV panel caused by the temperature change and sudden cloud passing. Modified incremental conductance-based optimum solar energy tracking is carried out. Feedforward controller is employed to create the standalone AC grid instead of capacitance-included decoupled controller. A complete system with all detailed model-based converters and controllers is modelled and simulated in real-time digital simulation (RTDS). The efficacy of active power reduction technique and battery-based control strategy for the MMC-HVDC system is evaluated against the severe balanced and unbalanced disturbances at the point of common coupling of AC grids and fluctuation of the solar radiation and temperature.

The following shortcomings in current studies are to be addressed as the main contributions of this research:

(a) Active power curtailment of PV-Battery integrated MMC-HVDC system has not been reported;
(b) Local voltage signal based PV-Battery control for the HVDC link voltage protection has not been addressed;
(c) Detailed model-based complete system with real-time simulation results has not been presented.
2. Modeling and Controller Design

2.1. System Overview

Figure 1 shows the complete system of solar and battery integration into MMC-based HVDC transmission network. The system consists of solar farms with a battery-based energy storage system. MMC2 terminal establishes the standalone AC grids for solar energy integration, whereas MMC1 controls the HVDC link voltage. The capacity is increased by scaling the output ($I_{abc}$) from the detailed model-based one unit of PV-Battery system through a controlled current source and multiplier (M).

![Figure 1. PV-Battery connected MMC-HVDC system.](image)

2.2. PV Side Converter Control

As the power of PV array changes with PV voltage, the PV side converter adjusts the DC link voltage for extracting the optimum solar energy under solar radiation and temperature change. In the steady-state, the following equation represents the inner current dynamics in the dq frame for the grid side converter (VSC-PV) as shown in Figure 1 [46].

$$L \frac{di_{gd}}{dt} + Ri_{gd} = L \omega_0 i_{qg} + V_d - V_{gd} \quad (1)$$

$$L \frac{di_{gq}}{dt} + Ri_{gq} = -L \omega_0 i_{gd} + V_q - V_{gq} \quad (2)$$

The following equation controls the dynamics of the DC link voltage of grid side converter (VSC-PV).

$$C \frac{dV_{dc}}{dt} = I_{dc} - i_{gd} \quad (3)$$

In this work, an enhanced incremental conductance method is employed to track the maximum power point (MPP) of PV.

The slope at the MPP point is

$$\frac{dP_{pv}}{dV_{pv}} = 0 \text{ or } \frac{d(V_{pv} I_{pv})}{dV_{pv}} = 0$$

$$I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}} = 0 \text{ or } \frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \quad (4)$$
However, under rapidly changing environmental conditions, Equation (4) results in a division by zero. After multiplying both sides of Equation (4) by $d V_{pv}$, we get

$$dP_{pv} = I_{pd}dV_{pv} + V_{pv}dI_{pv}$$  \hspace{1cm} (5)$$

If the voltage remains unchanged in the subsequent sample, then Equation (5) becomes

$$dP_{pv} = V_{pv}dI_{pv}$$  \hspace{1cm} (6)$$

Figure 2a illustrates the control block diagram of DC link voltage regulation that is formed based on Equations (1)–(3). The DC link voltage setpoint comes from the MPPT algorithm. Equations (4) and (6) form the basis of modified incremental conductance (MIC) algorithm where reference DC link voltage is produced. Converter $dq$ voltage produces the three phase modulating signal ($Ma,b,c$) for the VSC-PV.

2.3. Battery Side Converter Control

The operation of the battery side converter, as shown in Figure 1, is the same as the PV side converter presented in Section 2.2 except for the reference current generation. The reference current is produced from the constant power reference. The current dynamics are governed by Equations (1) and (2) through the converter $dq$ voltage, which further generates the modulating signal ($Ma,b,c$) for the VSC-B. The reactive current is set to zero for transferring only real power to the PCC. Figure 2b presents the battery side converter control. The reactive current reference for PV and battery side converter depicted in Figure 2 is zero, whereas real current references differ from each other.
2.4. Controller Design of MMC-HVDC System

Modular multilevel converter is the central unit of the high voltage high power HVDC transmission network. Figure 3 presents an MMC equivalent circuit. Apart from outer loop and inner current loop, it requires submodule balancing control and arm circulating current.

2.4.1. High-Level Control

High-level control generates the reference current from the HVDC voltage, reactive power and standalone AC voltage controller as presented in Figure 4. VDC controller comprises a PI controller that processes the error generated from the difference between the reference and actual HVDC voltage. The feedforward controller (information of DC link current) is added with the PI controller’s output for improved dynamic performance. Any current change in the HVDC link is reflected in the controller output signal that adjusts the real current command of MMC1. MMC1 could inject fixed reactive current or provide proportional reactive power with the PCC1 voltage. MMC2 creates an isolated AC voltage for renewable energy integration. It receives renewable energy while holding the AC voltage and injects it into the HVDC link.

AC voltage controller has a PI controller and a feedforward controller. PI controller adjusts its output based on the difference between the reference and actual AC side voltage of MMC2.

In contrast, the feedforward controller provides a signal based on any change occurring in the AC current signal beforehand. Altogether, it keeps AC voltage constant while receiving renewable energy. In addition, the AC voltage control strategy of MMC2 controller slightly increases the AC side reference voltage ($V_{sd-ref}$) with the HVDC link voltage during the fault in the point of common coupling of MMC1, which proportionally increases the PCC voltage. PV and battery controller take action to counteract the PCC voltage rise. If the HVDC link voltage surpasses 1.05 pu, the d-component of reference AC voltage ($V_{sd-ref}$) is increased proportionally, whereas it remains constant if HVDC link voltage is below 1.05 pu. The q-component of reference AC voltage ($V_{sq-ref}$) is regulated to zero.
2.4.2. Low-Level Control

The following equation represents the current control dynamics of MMC in dq frame in the steady-state

\[
\frac{L}{2} \frac{d i_{sd}}{dt} + \frac{R}{2} i_{sd} = \frac{L}{2} \omega_0 i_{sq} + V_d - V_{sd} \tag{7}
\]

\[
\frac{L}{2} \frac{d i_{sq}}{dt} + \frac{R}{2} i_{sq} = -\frac{L}{2} \omega_0 i_{sd} + V_q - V_{sq} \tag{8}
\]

The following equation governs the HVDC link voltage

\[
\left( C_d + \frac{6C}{N} \right) \frac{dV_{dc}}{dt} = I_{ex2} - i_{sd} \tag{9}
\]

Equations (7) and (8) form the inner current control loop, as depicted in Figure 4, to produce the modulating signal for the MMC converter. In addition to inner current control, a circulating current controller is needed to ensure symmetric current between the upper and lower arm.

The circulating current rotates at \(2\omega_0\) frequency, and its dynamics are controlled by the following equation [47].

\[
L \frac{d i_{d1}}{dt} + R i_{d1} = 2L \omega_0 i_{q1} + V_{d1} \tag{10}
\]

\[
L \frac{d i_{q1}}{dt} + R i_{q1} = -2L \omega_0 i_{d1} + V_{q1} \tag{11}
\]
In this equation, $i_d$ and $i_q$ are the dq current converted from the MMC three arms difference (between upper and lower arm) current. The PI controller produces the required adjustment in terms of $V_d$ and $V_q$, which further converts to modulating signal. The angle for circulating current conversion to dq frame and $V_{dq}$ conversion to modulating signal is $-2\theta_g$. After combining the modulating signal from inner current control and circulating current control, nearest level modulation (NLM) is employed to produce the number of submodules selection. Apart from the circulating current between the upper and lower arm of the MMC, submodule (SM) capacitor voltages within the upper or lower arms drift from each other. The uncontrolled charging and discharging are the reasons for such drifts. Therefore, it is expected to place a higher voltage sub module (SM) when the current leaves and a lower voltage SM when the current enters, to minimize the voltage imbalance among the SMs. This work employs a submodule-sorting algorithm (SSA) to place the appropriate SM from the set of SMs in the upper and lower arm based on current direction and current state of charge (voltage) of the SM capacitor. Figure 4 shows the complete control of MMC bridges. However, the AC side fault significantly reduces the converter’s power transfer capability, which in turn raises the HVDC link voltage. This work employs active power reduction of PV to protect the HVDC link voltage. If the PCC voltage surpasses the threshold, the PV power is reduced to control the HVDC link voltage, whereas the system becomes normal if the PCC voltage goes below the threshold. MMC2 controller switches from fixed AC voltage to variable AC voltage control during the abnormal rise of HVDC link voltage under fault at PCC1.

3. Proposed PV-Battery Based FRT Improvement and Power Levelling Controller

As can be seen from Figure 5 for any curve, the PV array power is changed with voltage. By moving PV voltage from its optimum point towards the open-circuit voltage, it is possible to curtail the PV power output during the fault. By obtaining the P-V characteristics for all possible cases, the range of effective PV voltages for MPPT is chosen. As can be seen from Figure 5, the range of PV voltage is selected between 1350–2750 V for uniform solar radiation. However, non-uniform solar radiation provides multiple peaks depicted in Figure 6. Usually, the location for large scale PV farm is selected in the open space or in the desert where the efficiency is the highest, and the land is not utilized for forestry, agriculture, and rural and urban development. Besides, the only source of shading for the PV panel is the cloud. Therefore, P-V characteristics are obtained under 50% panel shading at different solar radiations depicted in Figure 6 to consider the worst case scenario. 1000 Wm$^{-2}$ solar radiation is considered for the remaining 50% panel. It is inferred from Figure 6 that the peak occurs within the range of MPPT tracking when the solar radiation is above 400 Wm$^{-2}$. For all cases below 400 Wm$^{-2}$, the peak occurs outside the MPPT range and towards the low voltage side. Without an additional DC-DC converter for each PV module, exploring a wide range of PV voltages using a global tracking algorithm for a central inverter-connected PV system could violate the minimum DC link voltage of the PV inverter for reliable operation and might create stability problem. Besides, active power reduction by changing PV voltage would not be possible if the global peak occurs in the low voltage side. Therefore, the proposed MPPT range-restricted-based active power reduction works well and covers most of the partial shading cases in the open spaces.

During the normal operating condition, PV inverter operates in MPPT mode. However, any fault at PCC1 rises the HVDC link voltage. Hence, active power from the PV panel is reduced with the increasing HVDC link voltage. Therefore, HVDC link voltage is required to sense and feed into the PV-battery controller. However, this approach is not universal as there might be a considerable distance between the MMC2 converter station and PV inverter, which requires a long wire for sensing the HVDC link voltage. To remove the long wire-based HVDC voltage sensing, this work proportionally increases the PCC voltage with the HVDC link voltage, which in turn is used as the input command for the active power reduction controller of PV-Battery controller.

Thus, local voltage is monitored instead of remotely located HVDC link voltage. As can be seen from Figure 7a, the positive error is processed through the PI controller and added with the existing MPPT voltage to produce the reference voltage for the DC link voltage controller of VSC-PV.
The maximum DC link voltage is equal to the open-circuit voltage of the PV panel. Usually, MPPT voltage is approximately 80% of open-circuit voltage of the PV panel. Similarly, battery is charged proportionally if the PCC voltage rises above 1.05 pu during the fault at PCC1 to protect the HVDC link voltage as depicted in Figure 7b. Maximum setpoint for the battery charging power is equal to the MPPT power of the PV panel. During constant PCC voltage, any deviation from the nominal power of PV energy caused by solar radiation and temperature change is filled by the battery as shown in Figure 7c. P_{Set} is the nominal power of PV panel from which actual PV power (P_{PV,Ir_T}) deviation during partial shading is compensated by the battery. Positive power command for the battery means discharging; negative power command for the battery means charging.

**Figure 5.** PV characteristics during solar radiation and temperature change and active power reduction area.

**Figure 6.** PV characteristics under 50% panel shading at different solar radiations.
gradually control the HVDC link voltage towards 200 kV (1 pu). Similarly, the HVAC link voltage change. During temperature change from 25 °C to 50 °C, 56 units of PV array inject around 100 MW to MMC2 terminal as illustrated in Figure 11. It is also found from PV array characteristics that the optimum PV energy for one array is 0.1 MW at 100 Wm⁻².

4. Result and Discussion

RTDS is a hardware-based real-time digital simulation device and has the ability to interact with the physical system in real-time. The system and controller developed in RTDS are more realistic than the system developed in non-real-time simulation software. A 50 µs sample time is selected for the controller, whereas 2.3 µs sample time is selected for the power electronics component. Due to the complexity of the large system, a multirack platform is used in RTDS to implement the complete system. Nova core and PB5 processors are used to form the RTDS multirack hardware platform. MMC2 with PV and battery are implemented in Rack-2, and MMC1 is implemented in Rack-1. A 100 MW PV farm with a battery is developed by scaling the input current at PCC terminal from one complete unit of 1.74 MW PV array with a battery. Tables A1 and A2 provide required data for the different parameters.

The level for the x-axis of all figures illustrated from Figures 8–33 is time in seconds. To reduce the space in the y-axis, the y-axis level for some figures have been given inside the Figure with name, unit and color. As RTDS works in real-time, it generates vast amount of data which does not allow to record data for longer duration. Therefore, a small time window is used to capture the required response. Starting time could indicate any running time.

4.1. MMC-HVDC Voltage Control and Optimum PV Integration

Before transferring the renewable energy over the MMC-HVDC network, MMC1 gradually sets the HVDC link voltage. After that, MMC2 gradually sets the HVAC link voltage for renewable energy integration. Figure 8 shows the HVDC link voltage control, whereas Figure 9 illustrates the HVAC link voltage control. Initially, the current limiting resistor is activated to control the charging current of the submodule capacitor. After 0.72 s, the resistor is bypassed, and the controller is activated to gradually control the HVDC link voltage towards 200 kV (1 pu). Similarly, the HVAC link voltage controller regulates the d-component of HVAC voltage while the q-component is regulated at zero. Figures 10 and 11 show the optimum PV energy tracking during irradiance and temperature change in RTDS. It is seen from Figure 10 that 56 units of PV array are injected around 5.6 MW to 100 MW to MMC2 terminal during irradiance change from 100 Wm⁻² to 1000 Wm⁻². It is found from PV array characteristics that the optimum PV energy for one array is 0.1 MW at 100 Wm⁻² and 1.74 MW at 1000 Wm⁻² during constant temperature (25 °C). Therefore, MPPT is achieved as 56 units yield around 5.6 MW (56 × 0.1 MW) and 100 MW (56 × 1.74 MW) respectively in RTDS during irradiance change. During temperature change from 25 °C to 50 °C, 56 units of PV array inject around 100 MW to 80 MW to MMC2 terminal as illustrated in Figure 11. It is also found from PV array characteristics depicted in Figure 5 that the optimum PV energy for one array is 1.74 MW at 25 °C and 1.43 MW at 50 °C during constant irradiance (1000 Wm⁻²). This also confirms the optimum PV energy tracking.
during temperature change. During variable power injection, it results in small overshoot in HVDC link voltage.

![Figure 8. MMC1-HVDC voltage regulation in RTDS.](image)

![Figure 9. MMC2-HVAC link voltage control in RTDS.](image)

![Figure 10. Optimum PV energy tracking during irradiance change in RTDS.](image)
Figure 10. Optimum PV energy tracking during irradiance change in RTDS.

Figure 11. Optimum PV energy tracking during temperature change in RTDS.

4.2. Active Power Reduction of PV Based Excess Energy Control During Fault at PCC1

While transferring solar energy to the AC grids through the HVDC line, a three-phase-to-ground fault is applied at the PCC1 as depicted in Figure 13. It reduces the MMC1 converter's power transfer capacity to zero, as illustrated in Figure 14. Although the converter injects maximum real and reactive current, HVDC link voltage is increased, which proportionally increases the PCC voltage. Usually, a dynamic braking resistor (DBR) is used in the HVDC link to dissipate the surplus energy in the HVDC link. DBR is connected in parallel with the transmission line and remains inactive during normal conditions. However, any increase of HVDC link voltage beyond threshold due to excess energy under fault in the point of common coupling of AC grids activates the DBR to keep the HVDC link voltage below limits. As can be seen from Figure 12, HVDC link voltage is regulated around the threshold limit (1.2 pu) during the period of single line to ground (SLG), double line to ground (DLG) and three line to ground (3LG) faults employing conventional dynamic braking resistor (DBR). DBR is active when the HVDC link voltage exceeds 1.2 pu. DBR is turned off when the HVDC link voltage goes below 1.1 pu. A large number of series-parallel combination semiconductor switches are required to let the current flow through the dissipating resistor to dissipate a large amount of HVDC power (hundreds or thousands of megawatt) during the three-phase-to-ground fault at the point of common coupling of AC grids. Dynamic braking resistor also introduces several switches in the HVDC voltage, as shown in Figure 12, which could result in fluctuation in the real power flow. Instead of a DBR to dissipate the excess energy, this work reduces the PV array power proportionally with the PCC voltage increase. One second duration three line to ground (3LG) fault is applied at PCC1 at 1 s, as presented in Figure 13. Figure 14 shows that the delivered real power of MMC1 has been reduced to zero due to 3LG fault. As can be seen from Figure 15, PV voltage starts increasing when the PCC voltage exceeds 1.05 pu and rises to around its open circuit voltage, which dramatically reduces the PV power. Hence, HVDC link voltage is restricted to maximum 1.2 pu and then gradually decreases to normal. After fault clearance, the PV voltage comes back to the optimum point. Thus, the controller is able to control excess energy in the HVDC link voltage during the fault without using the DBR. The line current for the Y-Δ transformer remains limited to 1.33 pu, as presented in Figure 13. Due to the balanced fault, both side currents have a similar shape with equal magnitude.

Figure 12. HVDC voltage regulation of MMC1 in the course of SLG, DLG and 3LG faults employing conventional dynamic braking resistor (DBR).
Figure 13. PCC1 voltage, Y-Δ side current of MMC1 for the period of 3LG fault.

Figure 14. Id and Iq current and power of MMC1 for the period of 3LG fault.
Figure 14. Id and Iq current and power of MMC1 for the period of 3LG fault.

Figure 15. PCC voltage, PV voltage and power, MMC1-HVDC voltage for the period of 3LG fault.

Figure 16. PCC voltage, Y-Δ side current of MMC1 for the period of DLG fault.

Figure 17. Id and Iq current and power of MMC1 for the period of DLG fault.
Figure 16. PCC1 voltage, Y-Δ side current of MMC1 for the period of DLG fault.

Figure 17. Id and Iq current and power of MMC1 for the period of DLG fault.

Figure 18. PCC voltage, PV voltage and power, and MMC1-HVDC voltage for the period of DLG fault.
Figure 19. PCC1 voltage, Y-Δ side current of MMC1 for the period of SLG fault.

Figure 20. Id and Iq current and power of MMC1 for the period of SLG fault.
4.3. Battery Based Excess Energy Control During Fault at PCC1

The PV-battery combination supports the FRT and power smoothing during the faults and change of environment condition. In the previous section, PV-based FRT was demonstrated. Active power curtailment is efficient if the battery is fully charged. However, lightly charged battery could be used to take the extra energy during the fault at PCC1 without PV power curtailment. As the battery is a power-limited device, this work has considered an oversized battery for the FRT and power leveling purpose. Hence, this work uses a battery to capture the excess energy in the HVDC link during the fault at PCC1 while keeping the PV power unaffected. As can be seen from Figure 22, PV power remains unchanged while the battery is charged proportionally with the increase of PCC voltage during the 3LG fault at PCC1. When PCC voltage exceeds 1.05 pu, PV energy is delivered to the battery, which in turn keeps the HVDC link voltage below 1.2 pu. During this time, the state of charge (SOC) has increased from 69.85% to 70.3%. Figure 23 shows that the MMC1 has injected the maximum reactive current to PCC1 to support the PCC1 voltage. However, delivered real power is zero during 3LG fault at PCC1. Similarly, DLG fault at PCC1 has increased the HVDC link voltage, which has increased the PCC voltage, as shown in Figure 24. Consequently, the battery is charged when the PCC voltage exceeds 1.05 pu, while PV power is maintained constant. Battery charging has limited the HVDC link voltage within 1.06 pu. However, the energy delivered into the battery is less compared to 3LG fault. In contrast, Figure 25 points out that the MMC1 transfers around 50 MW to PCC1 during DLG fault, which is greater than 3LG fault. Besides, the delivered real current for both cases is 1.1 pu, whereas the reactive current is slightly less for DLG fault than 3LG fault. During DLG fault.

Figure 21. PCC voltage, PV voltage and power, and MMC1-HVDC voltage for the period of SLG fault.

4.2. Active Power Reduction of PV Based Excess Energy Control During Fault at PCC1

While transferring solar energy to the AC grids through the HVDC line, a three-phase-to-ground fault is applied at the PCC1 as depicted in Figure 13. It reduces the MMC1 converter’s power transfer capacity to zero, as illustrated in Figure 14. Although the converter injects maximum real and reactive current, HVDC link voltage is increased, which proportionally increases the PCC voltage. Usually, a dynamic braking resistor (DBR) is used in the HVDC link to dissipate the surplus energy in the HVDC link. DBR is connected in parallel with the transmission line and remains inactive during normal conditions. However, any increase of HVDC link voltage beyond threshold due to excess energy under fault in the point of common coupling of AC grids activates the DBR to keep the HVDC link voltage below limits. As can be seen from Figure 12, HVDC link voltage is regulated around the threshold limit (1.2 pu) during the period of single line to ground (SLG), double line to ground (DLG) and three line to ground (3LG) faults employing conventional dynamic braking resistor (DBR). DBR is active when the HVDC link voltage exceeds 1.2 pu. DBR is turned off when the HVDC link voltage goes below 1.1 pu. A large number of series-parallel combination semiconductor switches are required to let the current flow through the dissipating resistor to dissipate a large amount of HVDC power (hundreds or thousands of megawatt) during the three-phase-to-ground fault at the point of common coupling of AC grids. Dynamic braking resistor also introduces several switches in the HVDC voltage, as shown in Figure 12, which could result in fluctuation in the real power flow. Instead of a DBR to dissipate the excess energy, this work reduces the PV array power proportionally with the PCC voltage increase. One second duration three line to ground (3LG) fault is applied at PCC1 at 1 s,
as presented in Figure 13. Figure 14 shows that the delivered real power of MMC1 has been reduced to zero due to 3LG fault. As can be seen from Figure 15, PV voltage starts increasing when the PCC voltage exceeds 1.05 pu and rises to around its open circuit voltage, which dramatically reduces the PV power. Hence, HVDC link voltage is restricted to maximum 1.2 pu and then gradually decreases to normal. After fault clearance, the PV voltage comes back to the optimum point. Thus, the controller is able to control excess energy in the HVDC link voltage during the fault without using the DBR. The line current for the Y-Δ transformer remains limited to 1.33 pu, as presented in Figure 13. Due to the balanced fault, both side currents have a similar shape with equal magnitude.

Apart from excess energy control in the HVDC link, the control system also injects reactive current for voltage support at the point of common coupling. During the fault at PCC1, maximum 1.1 pu real current and 0.7 pu reactive current are selected for the MMC1 current controller in this work. Figure 14 illustrates that the maximum 1.1 pu real current (Id) and 0.7 pu reactive current (Iq) have been injected during the 3LG fault.
Figure 23. Id and Iq current and power of MMC1 for the duration of 3LG fault.

Figure 24. PCC voltage, Battery and PV power, SOC, and MMC1-HVDC voltage in the course of DLG.
Similarly, double-line-to-ground (DLG) fault and single-line-to-ground (SLG) fault are applied at PCC1. Figures 16–18 illustrate the response during the DLG fault, whereas Figures 19–21 illustrate the response during the SLG fault. Note that 3LG, DLG and SLG faults are 1s duration faults and are applied at 1s separately. As can be seen from Figures 17 and 20, the real power delivery is reduced to average 50 MW during DLG fault, but no average power reduction is observed during SLG fault due to higher capacity of the converter. However, both cases encounter double frequency oscillation in real power delivery because of negative sequence voltage. In addition, 0.7 pu reactive current during the period of DLG fault and 0.6 pu reactive current during the period of SLG fault have been injected. As the converter power transfer capability is reduced during the DLG fault, the HVDC link voltage rises, which increases the PCC voltage. As can be seen from Figure 18, the PV voltage starts increasing when PCC voltage surpasses 1.05 pu, which in turn reduces the PV power. As a result, the HVDC link voltage is limited within 1.1 pu. The PV voltage returns back to optimum voltage when the PCC voltage goes below 1.05 pu. However, PCC voltage did not crossed 1.05 pu during SLG fault as shown in Figure 21, which kept the PV voltage and PV power unchanged. In addition, the HVDC link voltage did not exceed 1.01 pu during SLG fault. Furthermore, Figures 16 and 19 illustrate that the Δ-side current of the transformer for SLG and DLG faults has been limited to around 1.33 pu, whereas Y-side current for both cases is asymmetric and greater than the 1.33 pu because of containing zero-sequence current.

**Figure 25.** Id and Iq current and power of MMC1 in the course of DLG fault.
Figure 26. PCC voltage, Battery and PV power, SOC, and MMC1-HVDC voltage for the duration of SLG fault.

4.3. Battery Based Excess Energy Control During Fault at PCC1

The PV-battery combination supports the FRT and power smoothing during the faults and change of environment condition. In the previous section, PV-based FRT was demonstrated. Active power curtailment is efficient if the battery is fully charged. However, lightly charged battery could be used to take the extra energy during the fault at PCC1 without PV power curtailment. As the battery is a power-limited device, this work has considered an oversized battery for the FRT and power leveling purpose. Hence, this work uses a battery to capture the excess energy in the HVDC link during the fault at PCC1 while keeping the PV power unaffected. As can be seen from Figure 22, PV power remains unchanged while the battery is charged proportionally with the increase of PCC voltage.
during the 3LG fault at PCC1. When PCC voltage exceeds 1.05 pu, PV energy is delivered to the battery, which in turn keeps the HVDC link voltage below 1.2 pu. During this time, the state of charge (SOC) has increased from 69.85% to 70.3%. Figure 23 shows that the MMC1 has injected the maximum reactive current to PCC1 to support the PCC1 voltage. However, delivered real power is zero during 3LG fault at PCC1. Similarly, DLG fault at PCC1 has increased the HVDC link voltage, which has increased the PCC voltage, as shown in Figure 24. Consequently, the battery is charged when the PCC voltage exceeds 1.05 pu, while PV power is maintained constant. Battery charging has limited the HVDC link voltage within 1.06 pu. However, the energy delivered into the battery is less compared to 3LG fault. In contrast, Figure 25 points out that the MMC1 transfers around 50 MW to PCC1 during DLG fault, which is greater than 3LG fault. Besides, the delivered real current for both cases is 1.1 pu, whereas the reactive current is slightly less for DLG fault than 3LG fault. During DLG fault, the state of charge (SOC) has increased from 68.31% to 68.38%. Figure 26 shows the battery response during SLG fault at PCC1. As can be seen from Figure 27, MMC1 has transferred almost the same power as before the SLG fault and injected leading reactive current. Note that 3LG, DLG and SLG faults are 1 s duration faults and are applied at 1 s separately. As a result, HVDC link and PCC voltage have not been increased, and thereby, have not charged the battery as illustrated in Figure 26. Both DLG and SLG fault have introduced double frequency oscillation in the real and reactive current, but no such oscillation is observed during 3LG fault. In all cases, the battery has effectively absorbed the excess energy from the HVDC link and thus protected the HVDC link without PV power reduction and DBR.

Figure 27. Id and Iq current and power of MMC1 for the period of SLG fault.
delivered real power of MMC1 encounters negligible overshoot during such change. In both cases, battery compensates the shortage of PV power due to temperature fluctuation.

Figure 28. Solar radiation, Battery and PV power, SOC, and power of MMC1.

Figure 29. Solar radiation, Battery and PV power, SOC, and power of MMC1.
3.39 6.66 9.93 13.19 16.46 19.73 23

Figure 29. Solar radiation, Battery and PV power, SOC, and power of MMC1.

Figure 30. Temperature, Battery and PV power, SOC, and power of MMC1.

4.5. Charging and Discharging of Battery

From the VSC controller of the battery, as depicted in Figure 2b, the battery can be charged and discharged by setting the $P_{\text{Battery}}$ to positive or negative. The positive value of $P_{\text{Battery}}$ indicates discharging, whereas the negative value of $P_{\text{Battery}}$ indicates charging. Figures 32 and 33 illustrate the battery charging and discharging. As can be seen from Figure 32, the battery is charged at 50% nominal power of PV array (1.74 MW), which reduces 0.87 MW net power injection from 1.74 MW at the PCC. Therefore, the power injection due to 56 units of PV array at the PCC1 reduces from around 96 MW to 47 MW. Normally, the battery is charged with a small percentage of PV power over a longer duration. However, high charging operation has been carried out in Figure 32 to show the significant charging profile change within a short period. The state of charge (SOC) of battery is increased from 73.5% to 78% within this period. Apart from power leveling due to temporary solar radiation and temperature change, the battery is discharged at night. As can be seen from Figure 33, the PV array power is zero, and the battery is discharged at 0.87 MW power to the PCC. As the PV power is zero, the net power is equal to the battery power. Fifty-six units of PV–battery combination yield around 46.7 MW power at PCC1. The state of charge is reduced from 80% to 73% within this period. Charging and discharging of the battery is performed during the constant PCC voltage. However, balanced and unbalanced fault at PCC1 changes the PCC voltage, which switches the battery's normal operation to excess energy control mode in the HVDC link.

Figure 31. Temperature, Battery and PV power, SOC, and power of MMC1.
4.4. Battery Based Power Levelling During Solar Radiation and Temperature Change

4.4.1. Solar Radiation Change

The solar radiation is changed from 1000 Wm\(^{-2}\) to 100 Wm\(^{-2}\) to evaluate the efficacy of the battery controller. As can be seen from Figure 28, battery compensates the shortage of PV power due to the reduction of solar radiation. PV power is reduced from 1.74 MW to 0.1 MW, whereas battery power is increased from zero to 1.6 MW. During this period, the battery state of charge is decreased from 81.1% to 80.6%. The real power delivery through the MMC1 remains almost constant. Similarly, delivered battery power is reduced from 1.6 MW to zero during the solar radiation that changed from 100 Wm\(^{-2}\) to 1000 Wm\(^{-2}\), as depicted in Figure 29. During this time, PV power is increased from 0.1 MW to 1.74 MW, and the battery state of charge is decreased from 73.4% to 72.85%. The delivered real power of MMC1 encounters negligible overshoot during the transient but maintains constant power in the steady-state.

4.4.2. Temperature Change

Figures 30 and 31 show the change of battery power to compensate the PV power fluctuation caused by the temperature change. As can be seen from Figure 30, the temperature is changed

![Figure 32. Battery charging.](image-url)
from 25 °C to 50 °C, which reduces the PV power from 1.74 MW to 1.55 MW. During this period, the battery injects from zero to 0.2 MW power to fill up the shortage, which in turn maintains the MMC1 delivered power constant. Similarly, battery power is reduced from 0.2 MW to zero, whereas PV power is increased from 1.55 MW to 1.74 MW during the temperature change from 50 °C to 25 °C. The delivered real power of MMC1 encounters negligible overshoot during such change. In both cases, battery compensates the shortage of PV power due to temperature fluctuation.

4.5. Charging and Discharging of Battery

From the VSC controller of the battery, as depicted in Figure 2b, the battery can be charged and discharged by setting the $P_{\text{Battery}}$ to positive or negative. The positive value of $P_{\text{Battery}}$ indicates discharging, whereas the negative value of $P_{\text{Battery}}$ indicates charging. Figures 32 and 33 illustrate the battery charging and discharging. As can be seen from Figure 32, the battery is charged at 50% nominal power of PV array (1.74 MW), which reduces 0.87 MW net power injection from 1.74 MW at the PCC. Therefore, the power injection due to 56 units of PV array at the PCC1 reduces from around 96 MW to 47 MW. Normally, the battery is charged with a small percentage of PV power over a longer duration. However, high charging operation has been carried out in Figure 32 to show the significant charging
profile change within a short period. The state of charge (SOC) of battery is increased from 73.5% to 78% within this period. Apart from power leveling due to temporary solar radiation and temperature change, the battery is discharged at night. As can be seen from Figure 33, the PV array power is zero, and the battery is discharged at 0.87 MW power to the PCC. As the PV power is zero, the net power is equal to the battery power. Fifty-six units of PV–battery combination yield around 46.7 MW power at PCC1. The state of charge is reduced from 80% to 73% within this period. Charging and discharging of the battery is performed during the constant PCC voltage. However, balanced and unbalanced fault at PCC1 changes the PCC voltage, which switches the battery’s normal operation to excess energy control mode in the HVDC link.

5. Conclusions

This research has developed a rapid active power control technique for fault ride-through support of the PV-battery-connected MMC-HVDC system. The proposed technique has replaced the dynamic braking resistor-based excess energy control in the HVDC link with fast active power curtailment. Besides this, a control strategy has been developed for the battery for both power levelling purpose during solar radiation and temperature fluctuation under normal condition of AC grids and fault ride-through improvement during fault at the point of common coupling of AC grids. An isolated AC grid has been formed that employs feedforward controller. A modified incremental conductance method has been used for optimum solar energy tracking. The complete system with the detailed model has been implemented in RTDS. The results confirmed the efficacy of active power reduction technique for keeping the HVDC link voltage around the threshold limit during the severe AC side disturbances. In addition, the battery-included system has improved the transient performance during normal and faulty conditions. The proposed controller improves low voltage ride through by supporting reactive power while remaining connected to the network without limit violations of converter current and HVDC link voltage under severe faults.

Author Contributions: Conceptualization, M.I.H.; methodology, M.I.H. and M.A.A.; software, M.I.H.; validation, M.I.H. and M.A.A.; formal analysis, M.I.H. and M.A.A.; investigation, M.I.H.; resources, M.A.A.; data curation, M.I.H.; writing—original draft preparation, M.I.H.; writing—review and editing, M.A.A.; visualization, M.I.H.; supervision, M.A.A.; project administration, M.A.A.; funding acquisition, M.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge the support provided by King Fahd University of Petroleum & Minerals through the Research Group funded project #DF191004. The authors also acknowledge the funding support by King Abdullah City for Atomic and Renewable Energy (K.A. CARE), Energy Research & Innovation Center (ERIC) at KFUPM.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

*PV and Battery Side Converter:*

- VSC-PV: Voltage source converter for PV
- VSC-B: Voltage source converter for Battery
- PV: Photovoltaic
- MPPT: Maximum power point tracking
- PCC: Point of common coupling
- R, L: Reactor resistance and inductance
- \(i_{gd} & i_{gq}\): PCC d-q axis current
- \(\omega_0\): PCC angular frequency
- \(V_d & V_q\): VSC terminal d-q axis voltage
- \(V_{gd} & V_{gq}\): PCC d-q axis voltage
- C: DC link capacitance
- \(I_{dc}\): DC link current
**Modular Multilevel Converter (MMC):**

- **PCC1** Point of common coupling of AC grid 1
- **R, L** Arm reactor resistance and inductance
- **ω₀** AC grid angular frequency
- **V_s, I_s** 3-phase voltage and current
- **i_{dq}** d-q axis current of I_s
- **V_{sd}, V_{sq}** d-q axis voltage of V_s
- **V_d, V_q** MMC terminal d-q axis voltage
- **I_{ext}** HVDC link current
- **V_{DC}** HVDC link voltage
- **C_d** DC link pole-to-pole capacitance
- **N** number of submodules
- **C** Submodule capacitance
- **V_{d1}, V_{q1}** Negative sequence d-q axis voltage
- **i_{d1}, i_{q1}** Negative sequence d-q axis current
- **SLG** Single line to ground
- **DLG** Double line to ground
- **3LG** Three line to ground
- **DBR** Dynamic braking resistor
- **FRT** Fault ride through

**Appendix A**

### Table A1. Photovoltaic Array and battery parameters.

| Parameters                                      | Value |
|------------------------------------------------|-------|
| **Photovoltaic Module Data**                   |       |
| Cells per module                               | 36    |
| Short circuit current (A)                       | 3.35  |
| Open circuit voltage (V)                        | 21.7  |
| Current at MPP (A)                              | 3.05  |
| Voltage at MPP (V)                              | 17.4  |
| Temperature coefficient of Isc (%/degree)       | 0.065 |
| Temperature coefficient of Voc (%/degree)       | −0.56 |
| **Photovoltaic Array Data**                    |       |
| Series connected modules per string             | 115   |
| Parallel strings                                | 285   |
| One PV array nominal capacity (MW)              | 1.74  |
| Total Number of PV array unit, M                | 55    |
| **Battery Data**                                |       |
| The capacity of a single cell (AH)              | 0.85  |
| Number of cells in series in a stack            | 250   |
| Number of stacks in parallel                    | 1090  |
| **Controller and VSC Parameters for PV/Battery**|       |
| Nominal DC-link Voltage (kV)                    | 2     |
| Rated power (MVA)                               | 2.2   |
| Resistance (pu)                                 | 0.004 |
| Inductance (pu)                                 | 0.15  |
| PI₄ (pu)                                        | (1 + 100/s) |
| PI₃ (pu)                                        | (0.64 + 5/s) |
| PI₂₃ (pu)                                       | (5 + 5/s) |
| PI₁₂₃ (pu)                                      | (20 + 15/s) |
| PI₁₂ (pu)                                       | (3 + 10/s) |
Table A2. MMC Controller parameters.

| Parameters                      | Value          |
|---------------------------------|----------------|
| Rated DC link voltage (kV)      | 200            |
| Rated power (MW)                | 200            |
| Rated frequency (Hz)            | 50             |
| Rated voltage (L-L) (kV)        | 100            |
| Inductance, L (pu)              | 0.2            |
| SM/arm                          | 200            |
| Resistance, R (pu)              | 0.002          |
| Modulation Nearest level        |                |
| \( P_{I_4} \) (pu)             | \(4 + 100/s\)  |
| \( P_{I_6} \) (pu)             | \(0.17 + 1/s\) |
| \( P_{I_7} \) (pu)             | \(0.6 + 6/s\)  |
| \( P_{I_8} \) (pu)             | \(0.6 + 6/s\)  |

References

1. Khan, S.A.; Hossain, M.I. Intelligent control based maximum power extraction strategy for wind energy conversion systems. In Proceedings of the 2011 24th Canadian Conference on Electrical and Computer Engineering (CCECE), Niagara Falls, ON, Canada, 11 May 2011; pp. 001040–001043.
2. Hossain, M.I.; Khan, S.A.; Shaﬁullah, M.; Hossain, M.J. Design and implementation of MPPT controlled grid connected photovoltaic system. In Proceedings of the 2011 IEEE Symposium on Computers & Informatics, Kuala Lump, Malaysia, 20–22 March 2011; pp. 284–289.
3. IRENA. Renewable Power Generation Costs in 2019; IRENA: Abu Dhabi, UAE, 2019. Available online: https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019 (accessed on 15 July 2020).
4. Hossain, M.I.; Shaﬁullah, M.; Abido, M. VSC controllers for multiterminal HVDC transmission system: A comparative study. Arab. J. Sci. Eng. 2020, 45, 1–12. [CrossRef]
5. Haleem, N.M.; Rajapakse, A.D.; Gole, A.M.; Fernando, I.T. Investigation of fault ride-through capability of hybrid VSC-LCC multi-terminal HVDC transmission systems. IEEE Trans. Power Deliv. 2019, 34, 241–250. [CrossRef]
6. Alassi, A.; Bañales, S.; Ellabban, O.; Adam, G.; MacIver, C. HVDC transmission: Technology review, market trends and future outlook. Renew. Sustain. Energy Rev. 2019, 112, 530–554. [CrossRef]
7. Li, Z.; Zhan, R.; Yazhou, L.; He, Y.; Hou, J.; Zhao, X.; Zhang, X.P. Recent developments in HVDC transmission systems to support renewable energy integration. Glob. Energy Interconnect. 2018, 1, 595–607.
8. Hossain, M.I.; Abido, M.A. SCIG based wind energy integrated multiterminal MMC-HVDC transmission network. Sustainability 2020, 12, 3622. [CrossRef]
9. Shaﬁul Alam, M.; Abido, M.A.Y. Fault Ride-through Capability Enhancement of Voltage Source Converter-High Voltage Direct Current Systems with Bridge Type Fault Current Limiters. Energies 2017, 10, 1898. [CrossRef]
10. Alam, M.; Abido, M.; Hussein, A.; El-Amin, I. Fault ride through capability augmentation of a DFIG-based wind integrated VSC-HVDC system with non-superconducting fault current limiter. Sustainability 2019, 11, 1232. [CrossRef]
11. Raza, M.; Perfalba, M.A.; Gomis-Bellmunt, O. Short circuit analysis of an offshore AC network having multiple grid forming VSC-HVDC links. Int. J. Electr. Power Energy Syst. 2018, 102, 364–380. [CrossRef]
12. Cui, S.; Lee, H.-J.; Jung, J.-J.; Lee, Y.; Sul, S.-K. A comprehensive AC-side single-line-to-ground fault ride through strategy of an MMC-based HVDC system. IEEE J. Emerg. Sel. Top. Power Electron. 2018, 6, 1021–1031. [CrossRef]
13. Xu, L.; Andersen, B.R. Grid connection of large offshore wind farms using HVDC. Wind Energy 2006, 9, 371–382. [CrossRef]
14. Nanou, S.; Papathanassiou, S. Evaluation of a communication-based fault ride-through scheme for offshore wind farms connected through high-voltage DC links based on voltage source converter. IET Renew. Power Gener. 2015, 9, 882–891. [CrossRef]
15. Cui, S.; Lee, H.-J.; Jung, J.-J.; Lee, Y.; Sul, S.-K. A comprehensive AC side single line to ground fault ride through strategy of a modular multilevel converter for HVDC system. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 20–24 September 2015; pp. 5378–5385.

16. Oguma, K.; Akagi, H. Low-voltage-ride-through (LVRT) control of an HVDC transmission system using two modular multilevel DSCC converters. *IEEE Trans. Power Electron.* 2017, 32, 5931–5942. [CrossRef]

17. Xu, L.; Yao, L. DC voltage control and power dispatch of a multi-terminal HVDC system for integrating large offshore wind farms. *IET Renew. Power Gener.* 2011, 5, 223–233. [CrossRef]

18. Feltes, C.; Wrede, H.; Koch, F.W.; Erlich, I. Enhanced fault ride-through method for wind farms connected to the grid through VSC-based HVDC transmission. *IEEE Trans. Power Syst.* 2009, 24, 1537–1546. [CrossRef]

19. Harnefors, L.; Jiang-Häfner, Y.; Hyttinen, M.; Jonsson, T. Ride-through methods for wind farms connected to the grid via a VSC-HVDC transmission. *Environ. Sci.* 2007.

20. Ramtharan, G.; Arulampalam, A.; Ekanayake, J.B.; Hughes, F.M.; Jenkins, N. Fault ride through of fully rated converter wind turbines with AC and DC transmission systems. *IET Renew. Power Gener.* 2009, 3, 426–438. [CrossRef]

21. Olowookere, O.; Skarvelis-Kazakos, S.; Habtay, Y.; Woodhead, S. AC fault ride through of modular multilevel converter VSC-HVDC transmission systems. In Proceedings of the 2015 50th International Universities Power Engineering Conference (UPEC), Stoke-on-Trent, UK, 1–4 September 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 1–6.

22. Chaudhary, S.K.; Teodorescu, R.; Rodriguez, P.; Kjær, P.C. Chopper controlled resistors in VSC-HVDC transmission for WPP with full-scale converters. In Proceedings of the 1st IEEE-PES/IAS Conference on Sustainable Alternative Energy, SAE 2009, Valencia, Spain, 28–30 September 2009; IEEE: Piscataway, NJ, USA, 2009.

23. Jiancheng, T.; Haili, G.; Guangzong, C. LVRT control strategy of VSC-HVDC connected large PV plant. In Proceedings of the 2017 China International Electrical and Energy Conference: CIEEC 2017, Beijing, China, 25–27 October 2018; IEEE: Piscataway, NJ, USA, 2017; pp. 504–509.

24. Neely, J.; Johnson, J.; Delhotal, J.; Gonzalez, S.; Lave, M. Evaluation of PV frequency-watt function for fast frequency reserves. In Proceedings of the Conference Proceedings—IEEE Applied Power Electronics Conference and Exposition—APEC, Long Beach, CA, USA, 12 May 2016; pp. 1926–1933.

25. Roy, T.K.; Mahmud, M.A. Active power control of three-phase grid-connected solar PV systems using a robust nonlinear adaptive backstepping approach. *Sol. Energy* 2017, 153, 64–76. [CrossRef]

26. Rodriguez, P.; Timbus, A.V.; Teodorescu, R.; Liserre, M.; Blaabjerg, F. Flexible active power control of distributed power generation systems during grid faults. *IEEE Trans. Ind. Electron.* 2007, 54, 2583–2592. [CrossRef]

27. Datta, M.; Senjyu, T.; Yona, A.; Funabashi, T.; Kim, C.H. A frequency-control approach by photovoltaic generator in a PV-diesel hybrid power system. *IEEE Trans. Energy Convers.* 2011, 26, 559–571. [CrossRef]

28. Craciun, B.I.; Kerekes, T.; Sera, D.; Teodorescu, R. Frequency support functions in large PV power plants with active power reserves. *IEEE J. Emerg. Sel. Top. Power Electron.* 2014, 2, 849–858. [CrossRef]

29. Hoke, A.F.; Shirazi, M.; Chakraborty, S.; Muljadi, E.; Maksimovic, D. Rapid active power control of photovoltaic systems for grid frequency support. *IEEE J. Emerg. Sel. Top. Power Electron.* 2017, 5, 1154–1163. [CrossRef]

30. Shi, H.; Zhuo, F.; Yi, H.; Wang, F.; Zhang, D.; Geng, Z. A novel real-time voltage and frequency compensation strategy for photovoltaic-based microgrid. *IEEE Trans. Ind. Electron.* 2015, 62, 3545–3556. [CrossRef]

31. Gevorgian, V.; O’Neill, B. Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants; National Renewable Energy Laboratory: Golden, CO, USA, 2016; p. 102.

32. Daoud, M.I.; Massoud, A.M.; Abdel-Khalik, A.S.; Elserougi, A.; Ahmed, S. A flywheel energy storage system for fault ride through support of grid-connected VSC HVDC-based offshore wind farms. *IEEE Trans. Power Syst.* 2016, 31, 1671–1680. [CrossRef]

33. Daoud, M.I.; Massoud, A.; Ahmed, S.; Abdel-Khalik, A.S.; Elserougi, A. Ride-through capability enhancement of VSC-HVDC based wind farms using low speed flywheel energy storage system. In Proceedings of the Conference Proceedings—IEEE Applied Power Electronics Conference and Exposition—APEC, Fort Worth, TX, USA, 16–20 March 2014; pp. 2706–2712.
34. Ahmed, K.H.; Abdel-Khalik, A.S.; Elserougi, A.; Massoud, A.; Ahmed, S. Fault ride-through capability enhancement based on flywheel energy storage system for wind farms connected via VSC high voltage DC transmission. In Proceedings of the IET Conference Publications, Birmingham, UK, 4–5 December 2012; Volume 2012. no. 610 CP.

35. Ribeiro, P.F.; Johnson, B.K.; Crow, M.L.; Arsoy, A.; Liu, Y. Energy storage systems for advances power applications. Proc. IEEE 2001, 89, 1744–1756. [CrossRef]

36. Chen, Z.; Zou, X.; Duan, S.; Wei, H. Power conditioning system of flywheel energy storage. In Proceedings of the 8th International conference on power electronics–ECCE Asia: Green world with power electronics, ICPE 2011-ECCE Asia, Jeju, South Korea, 30 May–3 June 2011; pp. 2763–2768.

37. Battery Storage for Renewables: Market Status and Technology Outlook. Available online: https://www.irena.org/publications/2015/Jan/Battery-Storage-for-Renewables-Market-Status-and-Technology-Outlook (accessed on 15 July 2020).

38. Beza, M.; Bongiorno, M. Identification of resonance interactions in offshore-wind farms connected to the main grid by MMC-based HVDC system. Int. J. Electr. Power Energy Syst. 2019, 111, 101–113. [CrossRef]

39. Jing, Y.; Li, R.; Xu, L.; Wang, Y. Enhanced AC voltage and frequency control on offshore MMC station for wind farm. J. Eng. 2017, 2017, 1264–1268. [CrossRef]

40. Manmohan, A.; Prasad, A.; Dharavath, R.; Karthikeyan, S.P.; Raglend, I.J. Up and down conversion of photons with modified perturb and observe MPPT technique for efficient solar energy generation. Energy Procedia 2017, 117, 786–793. [CrossRef]

41. Balato, M.; Costanzo, L.; Lo Schiavo, A.; Vitelli, M. Optimization of both perturb & observe and open circuit voltage MPPT techniques for resonant piezoelectric vibration harvesters feeding bridge rectifiers. Sens. Actuators A Phys. 2018, 278, 85–97.

42. Abdel-Salam, M.; El-Mohandes, M.-T.M.; Goda, M. An improved perturb-and-observe based MPPT method for PV systems under varying irradiation levels. Sol. Energy 2018, 171, 547–561. [CrossRef]

43. Ishaque, K.; Salam, Z.; Lauss, G. The performance of perturb and observe and incremental conductance maximum power point tracking method under dynamic weather conditions. Appl. Energy. 2014, 119, 228–236. [CrossRef]

44. Putri, R.I.; Wibowo, S.; Rifa’i, M. Maximum power point tracking for photovoltaic using incremental conductance method. Energy Procedia. 2015, 68, 22–30. [CrossRef]

45. Sitbon, M.; Lineykin, S.; Schacham, S.; Suntio, T.; Kuperman, A. Online dynamic conductance estimation based maximum power point tracking of photovoltaic generators. Energy Convers. Manag. 2018, 166, 687–696. [CrossRef]

46. Yazdani, A.; Iravani, R. Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications; IEEE Press/John Wiley: Hoboken, NJ, USA, 2010.

47. Martinez-Rodrigo, F.; Ramirez, D.; Rey-Boue, A.B.; De Pablo, S.; Herrero-De Lucas, L.C. Modular Multilevel Converters: Control. and Applications. Energies 2017, 10, 1709. [CrossRef]

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