Article

Decentralized Cooperative Active Power Control for Small-Scale Grids with High Renewable Penetration through VSC-HVDC

Jihun So 1, Hyun Shin 2, Thai Nguyen Tran 1 and Yeong-Jun Choi 1,*

1 Department of Electrical Engineering, Jeju National University, Jeju 63243, Korea; lllies@jejunu.ac.kr (J.S.); thnguyen@jejunu.ac.kr (T.N.T.)
2 Korea Battery Industry Association, Jeju 63309, Korea; hshin@k-bia.or.kr
* Correspondence: yeongjun.choi@jejunu.ac.kr

Abstract: Rising renewable penetration has accelerated the volatility and instability of the power grid. A small-scale grid is especially vulnerable. Therefore, flexibility and stability enhancement are required for small-scale grids. The interconnection with the large-scale grid through the voltage sourced converter-high voltage direct current (VSC-HVDC) can be a solution to the aforementioned problems. VSC-HVDC can deliver power bidirectionally and change the direction in a short time. Hereby, the cooperative operation of distributed generations (DG) and a large-scale grid through the VSC-HVDC system is proposed in this paper. The VSC-HVDC will take the role of the main source of the small-scale grid. It determines the grid frequency based on its output power. DGs adjust their output power according to the grid frequency, and then the balance between the demand and the supply is maintained. To verify it, a PSCAD/EMTDC simulation was conducted using actual data from Jeju Island, including transmission lines, loads, and climate. Consequently, by the proposed method, the RE share was improved and the grid was operated stably even though the fault situations.

Keywords: active power control; distributed generation; frequency control; renewable energy; small-scale grid; VSC-HVDC

1. Introduction

Over the decades, rising environmental concerns have driven the expansion of renewable energy sources (RES) and the diminution of traditional generations. The instability of the grid caused by declining synchronous generators has been an upcoming issue. Moreover, wind and solar energy are strongly related to the weather, and they inevitably accompany the intermittency. Notably, small-scale grids, such as the Jeju Island grid, react more sensitively.

Jeju Island is facing challenges with the drastic expansion of RESs. Therefore, an appropriate grid operation method is required to prepare for the spreading RESs in the coming future. Jeju Island grid consists of massive wind turbine generators (WTG) and photovoltaics (PV), as shown in Figure 1, and they are expanding continuously. The Jeju Island grid belongs to phase 3 of the integration of renewables so far, and it has been predicted that the phase will rise in six to ten years [1–3]. Additionally, rapidly disseminating electric vehicles (EV) make it difficult to forecast the peak load [1]. Curtailments were implemented 77 times in 2020, and it is expected that more curtailments will occur [4–6]. The Jeju Island grid is bound to become a highly volatile system in the future. Therefore, the traditional system operation method is no longer suitable for the Jeju Island grid and a suitable operation method is needed.
The method of reducing RE curtailments and enhancing grid flexibility by adding energy storage systems (ESS) was proposed [7–9]. However, the ESS has several considerations, including management of state-of-charge and heat flow. The hierarchical control structure of ESS, which is controlled by a transmission system operator’s (TSO) order, is insufficient to cover the high volatility of the grid. The power-to-heat method is introduced to mitigate the limitations of WTG and PV in the literature [10,11]. Similarly, a compensating method for the fluctuation of RES with power-to-gas was suggested [12–14]. It is difficult to handle the instability of the utility-scale system with the above sector-coupling technologies because of the lack of infrastructure and maturity. In addition, EV charging management to reduce grid operation costs and RESs curtailment was proposed [15]. However, there are hurdles such as policy restrictions and retaining the EVs for a sufficient amount of discharge.

In addition, methods to ensure the stability of power supply demand and improve the system robustness by interconnecting with a large-scale grid through HVDC have been proposed [16–18]. Each grid is decoupled by the DC stage of the HVDC, so it is suitable for linking nonsynchronous grids, such as those for islands, over long distances. In the early days, the HVDC system was designed as a line commutated converter (LCC) type for large-scale power transmission [19,20]. However, LCC-HVDC, which requires a minimum operating capacity and a relatively long time to change the direction of power flow, is unable to cope with the volatility of massive RESs [21–25]. Accordingly, newly installed HVDCs adopt the voltage-sourced converter (VSC) type. With advances in semiconductor devices and control methods, a large-capacity operation is also possible for VSC-HVDC. It can change the power transfer direction faster than LCC-HVDC [26–31]. Recently, solutions for improving grid stability based on the VSC-HVDC have been studied. The frequency regulation methods using VSC-HVDC were presented [32,33]. However, the VSC-HVDC is connected with an individual RES, it is hard to stabilize the entire grid or cooperate with other grids. A stabilization approach for a large grid was demonstrated in [34]. In this case, there is a huge generational capacity of traditional power plants, and VSC-HVDCs are used to connect large-scale grids, so they are not suitable for the small-scale grid with high renewable penetration.
Therefore, in this paper, a method of securing grid flexibility and improving RE accommodation for small-scale grids is proposed. Simulation analysis was conducted using PSCAD/EMTDC for Jeju Island, where VSC-HVDC is planned to be installed in 2023, and actual transmission line, load, and weather data were reflected.

In the case that the traditional power generation source, which has contributed significantly to maintaining the stability of the grid, is reduced, inverter-based power generation sources should maintain the reference voltage and frequency of the grid instead of the traditional ones. In this paper, a method to improve the uncertainty of RES and secure system stability by adjusting the output power of DGs through VSC-HVDC (HVDC no. 3), depicted in Figure 2, was proposed. HVDC no. 3 performs constant voltage variable frequency (CVVF) control to regulate grid voltage and frequency.

Figure 2. The overview of the proposed control method.

HVDC no. 3, which plays the role of the main source in the Jeju Island grid, operates like an uninterruptible power supply to maintain the grid voltage and frequency band of the grid. Where the nominal voltage of the mainland and of the Jeju Island grid is 154 kV. HVDC no. 3 keeps the voltage of the Jeju Island grid nominal and determines the frequency by the P-f droop control based on its output power. DGs such as WTG, PV, and HVDC no. 1&2 perform f-P droop control that adjusts their output power according to changes in grid frequency. The proposed method has a relatively fast response speed because it regulates the output power of each of the DGs using the grid frequency as a medium without exchanging an extra control signal.

If the proposed control method is applied, the output power of each DG is determined through the grid frequency, so the system can be operated without the TSO’s instruction, so the response speed can be increased. In addition, since HVDC no. 3 can transmit power in both directions, the intermittency of RESs can be compensated. Furthermore, RE, which had been discarded by curtailment during over-generation, can be minimized.

The remaining parts of this paper are organized as follows: the system description of each source is introduced in Section 2. In Section 3, the proposed decentralized active power control method for regulating the grid frequency and adjusting the output power
of DGs was presented. In Section 4, the simulation results are analyzed, and finally, the conclusion is summarized in Section 5.

2. System Descriptions

Figure 3 shows a grid frequency regulating method through VSC-HVDC (HVDC no. 3). The back-to-back structure consisting of a large-scale grid side converter and a small-scale grid side converter is widely used for VSC-HVDC [31], where small-scale grid refers to the Jeju Island grid, as illustrated in Figure 1. Both converters perform outer (voltage)—inner (current) double-loop control. Typically, the large-scale grid side converter keeps the voltage across the DC-link capacitor constant. The external loop of the small-scale grid side converter generates 3-phase voltage and outputs the current references expressed in Equations (3) and (4) through the PI regulator expressed in Equations (1) and (2). Where, \( u_{dv} \) and \( u_{qv} \) are the output signal of the PI regulator. \( K_{pv} \) and \( K_{iv} \) are the proportional gain and the integral gain respectively. \( i_{g} \), \( i \), and \( v_{g} \) indicate the grid current, converter output current, and grid voltage, respectively. \( C \) is the filter capacitance, as shown in Figure 3.

\[
\begin{align*}
\dot{u}_{dv} &= (K_{pv} + \frac{K_{iv}}{s})(v_{g,d}^* - v_{g,d}) \\
\dot{u}_{qv} &= (K_{pv} + \frac{K_{iv}}{s})(v_{g,q}^* - v_{g,q}) \\
i_{g,d}^* &= u_{dv} - \omega C v_{g,q} + i_{g,d} \\
i_{g,q}^* &= u_{qv} + \omega C v_{g,d} + i_{g,q}.
\end{align*}
\]

The inner loop receives a command from the outer loop and performs power control, as expressed in Equations (5)–(8). As shown in Equations (5) and (6), the compensator of the inner loop was a PI regulator. By Equations (7) and (8), the final output of the controller [35,36]. Where, \( u_{dc} \) and \( u_{qc} \) are the output signal of the PI regulator. \( K_{pc} \) and \( K_{ic} \)
are the proportional gain and the integral gain, respectively. $U_{dc\_link}$ is the DC-link voltage of HVDC no. 3 and the $L$ is the filter inductance, as depicted in Figure 3.

$$u_{dc} = (K_p + \frac{K_{dc}}{s})(i_d^* - i_d)$$  \hfill (5)$$

$$u_{iq} = (K_p + \frac{K_{dc}}{s})(i_q^* - i_q)$$  \hfill (6)$$

$$v_d^* = \frac{2}{U_{dc\_link}}(u_{dc} - \omega L_i + v_{g\_d})$$  \hfill (7)$$

$$v_q^* = \frac{2}{U_{dc\_link}}(u_{iq} + \omega L_i + v_{g\_q})$$  \hfill (8)$$

Equations (1)–(8) are dealt with in the synchronous reference frame, and the frequency and phase required for dq transform and inverse transform are determined by $P_3$ (HVDC no. 3 output power), as depicted in Figure 3. Through the above process, HVDC no. 3 takes on the role of the main power source that generates the reference voltage and frequency of the Jeju Island grid. Where, the voltage command maintains the nominal value of the Jeju Island grid, and the frequency command is adjusted within a predefined range. The details of the frequency regulation are discussed in Section 3.

Figure 4 shows the output power control method of HVDC no. 1&2. Due to the structural characteristics of LCC-HVDC, it is not easy to change the direction of power flow, so HVDC no. 1 and no. 2 transmit power in a negative direction (the Jeju Island grid to the mainland) and a positive direction (the mainland to the Jeju Island grid), respectively. Like VSC-HVDC, a large-scale grid side converter takes charge of the DC stage for inter-grid connection, and a small-scale grid side converter controls the output power. The command of each HVDC is determined according to the grid frequency. The current command is calculated through the Current Reference Calculator as shown in Figure 4, and power is supplied or absorbed according to the grid situation.

Figure 5 shows the control process of WTG. In this paper, the type 4 WTG model was used. Basically, since it is a variable wind speed generator, the actuator uses the maximum power point tracking (MPPT) algorithm by controlling the pitch angle and rotor speed so that WTG can capture maximum wind energy [37–39]. In addition, constant power control is performed above the rated wind speed. In general, PMSG is connected to the grid through a full-converter. The grid-side converter is responsible for maintaining the DC-link voltage, and the generator-side converter controls the output power [39,40]. In this paper, WTGs operate in MPPT and power adjustment modes according to the grid situation, and the mode is switched based on the grid frequency. If the grid frequency is upregulated, WTG reduces the output power by lowering the power reference until the grid frequency returns to its nominal, as depicted in Figure 5.

Figure 4. HVDC no. 1&2 control method.

Figure 5. Wind turbine generator control method.
Figure 6 shows the output power generation process of the PV. In this study, since a large-capacity PV power plant was simulated, the system was configured as a two-stage system consisting of a DC/DC boost converter and a DC/AC inverter. Like other DGs, the DC/AC inverter operates to connect with the grid. The boost converter extracts the energy generated by the PV by regulating the voltage of the PV. In general, the PV converter applies a P&O algorithm to perform MPPT control [41–43], which adjusts the voltage to output maximum power according to the amount of irradiation and temperature. As in the case of wind power generators, depending on the grid situation, PV outputs its maximum power or cuts down the reference, as shown in Figure 6.

3. Decentralized Active Power Control

When \( P_3 \), which is HVDC no. 3 output power, is within the dead band, the grid frequency is maintained at nominal. RESs operate in MPPT mode, and HVDC no. 1&2 only output the minimum power. HVDC no. 3 responds quickly to load changes to balance supply and demand. When the load increases or the MPP of the RESs decreases due to a change in weather, \( P_3 \) rises. When \( P_3 \) enters between the upper threshold (130 MW) and upper limit (200 MW), HVDC no. 3 lowers the grid frequency, as shown in Figure 7. Accordingly, all DGs keep the operation state except HVDC no. 2. At this moment, HVDC no. 2 is controlled to output more power, and if \( P_3 \) reaches the upper limit, it outputs its maximum. Conversely, when the load decreases or the amount of power generated by the RESs increases, \( P_3 \) begins to decrease. When \( P_3 \) is located at the increment band, the grid frequency becomes higher than the nominal frequency, HVDC no. 2 then outputs its minimum. The other DGs also adjust their output power. RESs start to reduce supply, and HVDC no. 1, which supports HVDC no. 3, delivers more power to the mainland. As mentioned earlier, LCC-HVDC has a must-run capacity, so it must transmit the minimum capacity regardless of the grid frequency.

In addition, when the load is momentarily increased due to EV charging, heating/cooling load, factory load, etc., the frequency may drop sharply. The combined cycle power plant has a fast start-up ability; hence, it has been used to compensate for the varying power and improve the load flexibility [44–46]. Hereby, in the proposed method, the thermal power plants (T/P) provide additional power based on a predetermined frequency to contribute to grid stabilization, as shown in Figure 8. If the grid frequency descends below the predetermined value, T/Ps participate in a power supply in order until the grid frequency recovers. In T/PI, as illustrated in Figure 1, a generator of 114 MW starts-up at 59.95 Hz and 59.9 Hz, respectively, and in T/P2, a generator of 105 MW begins to operate at 59.95 Hz, which is given by Equation (9). \( n \) is the number of power plants.

\[
P_{T/P} = \begin{cases} 
0, & f_g > f_1 \\
\sum_{k=1}^{n} P_{T/Pk}, & f_k < f_g \leq f_{k+1}
\end{cases} \quad (9)
\]
In the proposed method, the output power of DGs changes through the grid, frequency determined by HVDC no. 3, as depicted in Figure 2. As explained above, each DG adjusts its own production according to the grid frequency. The frequency reference is adjusted by changing $f_{g,adj}$ from the nominal frequency as follows:

$$f^* = f_{g,nom} + f_{g,adj}$$  \hspace{1cm} (10)$$

The adjustable term $f_{g,adj}$ can be expressed by p.u. as

$$f_{g,adj} = f_{g,base} \cdot f_{g,pu}$$  \hspace{1cm} (11)$$

By considering the frequency bands, as described in Figure 7, $f_{g,pu}$ can be summarized as

$$f_{g,pu} = \begin{cases} 
\frac{f^* - f_{g,nom}}{P_{g,lim} - P_{g,thr}} \cdot \left( \frac{P_{g,nom} - P_{g,thr}}{f_{g,base}} \right), & P_{g,nom} - P_{g,thr} \leq P_3 \leq P_{g,lim} \\
0, & P_{g,thr} \leq P_3 \leq P_{g,thr} \\
\frac{f^* - f_{g,nom}}{P_{g,lim} - P_{g,thr}} \cdot \left( \frac{P_{g,thr} - P_{g,nom}}{f_{g,base}} \right) - P_{g,thr}, & P_{g,thr} - P_{g,lim} \leq P_3 < P_{g,thr}
\end{cases}$$  \hspace{1cm} (12)$$

Figure 7. HVDC no. 3 power-frequency droop control.

Figure 8. Thermal power plant operation sequence.
Through the above process, HVDC no. 3 regulates the grid frequency, as shown in Figure 7. The output of the DGs can also be obtained in a similar way as follows:

\[
P^*_1 = P_{1,min} + P_{1,adj}
\]

(13)

\[
P^*_2 = P_{2,min} + P_{2,adj}
\]

(14)

\[
P^*_\text{wtg} = P_{\text{wtg,max}} + P_{\text{wtg,adj}}
\]

(15)

\[
P^*_\text{pv} = P_{\text{pv,max}} + P_{\text{pv,adj}}
\]

(16)

The output power of HVDC no. 1&2 are expressed in Equations (13) and (14), respectively, and the outputs of WTG and PV are determined by Equations (15) and (16), respectively. For HVDC no. 1&2, the command is changed by \(P_{1,adj}\), \(P_{2,adj}\) based on the minimum operating capacity. Similarly, RESs output is adjusted by \(P_{\text{wtg,adj}}\), \(P_{\text{pv,adj}}\) based on each maximum output. The \(P_{adj}\) terms are summarized as follows:

\[
P_{1,adj} = P_{1,base} \cdot A_{pu}
\]

(17)

\[
P_{2,adj} = P_{2,base} \cdot A_{pu}
\]

(18)

\[
P_{\text{wtg,adj}} = P_{\text{wtg,base}} \cdot A_{pu}
\]

(19)

\[
P_{\text{pv,adj}} = P_{\text{pv,base}} \cdot A_{pu}
\]

(20)

Finally, the commands of each DG are simultaneously adjusted by one factor, \(A_{pu}\), as depicted in Figure 9. HVDC no. 1, which is in charge of reverse power transfer, outputs only the minimum capacity in the decrement band and changes the output according to \(A_{pu}\) in the increment band. As \(A_{pu}\) approaches \(-1\), the output increases, and when \(A_{pu}\) reaches \(-1\), HVDC no. 1 transmits its maximum. Since HVDC no. 2 transmits power in the forward direction, only the minimum power is supplied in the increment band. In the decrement band, the output is adjusted in proportion to \(A_{pu}\), and when \(A_{pu}\) is 1, HVDC no. 2 delivers the maximum power. WTG and PV operate in MPPT mode in the decrement band, and output changes according to \(A_{pu}\) in the increment band. When \(A_{pu}\) reaches \(-1\), RESs stop generating power. The parameters used in Equations (10)–(20) are listed in Table 1.

![Figure 9. Distributed generation frequency-power droop control.](image-url)
Table 1. Decentralized active power control parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{g, nom} )</td>
<td>60</td>
<td>Hz</td>
</tr>
<tr>
<td>( f_{g, base} )</td>
<td>−0.2</td>
<td>Hz</td>
</tr>
<tr>
<td>( P_{1, \text{min}} )</td>
<td>−40</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{1, \text{base}} )</td>
<td>−110</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{2, \text{min}} )</td>
<td>40</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{2, \text{base}} )</td>
<td>210</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{\text{wtg, max}} )</td>
<td>( P_{\text{wtg, mppt}} )</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{\text{wtg, base}} )</td>
<td>( P_{\text{wtg, mppt}} )</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{\text{pv, max}} )</td>
<td>( P_{\text{pv, mppt}} )</td>
<td>MW</td>
</tr>
<tr>
<td>( f_{g, \text{lim}} )</td>
<td>60.2</td>
<td>Hz</td>
</tr>
<tr>
<td>( f_{g, \text{lim}} )</td>
<td>59.8</td>
<td>Hz</td>
</tr>
<tr>
<td>( P_{3, \text{lim}} )</td>
<td>200</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{3, \text{thr}} )</td>
<td>130</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{3, \text{thr}} )</td>
<td>−200</td>
<td>MW</td>
</tr>
<tr>
<td>( P_{3, \text{thr}} )</td>
<td>−130</td>
<td>MW</td>
</tr>
</tbody>
</table>

4. Simulation Results

PSCAD/EMTDC is suitable simulation software for the analysis of electromagnetic transients, including DC, by solving differential equations [47,48]. The Jeju Island grid was established by PSCAD/EMTDC, as shown in Figure 10. To assume 2023 when HVDC no. 3 is operated, a load increase rate of 5% [49] was considered in the load data for 2021. Table 2 summarizes the power load and power generation capacity applied to the simulation.

![Figure 10. Jeju Island grid single-line diagram in PSCAD/EMTDC.](image-url)
Table 2. Load and source capacities.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak load</td>
<td>927</td>
<td>MW</td>
</tr>
<tr>
<td>Average load</td>
<td>750</td>
<td>MW</td>
</tr>
<tr>
<td>HVDC no. 1 (rating)</td>
<td>150</td>
<td>MW</td>
</tr>
<tr>
<td>HVDC no. 1 (minimum)</td>
<td>40</td>
<td>MW</td>
</tr>
<tr>
<td>HVDC no. 2 (rating)</td>
<td>250</td>
<td>MW</td>
</tr>
<tr>
<td>HVDC no. 2 (minimum)</td>
<td>40</td>
<td>MW</td>
</tr>
<tr>
<td>HVDC no. 3</td>
<td>200</td>
<td>MW</td>
</tr>
<tr>
<td>WTG</td>
<td>640</td>
<td>MW</td>
</tr>
<tr>
<td>PV</td>
<td>996</td>
<td>MW</td>
</tr>
<tr>
<td>T/P1</td>
<td>105</td>
<td>MW</td>
</tr>
<tr>
<td>T/P2</td>
<td>105</td>
<td>MW</td>
</tr>
</tbody>
</table>

In the proposed method, HVDC no. 3 exchanges power with the mainland in case of over-generation or under-generation. The output power of HVDC no. 1&2, WTG, PV, and T/P is adjusted according to the preset frequency range. Therefore, when the amount of power generation is greater than the load, power is transmitted to the mainland, and in the opposite case, power is supplied from the mainland. HVDC no. 1 transmits only reverse direction (the Jeju Island grid to the mainland), and HVDC no. 2 only transmits forward direction (the mainland to the Jeju Island grid). RESs basically perform MPPT control and adjust the output according to the grid frequency. T/Ps participate only when a certain frequency is reached as an auxiliary device.

Simulations were conducted for the following cases:
- Case 1: Normal Operation;
- Case 2: Load Rapid Rise & Decline;
- Case 3: RES Sudden Stop.

4.1. Case 1: Normal Operation

Figure 11 describes the operation result of the Jeju Island grid during normal operation without sudden changes in load or power generation or accidents. In (a), both WTG and PV showed low power generation. Since the power demand exceeds the amount of power generated by RESs, it can be confirmed that power is supplied from the mainland through HVDC no. 3. Where $P_3$ is larger than 130 MW, the grid frequency was adjusted downward, and accordingly, HVDC no. 1 maintained minimum operation and the output power of HVDC no. 2 increased. The grid frequency decreased to about 59.93 Hz, and T/P1 and T/P2 were started to participate in power supply and frequency recovery. As a result, $P_3$ dropped below $P_{3,thr}$ and the grid frequency returned to nominal, as shown in (b). In this division, wind speed and irradiation increased, and $P_{wtg}$ and $P_{pv}$ rose. At about $t = 3$ s, the WTG began to produce its maximum output. $P_{pv}$ also increased gradually, and the power generation of RESs exceeded the load from $t = 4.8$ s. The excess power was transmitted to the mainland through HVDC no. 3. Since $P_3$ did not go below $P_{3,thr}$, the grid frequency was maintained 60 Hz. Accordingly, T/Ps remained in a stand-by state, and HVDC no. 1&2 delivered only the minimum capacity. In (c), because $P_3$ reduced below $P_{3,thr}$, $f_{3,thr}$ increased as expressed in Equation (12), and the grid frequency immediately upregulated. Thus, as shown in Figure 9, $A_{pu}$ decreased, and $P_{wtg}$ and $P_{pv}$ were cut down. Contrary to (a), HVDC no. 2, T/Ps maintained the minimum output, and $P_1$ rose and the excess power was transmitted to the mainland. In (d), the load ascended and $P_{pv}$ descended, so HVDC no. 3 changed the power transmission direction from reverse to forward. In this period, $P_3$ was between $P_{3,thr}$ and $P_{3,thr}$, so the grid frequency was fixed at 60 Hz. In (e), $P_3$ becomes larger than $P_{3,thr}$, so HVDC no. 3 lowers the grid frequency, and $P_2$ and $P_{T/P}$ rose accordingly.
Figure 11. Simulation results in case 1 (Load and output power of HVDC no. 3 and DGs; grid frequency).

Figure 12 shows the proportion of RES generation during normal operation. It is calculated by dividing the total generated RE by total power load consumption. By comparing Figures 11 and 12, it can be confirmed that the output power of the WTG and the PV of Figure 11, is directly related to the RE share of Figure 12. Especially, at t = 2.9 s, surplus power occurred in the Jeju Island grid, then HVDC no. 3 transmitted it to the mainland. At this moment, RE share goes above 100 %. It peaked at 124% at t = 6 s and then dropped below 100% at t = 8.7 s. This was achieved by transmitting power to the mainland without limiting the generation by exceeding the load demand. Moreover, as shown in Figure 11, it did not deviate from the stable frequency band. The energy sent by HVDC no. 3 to the mainland for t = 2.9–8.7 s is about 1.005 GWh.

Figure 12. RE Share.

4.2. Case 2: Load Rapid Rise & Decline

Figure 13 shows the operating results of each source when the load changes rapidly. The simulated load changes are listed as follows:
• 250 MW rise at t = 5 s;
• 350 MW decline at t = 7 s;
• 100 MW rise at t = 8 s.
Figure 13. Simulation results in case 2 (Load and output power of HVDC no. 3 and DGs; grid frequency).

HVDC no. 3 and DGs adequately compensated for unexpected load occurrence or elimination, thus the grid maintained a stable state, as illustrated in Figure 13. The results of $t = 4−12$ s are shown in Figure 14 at enlarged scales. At $t = 5$ s, a 250 MW load was added abruptly. At this moment, HVDC no. 3 stopped transmitting to the mainland and supplied power to the load. At $t = 7$ s, a 350 MW load disappeared. Accordingly, HVDC no. 3 responds flexibly to load reduction by sending the power consumed by the load to the mainland. At $t = 8$ s, a 100 MW load occurred additionally. It was handled in the same way at $t = 5$ s. As a result, the grid frequency did not deviate from 59.8 Hz and 60.2 Hz. The maximum grid frequency was recorded 60.03 Hz, and the minimum was 59.93 Hz. At $t = 5−8$ s, $P_3$ increased, as shown in Figure 14. However, the period that $P_3$ is higher than $P_{3,thr}$ was only about 0.5 s, and even it was almost at the same level as $P_{thr}$. At $t = 5$ s, the grid frequency was kept within approximately 59.97 Hz, as described in Figure 14. Therefore, HVDC no. 1 maintained the minimum, and the output power of HVDC no. 2 did not change significantly. RESs continued to perform MPPT, and T/Ps did not develop. At $t = 7$ s, as the load decreases, the supply momentarily exceeds the demand, and the frequency rises. However, as $P_1$ increased, and $P_{witg}$ and $P_{pv}$ lowered, the grid frequency returned to nominal within about 1.2 s. After $t = 8.2$ s, every result showed the same as Case 1, as shown in Figure 11.

4.3. Case 3: RES Stop

Figure 15 shows the response of each source in the situation where the RES abruptly stops. The 100 MW wind farm (WF) dropped out at $t = 6$ s, and the whole PVs stopped gradually from $t = 8$ s. Although the output power of RESs was drastically reduced, HVDC no. 3 covered it through the forward power transfer. The grid frequency fell, and $P_{T/P1}$, $P_{T/P2}$, and $P_2$ were raised. Despite the large-scale shutdown of the RES, the required power was supplied to the load by the other DGs, and the grid frequency was between 60.61 Hz and 59.89 Hz. Figure 16 shows the enlarged part of $t = 4−12$ s. When 100 MW WF was dropped ($t = 6$ s), HVDC no. 3 changed the output from −40 MW to 60 MW and supplied power to the load instead of WF. After that, PV stopped at $t = 8$ s. At this moment, $P_3$ further increased. As soon as $P_3$ crossed $P_{thr}^{−}$, the grid frequency was decreased, but did not go below 59.8 Hz until the end of the simulation. Because of the grid frequency drop, $P_2$ ascended, and at $t = 8.5$ s, the frequency went below 59.5 Hz, so T/Ps began to generate power, as shown in Figure 16. As RES, which accounts for a high proportion of power generation, was eliminated significantly, HVDC no. 3 continued to absorb electricity from
the mainland. Therefore, after \( t = 8.4 \) s, \( P_3 \) was always greater than \( P_{3,rer}^+ \), and the frequency was not restored to 60 Hz. However, as mentioned earlier, it did not go below 59.8 Hz and stayed around 59.5 Hz, as depicted in Figure 16. In addition, since there is a reserve in the capacity of HVDC no. 3, HVDC no. 2 and T/Ps, they can continuously supply power to the load without any issues.

Figure 14. Zoomed plot of simulation results in case 2 (load; output power of HVDC no. 3; grid frequency; output power of HVDC no. 1&2; output power of WTG & PV; output power of T/P 1&2).
were raised. Despite the large-scale shutdown of the RES, the required $P_{T}/P_{1}$ ascended, and at $t = 8.5$ s, the frequency went below 59.5 Hz, so $T/P$ began to cross, but did not go below 59.8 Hz until the end of the simulation. Because of the grid frequency of the RES and strengthens the flexibility of the small-scale grid.

In this paper, a control method to enhance the flexibility of a small-scale grid with a high renewable penetration was presented. In the proposed method, the small-scale grid is controlled using the grid frequency, determined by the output power of VSC-HVDC, as a medium. The proposed method increases the utilization rate of DGs; grid frequency).

To verify the proposed method, simulation analysis was performed on the Jeju Island main grid. The analyzed simulation cases are as follows:

- **Case 1**: Normal Operation; grid frequency; output power of HVDC no. 1, 2; output power of WTG & PV; output power of T/P 1 & 2.
- **Case 2**: Load Rapid Rise & Decline; grid frequency; output power of HVDC no. 1, 2; output power of WTG & PV; output power of T/P 1 & 2.
- **Case 3**: Load Rapid Rise & Decline; load; output power of HVDC no. 3; grid frequency; output power of HVDC no. 1 & 2; output power of WTG & PV; output power of T/P 1 & 2.

Figure 15. Simulation results in normal operation case 3 (Load and output power of HVDC no. 3 and DGs; grid frequency).

Figure 16. Zoomed plot of simulation results in case 3 (load; output power of HVDC no. 3; grid frequency; output power of HVDC no.1 & 2; output power of WTG & PV; output power of T/P 1 & 2).
5. Conclusions

In this paper, a control method to enhance the flexibility of a small-scale grid with a high renewable penetration was presented. In the proposed method, the small-scale grid is connected to the large-scale grid through VSC-HVDC. Where VSC-HVDC plays the role of the main source of the small-scale grid. The output power of the other DGs included in the small-scale grid is controlled using the grid frequency, determined by the output power of VSC-HVDC, as a medium. The proposed method increases the utilization rate of the RES and strengthens the flexibility of the small-scale grid.

To verify the proposed method, simulation analysis was performed on the Jeju Island grid using PSCAD/EMTDC, and actual transmission line, load, and weather data were applied. The analyzed simulation cases are as follows:

- Case 1: Normal Operation;
- Case 2: Load Rapid Rise & Decline;
- Case 3: RES Sudden Stop.

In Case 1, it was confirmed that HVDC no. 3 correctly transmits power according to the load. In addition, all DGs responded organically to the grid frequency change. In the case of excessive generation, power was transferred to the mainland, achieving a maximum RE share of 123.47%. The energy sent to the mainland was approximately 1.005 GWh, and this energy cannot be captured if the proposed method is not applied. Case 2 was carried out assuming that the load changes rapidly due to EV charging, heating and cooling, industrial load, etc. When the load suddenly increased, HVDC no. 3 responded immediately to supply power to the load, and when $P_3$ entered the decrement band illustrated in Figure 7, other DGs also adjusted their output power to share the load. Even when the load was reduced, HVDC no. 3 responded the most quickly and sent the power supplied to the load to the mainland. When $P_3$ enters the increment band, the output power of the DGs is changed to lower the power sent to the load or increase the power delivered to the mainland. Finally, Case 3 was conducted assuming a situation in which the RES output power rapidly drops due to harsh weather or accidents. Similarly to Case 2, when the output power of WTG and PV changed, HVDC no. 3 reacted the fastest. The other DGs also delivered power to the load as much as the reduced RES capacity, and as a result, the grid frequency did not deviate from the stable range. In addition, there is a reserve in the capacity of the sources, so blackouts or load shedding did not occur.

Combining the above results, the control method proposed in this paper contributes to securing the flexibility of a small-scale grid with high renewable penetration. Since DGs are controlled without instructions from TSO, the response speed is relatively fast, and the RE share is increased through the cooperative operation with a large-scale grid.

Author Contributions: Conceptualization, H.S. and J.S.; methodology, J.S. and H.S.; software, J.S. and H.S.; validation, J.S., H.S., T.N.T. and Y.-J.C.; resources, J.S., H.S., T.N.T. and Y.-J.C.; writing—original draft preparation, J.S. and H.S.; writing—review and editing, J.S. and Y.-J.C.; supervision, Y.-J.C.; All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1G1A1005334).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References


