Monitoring area screening of AC system to improve embedded VSC-HVDC operation efficiency

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Abstract
With the increasing number of embedded high-voltage DC (HVDC) projects in AC systems, there is growing research interest in controlling the operating point of the HVDC in real time. This real-time operation system requires the AC system information to be continuously updated, which involves practical challenges such as the burden of communication. To mitigate this problem, this paper proposes a novel technique to screen the AC system monitoring area for the efficient operation of the embedded HVDC. The screening algorithm determines the monitoring area by HVDC sensitivity analysis using the power transfer distribution factor. Then, a reliable and efficient grid operation is enabled using the limited data obtained from the determined area. The proposed methodology is verified using a Korean power system with multiple HVDCs. The effectiveness and advantages of the proposed technology are verified by comparing the results obtained using the system-wide data with those obtained from the monitoring area.

1 | INTRODUCTION

1.1 | Motivation

Highly advanced power systems are undergoing significant modifications because of the increasing integration of renewable energy sources and the application of power electronics facilities [1–5]. In response to the uncertainty and variability of distributed generation, the existing deterministic power system analysis is being replaced by probabilistic system analysis [6–10]. In addition, research on the operation of power electronics equipment to maintain system reliability is continuing because of the introduction of DC-based devices whose operating points need to be set [11, 12].

In particular, voltage source converter-high voltage DC (VSC-HVDC) enables independent control of active/reactive power, and this feature can be used to actively control the power flow and voltage of an AC system [11–13]. These controls can provide grid services to the AC system, such as loss reduction, voltage, and transient stability improvements [11, 13]. To provide effective grid services, appropriate operation and control of VSC-HVDC is necessary. The operating point may be adversely affected if it is set without considering the condition of the AC system. Various studies have been conducted to control HVDC by using AC system information [14–45].
TABLE 1  Operation strategies of HVDC for other published papers

|                  | [14] | [15] | [16] | [17] | [18] | [19] | [20] | [21] | [22] | [23] |
|------------------|------|------|------|------|------|------|------|------|------|------|
| RAS              | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| PAS              |      | ✓    | ✓    |      |      |      |      |      |      |
| Data acquisition | De\(^a\) | De | De | De | PMU\(^b\) | PMU | PMU | –  | –  | –  |
| Commercialized project | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Operation purpose | Re\(^c\) | Re | Re | Re | Re | Re | Re | Re | Ef | Angle |

|                  | [24] | [25] | [26] | [27] | [28] | [29] | [30] | [31] | [32] | [33] |
|------------------|------|------|------|------|------|------|------|------|------|------|
| RAS              | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    |
| PAS              |      | ✓    | ✓    |      |      |      |      |      |      |
| Data acquisition | –  | –  | PMU | PMU | –  | De | –  | –  | –  | –  |
| Commercialized project |      |      |      |      |      |      |      |      |      |
| Operation purpose | Cost\(^d\) | Re, Ef | Re, Ef | Cost | Angle | Re, Ef | Re | Cost | Cost | Angle |

\(^a\)Decentralized Control (De).
\(^b\)PMU-based (PMU).
\(^c\)Reliability (Re).
\(^d\)Efficiency (Ef).
\(^e\)Angle stability (Angle).
\(^f\)Cost effective (Cost).

1.2  Literature review

In general, HVDC is intended for interconnection between asynchronous systems or for long-distance power transmission that connects power generation plants and load sides. Therefore, the operating point is determined such that it balances the supply and demand [46]. HVDC control methods can maintain the reliability of AC systems against disturbances or uncertainties. Related research has been conducted previously. The operational strategies of commercialized HVDC projects are discussed in [14–20]. Cases or simulations were proposed in which a corrective action or remedial action scheme (RAS) was applied for system failures, to achieve stable power supply and maintain stability in terms of voltage, angle, and line overload. During the data acquisition for control, the information on the AC system is updated via the phasor measurement unit (PMU) [18–20]. Alternatively, the information of only a certain area is updated for a specific purpose [14–17], which enables fast and accurate control.

The preventive action scheme (PAS) of HVDC has also been studied [21–27]. RAS is more suitable for the operation of HVDC, in terms of an improvement in the system efficiency [21–25]. However, studies have been conducted on the PAS for operational convenience, considering uncertainties and system failure [24–27]. In recent years, both schemes have frequently applied a stochastic analysis method that considers uncertainties [21–24]. Nonetheless, shortcomings continue to exist in the acquisition of information on all the AC systems that use a measuring device, such as a PMU [26, 27].

In addition to the actual HVDC project cases and PAS mentioned above, research on RAS has been conducted for a long time considering several grid services. Studies have been conducted to improve voltage and phase angle stability under transient conditions [28, 29]; improve AC systems through RAS of HVDC, such as an operation to improve reliability and stability of isolated systems [30]; reduce system total losses [31, 32]; and collaborate with existing special protection scheme in AC systems [33], to enhance economic efficiency, efficiency, and reliability. Moreover, studies have been conducted considering the specificity of future power systems such as multi-terminal DC (MTDC) grid and renewable energy sources. For MTDC grids with many control elements, studies have been conducted on RAS aimed at short/long-term operation strategies [34, 35]; reduction of losses and improvement in transient response [36]; power sharing between converter stations; and improvement of frequency stability [37]. In addition, probability analysis has been applied to consider the uncertainty due to the increase in the availability of renewable energy sources [24, 38]. Furthermore, related research has been continued for various purposes, such as securing the reliability and reserve power of AC systems under the control of HVDC, specifically for wind farm connections [39, 40]. Table 1 shows the results of organizing existing research on operational purposes, control schemes, etc.

1.3  Necessity of the research

For these HVDC operation strategies, it is necessary to determine the operating point of the HVDC according to the purpose by updating the information related to the AC system. A commonly recommended method is to update the AC system information via measuring devices such as PMUs and wide area measurement systems (WAMS), and to control the operating point of the HVDC accordingly [17–20, 26, 27]. However, this can result in a communication burden and exert a negative impact on the economy by incurring excessive investments.
To overcome these shortcomings, studies were conducted to operate HVDC with limited data by applying methods such as state estimation [41, 42]; decentralized control [43]; and model predictive control [35, 44, 45]. These methods predict the AC system information based on the limited measurement values and apply the necessary control. However, even unnecessary data may be considered in the operation of an embedded HVDC. This may cause a computational burden, and paradoxically, the omission of necessary data, which may adversely affect system stability. To solve these problems, it is necessary to conduct research to clearly determine the area from where information necessary for the operation of the embedded HVDC should be obtained.

1.4 Novelty and main contribution

In this paper, we propose a method to screen the area from where AC system data should be acquired, to obtain an appropriate action scheme for embedded VSC-HVDCs. The sensitivity index for an embedded VSC-HVDC is calculated using the power transfer distribution factor based on DC power flow, and a method for screening the monitoring area is proposed considering the thermal limit of the AC system using the index. For unpredictable future power systems that require a more complex analysis, the monitoring area is classified using only the system topology. Moreover, the results are simple albeit convenient to apply to the operation strategy of the embedded VSC-HVDC. This study also addresses the application of remedial/preventive actions to the monitoring area determined using the proposed methodology.

The main contributions of this study are as follows: It is possible to operate the embedded VSC-HVDC efficiently with limited AC system information, by screening AC system monitoring areas. This filters out the data necessary for determining the operating point of the HVDC, thereby reducing the communication burden and improving the accuracy. In particular, because only the system topology is used in the screening process, the monitoring area can be determined conveniently regardless of the power generation and load conditions. An advantage of this feature is that it can be conveniently applied to future systems that are complex and challenging to predict.

1.5 Organization and structure of the paper

The remainder of the paper is organized as follows: The sensitivity index for the HVDC operation is proposed in Section 2. The algorithm for screening the monitoring area of the embedded VSC-HVDC is presented in Section 3. The HVDC operation strategy for a specified monitoring area is described in Section 4. A case study conducted on a Korean power system to verify the effectiveness of the proposed technique is described in Section 5. Finally, the conclusions from the study are presented in Section 6.

2 SENSITIVITY INDEX FOR HVDC OPERATION

Unlike AC systems, which calculate their own power flow based on the voltage and phase angle information, HVDC can set its own setpoint according to the operational purpose. In addition, the active and reactive power control of VSC-HVDC affects the power flow from nearby AC systems, and a sensitivity analysis is conducted to evaluate the impact of the HVDC operation. The voltage and the phase angle of the buses vary with the system conditions; therefore, the conditions can significantly impact the sensitivity analysis of the HVDC. To prevent these problems, a sensitivity analysis is conducted using the power transfer distribution factor (PTDF). Sensitivity analysis using PTDF simplifies the analysis of a future power system based on renewable energy sources with increasing complexity and uncertainty.

The PTDF is an index indicating the sensitivity of branches based on the DC power flow model [47]. In general, the DC power flow model is derived under the following assumptions: 1) the effects of resistance and reactive power are negligible and can be omitted, 2) all the buses have a voltage of 1 p.u., 3) the line resistance is very small compared with the line impedance, and the susceptance can be omitted. The above assumptions are expressed as Equations (1)–(4).

\[
\cos (\delta_{km}) \approx 1 \quad (1) \\
\sin (\delta_{km}) \approx \delta_k - \delta_m \quad (2) \\
Z_{km} = jx_{km} \quad (3) \\
B_{km} = -\frac{j}{x_{km}} \quad (4)
\]

Under the above assumptions, the active power flow between the buses can be expressed as Equation (5). That is, in the DC power flow model, the amount of power flow can be calculated using only the phase angle data.

\[
P_{km} = \frac{|V_k||V_m|}{x_{km}} \cdot \sin (\delta_{km}) = \frac{\delta_k - \delta_m}{x_{km}} \quad (5)
\]

To obtain the phase angle in the DC power flow model, it is necessary to calculate the inverse matrix as shown in Equation (6).

\[
\delta = B^{-1} \cdot P \quad (6)
\]

However, because the process of calculating the inverse matrix each time is complex, we omit the process by using Equations (7)–(9) to obtain the PTDF calculation formula of the line. First, the power flow variation in a line, when active power is supplied to an arbitrary bus, is expressed as
Equation (7).

\[ \varphi_i' = \frac{\Delta P_i}{\Delta P_i} \]  

Equation (8) can be derived by substituting Equation (5) in Equation (7).

\[ \varphi_i' = \frac{\Delta f_i}{\Delta P_i} = \frac{d f_i}{d P_i} = \frac{\frac{\delta_k - \delta_m}{\chi_{km}}}{\frac{d P_i}{d P_i}} \]

\[ = \frac{1}{\chi_{km}} \left( \frac{d \delta_k}{d P_i} - \frac{d \delta_m}{d P_i} \right) \]

\[ = \frac{1}{\chi_{km}} \left( X_{ik} - X_{im} \right) \]

Equation (8) can be expressed in the form of a matrix as shown in Equation (9).

\[ \pi = B_{tr} \cdot A \cdot X \]  

It is evident from Equation (9) that the PTDF result is dependent only on the topology regardless of the system conditions. That is, it is constant regardless of the generator or load conditions. Therefore, because iterative calculations with various system conditions are not required, it is suitable for use in the sensitivity analysis to determine the monitoring area of the embedded VSC-HVDC.

VSC-HVDC can be expressed as loads and FACTSs as shown in Figure 1. The active power absorption/emission across VSC-HVDC is expressed as loads. Furthermore, because independent control is performed, reactive power is expressed as FACTSs. The reactive power control of VSC-HVDC can affect the power flow of the system. However, in general, it is operated in the AC voltage control mode in the grid operation, and the impact on the power flow of the system is exceptionally low compared to active power control. Considering these aspects, the HDVC sensitivity analysis reflects only the analysis of the active power.

Because the active power is absorbed or released at both ends of the HVDC according to the active power setpoint, the larger the difference in sensitivity between the two, the larger is the effect on the AC branch. Using the PTDF, the index denoting the sensitivity of the AC line to variations in the HVDC active power setpoint is expressed as the difference in PTDF between the two ends of the HVDC:

\[ \pi_{\text{PDC}}^l = \varphi_{\text{Rec}}^l - \varphi_{\text{Inv}}^l \]  

3 | MONITORING AREA SCREENING (MAS) OF HVDC

The purpose of MAS is to achieve an efficient and reliable HVDC operation. The MAS method for HVDC operation using sensitivity index (which is defined in Section 2) is introduced in this section.

In general, the most important aspect regarding the control of the active power of embedded HVDC is the variation in the power flow of the AC system and the resulting line overloads. The easiest way to screen for sensitive lines is to determine based on \( \pi_{\text{PDC}}^l \). However, this method excludes the lines that can be easily overloaded because of the HVDC, despite having a low sensitivity. For example, among the transmission lines with low voltage levels, there are cases where both the sensitivity (\( \pi_{\text{PDC}}^l \)) and line thermal limit are small. Such lines can be overloaded by slight changes in active power by HVDC control. Therefore, the monitoring area in terms of active power is determined by comparing the capacity of the AC lines with the impact of the HVDC on AC systems. The impact of the HVDC on an AC system is expressed as the maximum variation in the power flow of the AC lines according to the control of the HVDC. It is calculated using Equation (10) as follows:

\[ M_{\text{DC}}^l = 2 P_{\text{rated}} \left| \pi_{\text{PDC}}^l \right| \]  

In Equation (11), since VSC-HVDC can flexibly control the active power setpoint in both directions, it is possible to express the maximum impact of the HVDC on line / by doubling \( P_{\text{rated}} \) and multiplying it by \( \left| \pi_{\text{PDC}}^l \right| \).

In addition, the capacity of the AC lines is used to compare \( M_{\text{DC}}^l \). The ratio of the line capacity is calculated as a reference to assess the extent to which the control of the HVDC can affect the line load. The reference values for AC, as shown in Equation (12), are compared in Equation (13).

\[ M_{\text{ref}}^l = S_{\text{MVAs}} \cdot \alpha_w \]  

\[ \text{(12)} \]
\[ M_{\text{DC}}^l \geq M_{\text{ref}}^l \tag{13} \]

An inequality, Equation (14), is derived by comparing Equations (12) and (13). The left-hand side of Equation (14) is constant with the system topology, including the HVDC and branch data. Therefore, the MAS method is determined according to \( \alpha_w \).

\[
\frac{2P_{\text{rated}} |\pi_{l\text{DC}}|}{S_{\text{MUA}}} \geq \alpha_w \tag{14}
\]

The smaller \( \alpha_w \) is, the larger is the monitoring area and more accurate is the data obtained. Conversely, the larger \( \alpha_w \) is, the smaller is the monitoring area, despite data processing being more flexible. Thus, \( \alpha_w \) plays a significant role in screening the monitoring area. A criterion for determining \( \alpha_w \) is required; therefore, in this paper, a system reliability criterion is presented as the criterion for determining the value of \( \alpha_w \). In particular, this study intends to present the margin of the thermal limit of the lines as the criterion. If \( \alpha_w \) is the thermal capacity margin ratio, \( M_{\text{ref}}^l \) becomes the thermal capacity margin of the line \( l \), as shown in Equation (12). That is, Equation (13) implies that the maximum impact of the HVDC \( (M_{\text{DC}}^l) \) on the line \( l \) is compared with the thermal limit capacity margin on the line \( l \). Therefore, based on the reliability criteria provided by the system operator, the thermal limit capacity constraint of the line in the “N” condition may be the criterion for determining \( \alpha_w \). Most countries recommend an overload criterion in the “N-1” condition. However, a few others, such as Italy, consider and recommend a line load criterion of 80% in the “N” condition [48]. Therefore, as in Equation (15), \( \alpha_w \) is determined based on the reliability criteria in the “N” condition by each country.

\[
\alpha_w = 1 - S_{\text{load}} \tag{15}
\]

In addition, the system topology can be altered in the event of contingencies, such as a line trip, for fault recovery. Because the variations in topology can affect \( \pi_{l\text{DC}} \) in Equation (14), MAS is performed under normal and transient conditions (as shown in Figure 2) to generate additional monitoring targets even after the contingencies.

The MAS method proposed in this paper can also be applied to a system composed of multiple HVDCs. In general, the monitoring area between HVDCs whose electrical distances are large is unlikely to overlap. The change in the utilization rate of line \( l \) according to the HVDC control can be expressed as \( \Delta f_l = \frac{\Delta P_{\text{DC}} |\pi_{l\text{DC}}|}{S_{\text{MUA}}} \). Although the HVDC control has a large effect on the lines in the monitoring area, the change in the utilization rates of lines outside the monitoring area can be neglected because \( \frac{|\pi_{l\text{DC}}|}{S_{\text{MUA}}} \) outside the monitoring area is relatively small. Therefore, a non-overlapping monitoring area implies that the operation of each HVDC does not affect the area of other HVDCs when the operating points for special purposes (such as line utilization rate control) are adhered to. This feature implies that the determination of the operating point of each HVDC is independent. Furthermore, it is not necessary to consider the cooperative control among these, which reduces the computational burden and provides operational convenience. Conversely, in cases where multiple HVDCs are installed in an electrically dense system, the monitoring areas of the HVDCs may overlap. As in the previous case, the variation in the operating point of each HVDC can influence the area of other HVDCs substantially when the HVDCs are operated independently. This makes it infeasible to provide an intended grid service for the AC system. Therefore, for cases where there is an overlap between screened monitoring areas, the monitoring areas must be combined into one and managed as an integrated monitoring area. Figure 3 shows the independent and non-independent monitoring areas described above.
APPLICATION OF MAS WITH OPERATION STRATEGIES

As mentioned in the literature review in Section 1, RAS or PAS can be performed according to various purposes and constraints, such as improving system efficiency, securing system stability, and operational convenience. The operating point of the embedded VSC-HVDC can be determined based on the information on the AC system obtained from the monitoring area, as illustrated in Equations (16) and (17).

\[ Z = \alpha_X \langle X \rangle \] (16)

\[ Y = \alpha_Z \langle Z \rangle \] (17)

As in Equation (15), it is possible to identify an optimum HVDC operation point based on the data obtained from the monitoring area. The objective functions used for the optimum operating point can have various purposes related to the power flow [as in Equation (16)], such as loss minimization [31, 32] and enhancement of line capacity utilization [49]. Then, the determined operating point is examined to verify whether it is suitable for system reliability and stability as in Equation (17).

CASE STUDY

5.1 Simulation overview

To verify the feasibility and effectiveness of the proposed screening algorithm, simulations are conducted on the Korean power system to discuss the application of the two embedded VSC-HVDCs. The simulations are divided into two parts: First, MAS is applied to the given system, and the results are analyzed. It is possible to confirm proper screening by analyzing the range of the monitoring area, number of monitored buses, and variations in AC line loading according to HVDC control. Second, steady-state/dynamic studies are conducted to show that the HVDC operation related to power flow is feasible for the monitoring area. The effectiveness of this study can be verified by comparing the results using the data of the entire system with the data of the monitoring area. Power System Simulator for engineering (PSS/e) is used for the simulation, and the application of the proposed algorithm is implemented using Python code.

5.2 System description

The two HVDCs are intended to be placed in the “Sinkimp-Sinpaju (DC#1)” and “SeoSeoul-Sinseongnam (DC#2)” located in the metropolitan area. Korea Electric Power Corporation (KEPCO)’s power system in the metropolitan area has multiple loops to ensure system reliability. However, this configuration resulted in increased fault current, and the fault current levels are a cause for concern. To solve this problem, system topology reconstruction, bus separation etc. are applied, but there are concerns of line overloads. As the solution to these problems, KEPCO is proposing to segment the grid using back-to-back (BTB) VSC-HVDCs in the metropolitan area [32, 50]. The HVDC can help reduce the fault current and can potentially alleviate the thermal overload of the AC system by carrying a controlled amount of active power.

The system diagram, including the two BTB VSC-HVDCs and detailed specifications of the two HVDCs, is presented in Figure 4 and Table 2 [33]. It is assumed that the specifications of the two HVDCs are identical; the total power generation and load of the KEPCO system are 104,230 MW and 102,412 MW, respectively, and those of the metropolitan area are 21,952 MW and 39,139 MW, respectively.

5.3 Monitoring area screening

\[ \alpha_w \] is determined as 0.2 in accordance with the reliability standard for the line load factor under N conditions recommended by several European countries [48]. Then, the case where \[ \alpha_w = 0.3 \] is also screened to compare the variation in the monitoring
area according to the magnitude of $\alpha_w$. MAS is performed on the Korean transmission system with voltage levels of 765 kV, 345 kV, and 154 kV. Table 3 and Figure 5 present the screening results. The numbers of essential monitoring buses can be reduced to 3.56% and 2.72% of the number of buses with a voltage level of more than 154 kV in KEPCO’s power system (i.e., 3.56% and 2.72% of 1433 buses). These are equivalent to 9.64% and 7.37% of the number of buses classified in the metro area considering regional factors (i.e., 9.64% and 7.37% of 529 buses). This can reduce the burden on the monitoring buses to within 10%. The loading variation analysis of the AC lines under HVDC control is performed as shown in Figure 6, to verify whether MAS has been performed effectively. The target line list is selected from 51 lines with sensitivities of 0.1 or higher for the HVDCs and is randomly selected from 29 of the remaining lines. In the figure, the red side is a line sensitive to DC #1, the blue side is a line sensitive to DC #2, and the green side is a line sensitive to both the sides. As a result, the load factor of the line varies significantly only in the screening area. This indicates that the screening has been performed effectively.

5.4 Application of MAS on HVDC operation

In this section, the effectiveness of MAS is verified by comparing the operating point of the case using only the AC system information obtained from the monitoring area and the case using the entire system information. Because loss reduction is a grid service that HVDC can provide most conveniently through the power flow of the AC system, MAS is applied to the loss minimization-based operation strategy proposed in [32] to verify its effectiveness.

5.4.1 Loss minimization-based operation

Lee et al. [32] consider both the total losses of the AC system and conversion loss of the BTB VSC-HVDC and follow the operating point to loss minimization as in Equation (18). For system reliability, only voltage and thermal limit are considered as system constraints. The steady-state voltage reference is $\pm 0.05$ p.u. at the 345-kV level and $\pm 0.10$ p.u. at the 154-kV level. Furthermore, the thermal limit should not exceed 100%. The conversion loss of the BTB VSC-HVDC varies depending on the operating point. However, for convenience, the conversion loss rate in this simulation is assumed to be constant, i.e., 1.8% of the active power setpoint.

Minimize $P_{\text{loss, total}} = \sum_{h} AC_{h} + \sum_{h \in DC} DC_{h}$ (18)

subject to $V_{l} \leq V_{i} \leq \bar{V}_{l}$ (19)

$F_{\text{line,l}} \leq F_{\text{line,l}} \leq \bar{F}_{\text{line,l}}$ (20)

Considering the above points, a simulation is performed to determine the HVDC operating point based on loss minimization by applying $\alpha_w = 0.2$ and 0.3. The operating point step of the HVDCs is set to 10 MW. The results are presented in Tables 4 and 5.

The smaller $\alpha_w$ is, the wider is the monitoring area, and therefore, larger is the amount of system data that can be acquired.
Accordingly, it can be verified that the accuracy is higher. Cases with $\alpha_w = 0.3$ have low accuracy compared to those with $\alpha_w = 0.2$. However, since the number of monitoring buses is less, as shown in Table 3, it can be advantageous from an economical aspect. Therefore, the system operator must determine $\alpha_w$ in advance, considering the communication infrastructure and the reliability and accuracy of the system.

5.4.2 Remedial action scheme

This section describes the embedded VSC-HVDC control in a generator trip scenario, to demonstrate that MAS can be applied to the RAS. As shown in Figure 7, the “SeoSeoul#2-Sinonyang” line in the monitoring area is overloaded after the outage of the “Yeongseo” generator. First, the sensitivity of the two HVDCs to the “SeoSeoul#2-Sinonyang” line is analyzed using Equation (10). The results are $\pi_{P,DC}^1 = 0.2973$ for DC#1 and $\pi_{P,DC}^2 = 0.1178$ for DC#2. A simulation to relieve the
TABLE 3 MAS results for the Korea power system

| 𝛼_ω = 0.2 | # of monitoring buses | DC #1 | DC #2 | Integrated area |
|-----------|-----------------------|------|-------|-----------------|
|           | Screening rate        |      |       |                 |
|           | comparison with all systems | 36   | 28    | 51              |
|           | comparison with metro systems | 2.51% | 1.95% | 3.56%          |
|           |                        | 6.81% | 5.29% | 9.64%          |
| 𝛼_ω = 0.3 | # of monitoring buses | 21   | 23    | 39              |
|           | Screening rate        |      |       |                 |
|           | comparison with all systems | 1.47% | 1.61% | 2.72%          |
|           | comparison with metro systems | 3.97% | 4.35% | 7.37%          |

TABLE 4 Comparison of operating point using MAS (𝛼_ω = 0.2)

|                | With MAS | With total system | Error |
|----------------|----------|-------------------|-------|
| P_{DC1}       | 550 MW   | 550 MW            | 0     |
| P_{DC2}       | 1770 MW  | 1720 MW           | 50 MW (2.91%) |
| Losses (MAS)  | 98.63 MW | 98.78 MW          | –0.14 MW (–0.15%) |
| Losses (total)| 1676.53 MW | 1676.50 MW   | 0.03 MW (0.00%) |

Overload is performed by controlling DC#1 because the sensitivity of DC#1 is higher. To address the line overload in this simulation, the active power control of HVDC is determined using Equation (10), as illustrated in Equations (21) and (22).

\[ \pi_{RDC} \cdot \Delta P_{DC} = \left( L_{eq} - L_{obj} \right) \cdot S_{MVA}^{\prime} \]  \hspace{1cm} (21)

\[ \Delta P_{DC} = \frac{\left( L_{eq} - L_{obj} \right) \cdot S_{MVA}^{\prime}}{\pi_{RDC}'} \]  \hspace{1cm} (22)

The sensitivity of the HVDC and the capacity of the line have been determined as \( \pi_{RDC}' = 0.2973 \) and \( S_{MVA}' = 2173 \) MVA, respectively. The load rating of the line targeted for the control is assumed to be \( L_{obj} = 0.95 \). \( L_{eq} \) and \( \Delta P_{DC} \) can be obtained from the overload data after the outage. Figure 8 shows the RAS of the embedded VSC-HVDC to eliminate the line overload after an accident.

Meanwhile, the overload of the lines outside the monitoring area is almost infeasible to control, as shown in the gray area in Figure 6. That is, it is determined that in the RAS application of the MAS, it is not a control target outside the monitoring area. Furthermore, only the HVDC control for maintaining internal reliability needs to be applied.

5.5 Comparison with conventional decentralized control

The MAS method proposed in this paper is a type of decentralized control. To compare it with the existing decentralized control, “the area requiring data acquisition” must be set, which is determined using another technique (such as engineer’s experience) rather than MAS. In a commercial HVDC project, the operating point of HVDC for contingencies is controlled using a look-up table through an offline study. Because there are no specific criteria, the number of monitoring buses or contingencies can vary significantly depending on the range we set. To compare and verify this method, a simulation is performed by setting the buses within a certain range from the HVDC as data acquisition areas. If the buses within level “2” from the HVDC...
Table 5
Comparison of operating point using MAS (\(\alpha_w = 0.3\))

|   | With MAS | With total system | Error   |
|---|----------|-------------------|---------|
| \(P_{DC1}\) | 550 MW   | 550 MW            | 0       |
| \(P_{DC2}\) | 1770 MW  | 1,570 MW          | 200 MW  | (12.74%) |
| Losses (MAS) | 58.03 MW | 58.20 MW          | -0.17 MW| (-0.29%) |
| Losses (total) | 1676.82 MW | 1676.50 MW | 0.32 MW | (0.02%) |

Table 6
Comparison of the number of buses according to control methods

| # of buses | With MAS(\(\alpha_w = 0.2\)) | Conventional method |
|------------|--------------------------------|---------------------|
|            | 51                             | 57                  |

Table 7
Comparison of the operating points between MAS and the conventional method

|   | With MAS | With total system | With conventional method |
|---|----------|-------------------|--------------------------|
| \(P_{DC1}\) | 550 MW   | 550 MW            | 630 MW                   |
| \(P_{DC2}\) | 1770 MW  | 1720 MW           | 520 MW                   |
| Losses (total) | 1676.53 MW | 1676.50 MW | 1690.04 MW |

That the proposed technique can be used for an accurate HVDC operation with an appropriate number of monitoring buses.

6 | Conclusion

The range and amount of data collected for HVDC control affect the number of monitoring devices and the speed of computation. In this study, a PTDF-based sensitivity analysis is used to screen the range of monitored AC systems for the stable operation of an embedded VSC-HVDC. Then, the power flow change by the HVDC and the margin of the lines are compared to determine the monitoring line. Through these comparisons, the lines that can cause incorrect control of HVDC to substantially affect the lines' thermal limit can be selected in advance.

Despite the limited information obtained by restricting the monitoring area, it is possible to perform an efficient and accurate embedded VSC-HVDC operation including RASs and PAs. In addition, because this screening technique uses a PTDF that is determined solely by the topology of the system, it is suitable for practical system operations, i.e. it provides a constant monitoring area regardless of the uncertainty of future systems. Furthermore, a more stable operation of the HVDC is feasible by reducing the problems originating from communication errors.

Through MAS, investments in a communication infrastructure such as a PMU can be minimized, and various operational strategies can be applied simultaneously. The proposed MAS technique can be applied to the complex operations of future power systems, including embedded VSC-HVDC. Furthermore, it is possible to achieve economic benefits by securing system efficiency and stability.

This paper can provide a basis for future studies. First, it is possible to conduct a study on a MAS technique using voltage sensitivity analysis along with the active power-based screening technique proposed in this paper. Through this, the active/reactive power integrated monitoring area can be screened, which also reflects the reactive power control characteristics of VSC-HVDC. Second, it is necessary to study the HVDC integrated operation strategy by reflecting the system operation conditions in real time. Using the proposed technique, it is possible to apply research related to conventional HVDC operations, such as the method of updating the information regarding the monitoring area in real-time (state estimation, PMU, etc.) and the HVDC operation strategies that respond to future system variability using the information.

Nomenclature

- \(\delta_k\): the phase angles of bus \(k\)
- \(\delta_{km}\): the phase angle difference between buses \(k\) and \(m\)
- \(Z_{km}\): the line impedance between buses \(k\) and \(m\)
- \(x_{km}\): the line reactance between buses \(k\) and \(m\)
- \(B_{km}\): the susceptance between buses \(k\) and \(m\)
- \(P_{km}\): the power flow between buses \(k\) and \(m\)
- \(V_k\): the voltages at buses \(k\) and \(m\), respectively
- \(\phi_l\): an PTDF of bus \(i\) for branch \(l\)
- \(P_l\): the amount of power flow of branch

FIGURE 9
Monitoring area for decentralized control of conventional methods

are considered as monitoring targets, the number of monitoring buses is as shown in Table 6 and Figure 9.

To verify the accuracy of the proposed method, the HVDC operating points for the two cases are compared based on the loss minimization (as shown in Table 7). As a result of the simulation, it can be confirmed that the conventional methodologies have very low accuracy in determining the operating point, and
\[ P_m \] the amount of power flow injection to bus \( i \)
\[ \pi \] the set of PTDFs for the given power system
\[ B_{ir} \] the set of susceptances
\[ A \] the incidence matrix for the system lines
\[ \varphi_{ref} \] the PTDFs for branch \( l \) at the rectifier ends of the HVDC
\[ \varphi_{inv} \] the PTDFs for branch \( l \) at the inverter ends of the HVDC
\[ \pi_{DC} \] the sensitivity index for branch \( l \) of the HVDC
\[ M_{DC} \] the maximum impact of the HVDC on line \( l \)
\[ P_{total} \] the active power rating of the HVDC
\[ M_{ref} \] the reference value of line \( l \)
\[ S'_{MA} \] the thermal limit of line \( l \)
\[ \alpha_{AC} \] the reference value of the MAS
\[ S_{load} \] the load limit under the normal operating condition
\[ \alpha_{X} \] the objective functions for the specific HVDC operation
\[ \alpha_{Z} \] the nonlinear power flow functions for the power system
\[ P_{loss,total} \] the total losses of the system
\[ n_{AC} \] the number of AC lines
\[ n_{HVDC} \] the number of HVDCs
\[ AC_{nj} \] the AC system losses
\[ DC_{nj} \] the DC conversion losses
\[ \Delta P_{DC} \] the active power control of the HVDC
\[ I_{ref} \] the line overload rating after contingency
\[ I_{obj} \] the object of the line load rating after HVDC control
\[ \Delta j_l \] the change in utilization rate of line \( l \)
\[ X \] the input vector (AC system information in the monitoring area)
\[ Y \] the state vector at a specified operation point (voltage angle and magnitudes)
\[ Z \] the output vector (HVDC operation point)

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