Abstract—This paper presents operation and control strategies of an offshore wind farm interconnected to a high-voltage dc (HVDC) system. The offshore wind farm composed of variable speed wind turbines driving permanent magnet synchronous generators is considered in this study, based on dc-bus concept. The HVDC transmission system based on a three-level neutral point clamped voltage source converter (VSC) is used for the interconnection between the offshore wind farm and onshore grid. Detailed modeling and control strategies are developed for the individual component of the overall system. A simple fuzzy logic controller is adopted in the offshore VSC station, which is one of the salient features of this study. Real wind speed data is used in the simulation study to obtain realistic response. Both dynamic and transient analyses of the proposed system are carried out using the laboratory standard power system software package, PSCAD/EMTDTC.

Index Terms—Fuzzy logic controller (FLC), high-voltage dc (HVDC), offshore wind farm, permanent magnet synchronous generator (PMSG), transient stability, variable speed wind turbine (VSWT), voltage source converter (VSC).

I. INTRODUCTION

The conventional energy sources such as oil, natural gas, coal, or nuclear are finite and generate pollution. Alternatively, the renewable energy sources like wind, fuel cell, solar, biogas/biomass, tidal, geothermal, etc. are clean and abundantly available in nature. Among those, wind energy has the huge potential of becoming a major source of renewable energy for this modern world. In 2008, 27-GW wind power has been installed all over the world, bringing world-wide installed capacity to 120.8 GW. This is an increase of 36% compared with the 2007 market, and represents an overall increase in the global installed capacity of about 28.8% [1].

As well as the onshore trend, offshore wind farms have also been continuing its growth rapidly. Some leading countries in the wind energy area are focusing more on offshore technology. The main reasons for adopting offshore are lack of the suitable onshore sites and much better wind conditions of offshore sites (wind is much stronger and more constant). By 2007, the industry had developed 25 projects with a total capacity of around 1100 MW in five countries in Europe [2], many of which are large-scale and fully commercial.

The offshore wind farm is located, in general, far away from the onshore grid point of common coupling (PCC). If the distance is long or if the grid to which the offshore wind farm is connected is weak, a high-voltage dc (HVDC) transmission system might be a more suitable and feasible solution than the high-voltage ac transmission. This paper focuses on the HVDC system for offshore wind farm interconnection with the onshore grid, where the distance between the two systems is assumed to be 100 km. Two types of HVDC transmission topologies, i.e., HVDC with voltage source converter (VSC-HVDC) using insulated gate bipolar transistors (IGBTs) and line-commutated converter HVDC (LCC-HVDC) are used today for offshore wind farm connectivity [3]–[11]. In this study, a VSC-based HVDC transmission system is considered for offshore wind farm connectivity to the grid.

The HVDC transmission using VSC came in service for the first time in Sweden in 1997 as a trial 3-MW scheme [12]. At the present time, 100 MW class VSC-based HVDC systems are in service. They have become possible due to the synchronized development in a number of technical areas, including semiconductor switches, dc transmission lines (especially the dc cables), main circuit of converter station, and system controls [13]. The use of VSC-HVDC for offshore wind farm connectivity has been reported already in some literature [6]–[11]. In [6]–[8], the wind farms considered are composed of fixed speed induction generators. In [9], synchronous generators are used in the offshore wind farm. A doubly fed induction generator (DFIG) is chosen as the wind generator for the offshore wind farm in [10]. However, a permanent magnet synchronous generator (PMSG) is becoming very popular today as a variable speed wind generator. In PMSG, the excitation is provided by permanent magnets instead of field winding. Permanent magnet machines are characterized as having large air gaps, which reduce flux linkage even in machines with multimagnetic poles [14], [15]. As a result, low rotational speed generators can be manufactured with relatively small sizes with respect to its power rating. Moreover, gearbox can be omitted due to low rotational speed in PMSG wind generation system, resulting in low cost. In a recent survey, gearbox is found to be the most critical component, since its downtime per failure is high in comparison with other components in a wind turbine generator system (WTGS) [16].

Therefore, in our previous work [11], we reported a variable speed wind turbine (VSWT) driven PMSG as an offshore wind generator, where each PMSG is connected to the ac-bus using a frequency converter composed of an ac–dc converter, dc-link, and dc–ac inverter. A time averaged model is considered therein for the frequency converter used in VSWT-PMSG. Moreover, in that study, the hydrogen generation scheme using electrical power generated from the wind farm is emphasized, and therefore, conventional controllers for an offshore wind farm are considered therein. In this study, the focus is given to develop the

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suitable control strategy for the individual component of HVDC connected offshore wind farm during normal and grid fault conditions.

In this study, each VSWT-PMSG of the wind farm is connected to the common dc-bus through an ac–dc converter. The dc-bus is connected to the wind farm ac-bus through only one dc–ac inverter system. In this way, the number of dc–ac inverters and transformers necessary for the ac–ac connected wind farm explained in [11] can be decreased and as a result the cost of the overall system can also be reduced. The ac–dc converter of each VSWT-PMSG ensures the maximum power transfer to the dc-bus by using a maximum power point tracking (MPPT) controller. The dc voltage of the dc-bus is converted to ac voltage of the wind farm ac-bus using a dc–ac inverter. In both offshore and onshore HVDC stations, three-level (3L) neutral point clamped (NPC) VSCs are considered. Suitable control strategies are developed for both offshore and onshore VSC stations. A simple fuzzy logic controller (FLC) is adopted for the offshore VSC station control which is one of the salient features of this study. This reduces the intricacy of the control for the offshore VSC station. For dynamic analysis, real wind speed data measured in Hokkaido Island, Japan, is used in the simulation analyses to obtain the realistic responses. Moreover, transient stability analysis is also performed considering severe line to ground fault, in this study. Finally, it is concluded that the proposed HVDC interconnected offshore wind farm is dynamically and transiently stable under the developed control schemes.

II. MODEL SYSTEM

The single line diagram of the proposed system composed of the offshore wind farm, two 3L VSC-HVDC stations, and two dc cross-linked polyethylene (XLPE) cables is shown in Fig. 1. The offshore wind farm is composed of VSWTs driving PMSGs. Each VSWT-PMSG is connected to the dc-bus through an ac–dc converter and then the dc voltage of the dc-bus is converted to ac voltage using only one dc–ac inverter. To speed up the simulation, an aggregated model of the wind farm is considered in the simulation analyses, where several small size wind generators are represented with a large capacity wind generator. Therefore, though offshore wind farm power capacity is assumed as 300 MW, two 150-MW wind generators are considered to be connected to the dc-bus, in this study. The parameters of PMSG are shown in Table I.

The proposed system is connected to the main grid through transmission lines. Hence, the active power from the offshore wind farm is transmitted to the main grid via two dc XLPE cables. The cable model available in PSCAD software is used in the simulation. The ABB 150-kV XLPE cable parameters shown in the Appendix are used in this study. The cable length is considered as 100 km. A high-pass filter (HPF) is connected at both offshore and onshore VSC stations to absorb the well-defined harmonics for 3L converter/inverter systems. The individual component modeling is demonstrated below.

III. WIND TURBINE MODELING

The mathematical relation for the mechanical power extraction from the wind can be expressed as follows [17]:

\[ P_M = 0.5 \rho C_p(\lambda, \beta) R^2 \frac{V_W^3}{2} \]  \hspace{1cm} (1)

where \( P_M \) is the extracted power from the wind, \( \rho \) is the air density [kg/m\(^3\)], \( R \) is the blade radius [m], \( V_W \) is the wind speed [m/s], and \( C_p \) is the power coefficient which is a function of both tip speed ratio, \( \lambda \), and blade pitch angle, \( \beta \) [deg]. \( C_p \) is expressed in the next equations [18]:

\[ C_p(\lambda, \beta) = 0.5(\Gamma - 0.02\beta^2 - 5.6)e^{-0.17\Gamma} \]  \hspace{1cm} (2)

\[ \lambda = \frac{\omega_m R}{V_W} \]  \hspace{1cm} (3)

\[ \omega_m = \frac{0.0775V_W}{\text{pu}} \] \hspace{1cm} (4)

where \( \omega_m \) is the rotational speed [rad/s]

\[ P_{\text{ref},1} = 0.197V_W - 1.451 \] \hspace{1cm} (5A)

\[ P_{\text{ref},2} = 0.127V_W - 0.749 \] \hspace{1cm} (5B)

\[ P_{\text{ref},3} = 0.068V_W - 0.282 \] \hspace{1cm} (5C)

The characteristic of \( C_p \) changes depending on the wind speed. Equation (4) is a relation between the optimal rotational speed \( \omega_m,\text{opt} \), corresponding to the optimum power coefficient \( C_{p,\text{opt}} \), and the wind speed \( V_W \). This expression is obtained by differentiating \( C_p \) with respect to \( \omega_m \) assuming that \( \beta \) equals zero. Fig. 2 shows characteristics between the wind turbine power \( P_M \) and the rotor speed \( \omega_m \) for various wind speed, in which the locus of the maximum output power \( P_{\text{max}} \) is
shown by a dashed line. The $P_{\text{max}}$ is chosen as the reference power $P_{\text{ref}}$ for ac–dc converter for each VSWT-PMSG, so that maximum power can be transferred to the common dc-bus and it is calculated using an MPPT controller, as shown in Fig. 3. The MPPT controller is designed based on linear functions as expressed in (5). At the same time, wind turbine should be operated at $\omega_{\text{ref}}$ as expressed in (4) to achieve the power capture corresponding to $P_{\text{ref}}$. In addition, it is ensured that the rotor speed $\omega_r$ does not go below 0.4 pu during the low wind speed, which is considered the minimum speed, in this study.

When the rotor speed $\omega_r$ goes beyond the rated speed of PMSG, then the pitch controller presented in [19] is considered to control the rotational speed. Therefore, output power will not exceed the rated power of the PMSG.

### IV. Modeling and Control Strategy of Wind Farm

A detailed switching model is considered in this study instead of a time averaged model described as follows.

#### A. Generator Side AC–DC Converter Connected to DC-Bus

In this study, the direct drive VSWT-PMSG connected to the wind farm dc-bus through an ac–dc converter is considered. In the simulation analyses, the PMSG model available in the package software PSCAD/EMTDC [20] is used. The electrical scheme of the VSWT-PMSG adopted in the study is shown in Fig. 4.

Each converter is a standard three-phase two-level unit, composed of six IGBTs and antiparallel diodes. The well-known cascaded control technique shown in Fig. 5 is adopted in this study for VSWT-PMSG operation. As the converter is directly connected to the PMSG, its q-axis current is proportional to the active power. The active power reference $P_{\text{ref}}$ is determined in such a way to provide the maximum power to the dc-bus with the help of MPPT controller as shown in Fig. 3. However, when a network disturbance occurs, $P_{\text{ref}}$ set-point is changed according to the command signal from onshore VSC station, determined from the terminal voltage of the onshore grid as shown in Fig. 5. It gives excellent transient performance as demonstrated in Section VI-B. On the other hand, the d-axis stator current is proportional to the reactive power. The reactive power reference is set to zero to perform unity power factor operation. In Fig. 5, the subscript $n$ represents the individual number for each wind generator.

#### B. DC–AC Inverter Connected to Wind Farm AC-Bus

The well-known cascaded control scheme shown in Fig. 6 is used as a control methodology for the grid side inverter of wind farm. The grid side voltage phasor is synchronized with the controller reference frame by using the phase-locked loop (PLL), as shown in Fig. 7 [21]. The d-axis current can control the dc voltage of the dc-bus. On the other hand, the q-axis current
can control the reactive power of wind farm ac-bus and hence the terminal voltage at high-voltage side of the transformer can be kept constant at the desired reference level.

V. Modeling and Control of HVDC Stations

Multilevel converter/inverter topology is more suitable to high-voltage application considering the factors of better harmonic performance and capability to withstand high phase currents. Three-level (3L) NPC VSC is preferred in this study, both for offshore and onshore stations. The one pole structure of a 3L NPC-based IGBT converter is shown in Fig. 1. The detailed control strategies for offshore and onshore stations are presented in Sections V-A and B.

A. Onshore VSC Station

The objective of the onshore 3L NPC VSC station is to maintain constant voltages at HVDC line and onshore grid. The IGBT switching table for the 3L NPC-based onshore VSC station is shown in Table II. The gate signals generation scheme for the IGBT devices used in onshore VSC station is shown in Fig. 8. The cascaded control scheme explained in Section IV-B is considered for the onshore VSC station, which is used in the control block shown in Fig. 8 by the dotted line. The onshore grid voltage and HVDC line dc voltage are the control inputs for the cascaded control of VSC. However, in this case, the reference signals are compared with double carrier wave signal to generate the switching signals for 3L NPC VSC according to the switching rule shown in Table II.

B. Offshore VSC Station

In the proposed scheme, the wind farm dc–ac inverter can maintain constant voltage and frequency of the ac-grid side. Therefore, the intricacy of vector control can be avoided in the offshore VSC station adopting a simple control strategy based on modulation control. The offshore VSC is controlled and operated as a voltage source with constant ac frequency and phase angle. Control strategy including the modulation index $M$ used in this study is shown in Fig. 9 where a simple FLC is adopted. This gives excellent transient and dynamic
4) Rule Base: The fuzzy mapping of the input variables to the output is represented by IF–THEN rules of the following forms:

IF \( \varepsilon_1 \) is NB and \( \Delta \varepsilon \) is NB THEN \( M_n \) is NB

IF \( \varepsilon_1 \) is PB and \( \Delta \varepsilon \) is PB THEN \( M_n \) is PB.

The entire rule base is given in Table III. There are a total of 25 rules to achieve desired index \( M_n \).

3) Inference and Defuzzification: In this work, for the inference mechanism, Mamdani’s maximum–minimum (or sum-product) [22] method is used. The center of gravity method [22] is used for defuzzification to obtain \( M_n \), which is given by the following equation:

\[
M_n = \sum_{i=1}^{N} \mu_i C_i / \sum_{i=1}^{N} \mu_i
\]

where \( N \) is the total number of rules, \( \mu_i \) is the membership grade for \( i \)th rule, and \( C_i \) is the coordinate corresponding to the respective output or consequent membership function \([C_i \in \{-0.1, -0.01, 0, 0.01, 0.1\}]\). The actual modulated index \( M \) can be found by multiplying \( M_n \) by the scaling factor \( K_M \).

VI. SIMULATION RESULTS

In this study, detailed switching models are used for all converter/inverter models instead of a time averaged one. Both dynamic and transient characteristics are analyzed using the proposed system. The simulation time step is chosen as 0.00002 s. The simulation time for dynamic and transient analyses are chosen as 600 and 10 s, respectively.

A. Dynamic Characteristics Analysis

The real wind speed data used in the simulation are shown in Fig. 11, which were measured in Hokkaido Island, Japan.

TABLE III

<table>
<thead>
<tr>
<th>( M_n )</th>
<th>( \Delta \varepsilon )</th>
<th>NB</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
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<td>NS</td>
<td>NS</td>
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<td>NS</td>
<td>ZO</td>
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<td>ZO</td>
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<td>ZO</td>
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<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

where \( \mu(x) \) is the value of grade of membership, \( w \) is the width, \( m \) is the coordinate of the point at which the grade of membership is 1, and \( x \) is the value of the input variable.

Fig. 10. Fuzzy sets and their corresponding membership functions.

Fig. 11. Wind speeds used in the VSWTs.

Fig. 12. Reference powers for ac–dc converters used in VSWT-PMSGs.
The MPPT controller determines the reference power set-point using wind and rotor speeds. The responses of reference powers and rotor speeds for the two WTGSs are shown in Figs. 12 and 13, respectively. The dc–ac inverter of the wind farm can maintain the wind farm dc-bus and ac-bus voltages at a constant level, as shown in Figs. 14 and 15, respectively. The dc-bus topology-based wind farm makes the system less costly as explained in Section I. On the other hand, the simple fuzzy logic controlled offshore VSC station can transfer the wind farm real power efficiently to the onshore grid as shown in Fig. 16. The onshore VSC-station can maintain voltages at the HVDC line and onshore grid constant as shown in Figs. 17 and 18, respectively. Therefore, it is seen that the developed control strategies are well suitable for the normal operation of wind farm under randomly varying wind conditions.

B. Transient Characteristics Analysis

For transient stability analysis, the most severe symmetrical three-line-to-ground (3LG) fault is considered as a network disturbance, which occurs at the grid side of the onshore VSC station (fault points $F$ in Fig. 1). The fault occurs at 0.1 s, the circuit breakers (CBs) on the faulted lines are opened at 0.2 s, and at 1.0 s, the CBs are reclosed. In this analysis, it is assumed that wind speed is constant and equivalent to the rated speed for the wind turbines. This is because it may be considered that wind speed does not change dramatically during the short time interval of the transient stability simulation. When the onshore grid voltage goes lower than a certain value during network disturbance (in this study 0.9 pu), the wind farm power command signal is varied according to the grid voltage at the onshore grid.
as shown in Fig. 5. The responses of ac voltages at both VSC stations are shown together in Fig. 19.

The reference powers used in wind farm ac–dc converters are shown in Fig. 20. The real and reactive power responses at onshore grid are shown in Fig. 21. The pitch controller controls the mechanical power of wind turbine in order for the PMSG to become stable. Therefore, the PMSG rotor speeds become stable as shown in Fig. 22. The dc voltage at both offshore and onshore VSC stations are shown in Figs. 23 and 24, respectively. Simulation results clearly show that the proposed system can overcome severe 3LG fault under the developed control strategies.

VII. CONCLUSION

In this paper, the operation and control of dc-bus-based offshore wind farm topology is investigated which is connected with an HVDC system through the 3L NPC-based VSC stations and XLPE cables. The maximum power is transferred from VSWT generator systems to the dc-bus through the ac–dc converters due to the MPPT controllers. Only one dc–ac inverter converts the dc-bus voltage to a suitable ac voltage of wind farm ac-bus. It is seen that the FLC controlled offshore 3L-NPC VSC station can transfer the real power of the offshore wind farm to the onshore grid successfully and efficiently. The onshore 3L VSC station can ensure the constant HVDC line voltage as well as supply necessary reactive power to the onshore grid. As a result, the onshore grid voltage can be maintained constant even in the case of network disturbance. The control strategies developed for the HVDC connected dc-bus-based offshore wind farm are verified by both dynamic and transient characteristics analyses. Finally, it is concluded that the proposed system performs sufficiently well for HVDC interconnected dc-bus-based
offshore wind farm under both normal and network fault conditions.

APPENDIX

The ABB 15-kV XLPE cable parameters are shown in Table IV [23].

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>CABLE PARAMETERS</th>
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</thead>
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<tr>
<td>Conductor Radius</td>
<td>0.0178 m</td>
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<tr>
<td>Insulator Outer radius</td>
<td>0.0370 m</td>
</tr>
<tr>
<td>Copper Resistivity</td>
<td>1.724e-8</td>
</tr>
<tr>
<td>Permittivity</td>
<td>2.3</td>
</tr>
<tr>
<td>Resistance at 20°C</td>
<td>0.0172 Ω/km</td>
</tr>
</tbody>
</table>

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REFERENCES


