Voltage Control Strategies for Offshore Wind Power Collection Systems upon Faults

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***Abstract*—Three types of offshore wind power collection topologies are studied for DC power systems in this paper. Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion System (WECS) is considered and the Optimal Power Control (OPC) is used for the Maximum Power Point Track (MPPT) control. The failure of a wind power unit is regarded as the fault condition in this paper. Voltage control strategies are proposed for series and series-parallel power collection topologies when such a fault happens. Input and output voltage references of the Grid-Side Converter (GSC) are modified for series power collection systems on fault conditions. For series-parallel collection systems, power switches are employed between wind power branches and different voltage control effects with different switch options are discussed. Simulation studies are conducted base on PSCAD/EMTDC to validate the proposed control strategies.**

***Index Terms*— Collection Systems, WECS, MPPT, Fault.**

I. INTRODUCTION

Various renewable energy technologies are getting integrated in power systems as a result of serious environmental problems caused by fossil fuel consumption. Wind resource is one of the most popular energy choices due to its relatively cheaper cost. Furthermore, the availability of enormous amount of wind energy makes it advantageous in massive power supply compared to other renewable sources [1-2]. Offshore wind is especially drawing attention as it has bigger quantity potential than onshore wind [3]. Besides, with current concern of the side effects that wind turbines might generate, offshore wind farms are eco-friendlier as they are far away from human residences [4].

PMSGs are employed in this paper to study offshore wind power collection topologies and their control strategies. Although permanent magnets are expensive, PMSGs are the most promising wind generators due to their advantages below. First, the use of a full-capacity power converter greatly enhances the performance of the WECS and decouples the generator side from the grid side. This is especially important for offshore wind farms with high wind speeds to satisfy the increasingly stringent grid code requirements. Second, the size of PMSGs is small because of their large air gaps and reduced flux linkage. Third, PMSG based WECSs can be gearless when low-speed synchronous generators with large number of poles are employed [5-9]. The Back-to-Back (BTB) Voltage Source Converter (VSC) topology is chosen in this paper considering its commercial popularity [7], [10]. The Optimal Power Control (OPC) based MPPT generator control is applied to the Wind-Side Converter (WSC) [11], while the Grid-Side Converter (GSC) maintains the DC voltage at a constant value.

Power from wind turbines can be collected by either AC or DC systems. Reference [12] proposes an AC collection system with transformers boosting voltages to the transmission level. Compared to AC collection, the size of DC collection systems is reduced and transformer weights are decreased [13]. The series-parallel topology is promising among DC power collection systems [14]. Identical generators with WSCs are connected in series to form wind power branches and the branches are then connected in parallel. The DC terminal voltage of the collection system is controlled by a common GSC. Reference [13] gives another topology of the DC collection system with parallel connections and boost converters. The series-parallel topology has the advantage that voltage boosting stages can be omitted and the converter quantity is greatly reduced. However, the fault tolerance of the series-parallel DC collection system is low due to the series interconnection [14]. Reference [14] presents a matrix interconnected topology by using auxiliary paths for topology reconfiguration. However, it only considers the very ideal situation when all wind turbines are operating at rated power.

This paper proposes a wind power collection topology with only series connections on DC sides of WSCs. Voltage control strategies on fault conditions are proposed for both series and series-parallel DC collection systems. The expected control effects are validated using PSCAD/EMTDC.

II. PMSG BASED WIND ENERGY CONVERSION SYSTEMS

WECSs include wind turbines to convert wind kinetic energy to mechanical energy, wind generators to generate electric energy and power converters to control wind power supply. The pitch control of wind turbines employs a PI controller, where the pitch angle is obtained based on the error feedback between the measured output power and the reference power [15]. The wind generator used in this paper is the PMSG model package provided by PSCAD [16], which is a non-salient gearless synchronous generator. Relevant parameters of the wind turbine with its pitch control and wind generator are listed in the Appendix. Fig. 1 shows the PMSG based WECS with its control loops.

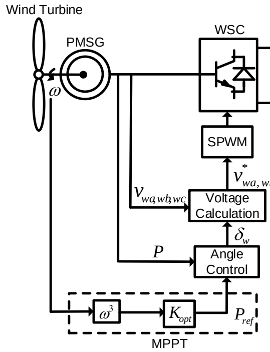


Fig. 1. PMSG with BTB VSC.

The MPPT control is applied to the WSC to draw maximum power from the wind energy. A similar method to the Optimal Torque Control (OTC) [7], which is named as the Optimal Power Control (OPC), is used in this paper [11]. OPC is based on the theory that the generator power is proportional to its speed cubed in steady state when maximum wind power is extracted [11]. As shown in the dashed frame of Fig. 1, ω is the generator speed, K_{opt} is the coefficient for the optimal power and P_{ref} is the power reference. K_{opt} is calculated according to the generator rated parameters.

The power reference for the WSC control is obtained through the OPC based MPPT method described above, while the DC voltage reference for the GSC control is set according to the WECS demand. Two references with their measured values are sent to two angle control components respectively, as shown in Fig. 1. For the angle control, the generated voltage angle deviations from the wind side voltage (δ_w) and the gird side voltage (δ_g) are calculated by PI control, as

$$\begin{cases} \delta_w = K_{Pw}\left(P_{ref} - P\right) + K_{Iw}\int\left(P_{ref} - P\right)dt \\ \delta_g = K_{Pg}\left(V_{dcref} - V_{dc}\right) + K_{Ig}\int\left(V_{dcref} - V_{dc}\right)dt \end{cases} \tag{1}$$

where P is the measured power, V_{dcref} and V_{dc} are the reference and actual DC voltages respectively. K_{Pw}, K_{Pg}, K_{Iw} and K_{Ig} are proportional and integral gains of PI controllers. With the input of angle deviations (δ_w and δ_g) and AC side voltages ($v_{\omega a,\omega b,\omega c}$ for wind side and $v_{ga,gb,gc}$ for grid side), the SPWM reference voltages ($v^*_{\omega a,\omega b,\omega c}$ for wind side and $v^*_{ga,gb,gc}$ for grid side) are obtained. In this way, the active power of the WECS is controlled by the WSC, while the DC voltage is controlled by the GSC.

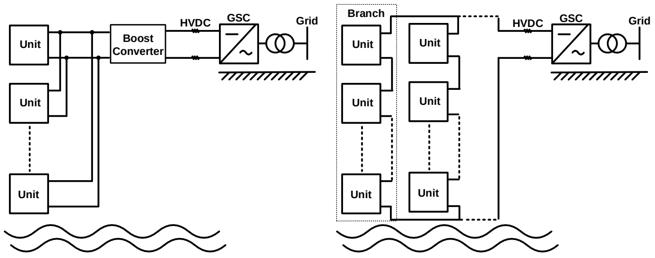
III. WIND POWER COLLECTION TOPOLOGIES

This paper focuses on the condition of uniform turbine employment within a wind farm since the majority of wind power projects employ a single type of wind turbines. Here, a wind turbine with its PMSG and WSC is called a "wind power unit" or simply a "unit". As far as DC power collection systems are concerned, two types of unit connection patterns exist – series-parallel connection and parallel connection. A third pattern with only series connection is proposed here, and is studied together with the two existing connections.

A. Characteristics of Wind Power Collection Topologies

The HVDC transmission technique is employed to deliver the collected offshore wind power to an onshore station. The schematics of collection structures for offshore wind turbines are illustrated in Fig. 2, where the wavy lines represent water, while the horizontal lines with slashes indicate land surface. All the HVDC cables are assumed to be at sub-sea level.

It can be seen from Fig. 2 (a) that in the case of parallel collection, a boost converter must be employed to increase the DC voltage for HVDC delivery. Wind turbines, WSCs and the boost converter are all built offshore. If some turbines in the parallel collection system fail, their relevant units can be simply disconnected from the system without causing voltage fluctuations.



(a) (b)

Fig. 2. DC collection systems: (a) parallel and (b) series-parallel.

The series-parallel wind power collection system is shown in Fig. 2 (b) [14], where only wind power units are above water. Here each series connected cluster is called a "wind power branch" or "branch". This topology adds up both the DC voltage and DC power through the connection structure itself instead of using boost converters. For the concern of investment cost on the DC power collection system, the series-parallel connection has greater advantages than the use of only parallel connections. However, the series-parallel topology requires extra devices to deal with fault conditions.

The realization of collecting wind power in a purely series connected pattern is based on the special environment of offshore wind farms. Compared to onshore wind farms, wind in an offshore area is not blocked by buildings or trees. Wind speeds can thus be considered the same or slightly uneven (in the case of very large wind farms). Therefore, power outputs from uniform turbines within a wind farm do not vary much. According to [17], no obvious power magnitude difference from turbine to turbine can be discerned. The natural condition and construction feature facilitate offshore wind turbines being stacked up. The series connection topology is the same as in Fig. 2 (b) except that it only contains one branch. Similar to the series-parallel connection, no boost converters are needed and no extra devices other than wind power units are above water. An important difference is that overvoltage caused by fault in the series topology can be prevented by modifying control strategies instead of using extra devices. Voltage control strategies under fault conditions are discussed for both the series and series-parallel collection systems.

B. Determination of Voltage Restrictions

For series and series-parallel wind power collection systems, the GSC can only maintain the total voltage at the collecting point constant. The DC voltage of each wind power unit cannot be controlled independently. Neglecting HVDC line losses, the input voltage reference of the GSC is set as

$$U_T = n \times U_N \tag{2}$$

where U_T is the rated transmission voltage, U_N is the nominal DC voltage of each unit, and n is the number of series connected units in a branch. Since series connection requires the same DC current to flow out of each unit in a branch, their DC voltages are proportional to their own power outputs. However, U_T is kept constant as per (2). This dependent voltage control method is termed as Voltage Distribution Principle (VDP) in this paper.

When power outputs of series connected units are different, DC voltages of some units will deviate from U_N according to VDP. For power converters under SPWM control, the DC side voltage reference must be big enough to avoid signal tracking failure. It is assumed that the DC voltage of each unit can meet this signal tracking requirement under all conditions. Overvoltage prevention is considered as the only voltage control target in this paper. Overvoltage limits of $1.1U_N$ and $1.5U_N$ are allowed for each unit after fault and during transients [14].

IV. VOLTAGE LIMITING STRATEGY FOR SERIES COLLECTION SYSTEMS

A control strategy is proposed and applied to the input DC voltage and output AC voltage of the GSC for the series power collection system when a fault occurs.

A. GSC Input Voltage Reference Modification

Wind power units in a series connected system are named as unit-1, unit-2, …, unit-n. Their DC voltages and power outputs are denoted by U_1, U_2, …, U_n and P_1, P_2, …, P_n respectively. With similar levels of power outputs, a rough estimation is made by assuming

$$U_1 = U_2 = \cdots = U_n = U_N = \frac{U_T}{n} \tag{3}$$

Suppose the maximum number of faulty units is m. The DC voltages of the non-faulty units can then rise to a maximum level of $U_T/(n-m)$. If no voltage limiting strategy is applied, this maximum voltage must be no bigger than $1.1U_N$. It is thus obtained that

$$n \geq 11 \times m \tag{4}$$

The above equation indicates that at least $11m$ wind turbines are required in a series collection system. More turbines means a stronger system to tolerate fault conditions. In some small wind farms, however, the number of wind turbines is not big enough to meet (4). For such a case, the GSC Input Voltage Reference Modification (IVRM) method is proposed.

Presume turbines of unit-(n-m+1) to unit-n are faulted at the same time and unit-k is found to have the biggest power output among the (n-m) non-faulty units. U'_1, U'_2, …, U'_k, …, U'_{n-m} represent the DC voltages of unit-1 to unit-(n-m) after the fault. According to VDP, U'_k is the biggest among U'_1 to U'_{n-m}. As long as U'_k is controlled below the voltage limit, DC voltages for other non-faulty units are restricted.

It is assumed that overvoltage will occur to at least one unit without IVRM. By modifying U_T to U''_T, the DC voltage of unit-k is limited at $1.1U_N$. Voltages of the non-faulty units after the modification are denoted by U''_1, U''_2, …, U''_k, …, U''_{n-m}. Based on VDP, DC Voltage Decrease Ratio (DVDR) is defined as

$$r_d = \frac{U'_1}{U''_1} = \frac{U'_2}{U''_2} = \cdots = \frac{U'_k}{U''_k} = \cdots = \frac{U'_{n-m}}{U''_{n-m}} = \frac{U_T}{U''_T} \tag{5}$$

where r_d ($r_d > 1$) is DVDR. As $U''_k = 1.1U_N$, the modified voltage reference is expressed as

$$U''_T = \frac{1.1 \times U_N}{U'_k} \times U_T \tag{6}$$

Since U_k changes to U''_k directly following the IVRM, U'_k is just a suppositional value. To calculate U'_k, suppose U_T is not modified after fault happens, then according to VDP,

$$U'_k = \frac{P_k}{P_1 + P_2 + \cdots + P_k + \cdots + P_{n-m}} \times U_T \tag{7}$$

The modified reference is therefore derived by combining (6) with (7), which gives

$$U''_T = \frac{P_1 + P_2 + \cdots + P_k + \cdots + P_{n-m}}{P_k} \times 1.1 \times U_N \tag{8}$$

B. GSC Output Voltage Reference Reset

Assume the rated line-to-line RMS voltage input of the WSC and output of the GSC are denoted by U_w and U_g respectively. Following the same voltage reference determination pattern of the WSC, U_g is set as

$$U_g = n \times U_w \tag{9}$$

However, with the decrease of U_T when IVRM is applied, tracking failure of the GSC control might happen.

To suit IVRM, the output voltage reference of the GSC is reset at a relatively low value of U''_g. Let us assume

$$U''_g = r_a \times U_g \tag{10}$$

where r_a ($0 < r_a < 1$) is termed as the AC Voltage Decrease Ratio (AVDR). Based on VDP, U_T will be decreased most by applying IVRM when all units' power outputs are equal. According to (8), in this situation, we have

$$U''_T = 1.1 \times (n-m) \times U_N \tag{11}$$

Suppose k_w and k_g are the modulation indices of the WSC and GSC respectively, then [18]

$$U_w = \frac{1}{2}\sqrt{\frac{3}{2}} \times k_w \times U_N, \quad U''_g = \frac{1}{2}\sqrt{\frac{3}{2}} \times k_g \times U''_T \tag{12}$$

The AVDR is therefore obtained by solving (9-12) as

$$r_a = 1.1 \times \frac{n-m}{n} \times \frac{k_g}{k_w} \tag{13}$$

To achieve a better utilization of the GSC, a large value of U''_g is preferred. The reset reference of the GSC output voltage is thus calculated with $k_g = 1$ as

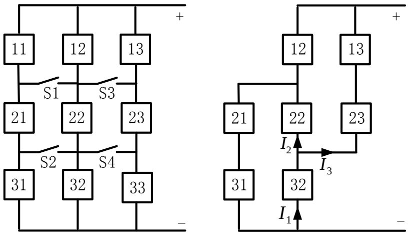
$$U''_g = \frac{1.1 \times (n-m)}{n k_w} \times U_g = 1.1 \times (n-m) \frac{\sqrt{3}}{2\sqrt{2}} \times U_N \tag{14}$$

V. VOLTAGE LIMITING STRATEGY FOR SERIES-PARALLEL COLLECTION SYSTEMS

Switches between adjacent branches to change the collection topology upon fault were applied in [14]. But it only considered faulty units in the same branch with the ideal operating condition. In practical situations, however, all types of fault scenarios can happen. In this paper, random fault conditions of the series-parallel collection topology are considered.

With power switches employed between adjacent wind power branches, a "bridge" can be formed by closing certain groups of switches when units in different branches get faulty. A simple example is given in Fig. 3 (a), which shows a simple

3×3 series-parallel topology. In this, each box represents a wind power unit and is denoted in a matrix pattern. S1, S2, S3 and S4 are power switches. Power outputs from all units are assumed to be equal. Suppose the switches S1 and S4 are closed when units 11 and 33 are disconnected due to fault. The new collection topology is shown in Fig. 3 (b), where the closed switches are shorted and the open switches are removed.



(a) (b)

Fig. 3. Simple series-parallel connection with switches: (a) normal operation and (b) under fault condition.

Assume DC currents through unit-32, unit-22 and unit-23 are I_1, I_2, and I_3 respectively, as shown in Fig. 3 (b). Then using KCL, we get $I_1 = I_2 + I_3$, and hence $I_1 > I_2$. For equal power from all units, we get

$$U_{32}\times I_1 = U_{22}\times I_2 \tag{15}$$

This implies that $U_{22} > U_{32}$. Also since $U_{21} + U_{31} = U_{22} + U_{32}$, $U_{21} = U_{31}$, we get $U_{21} = U_{31} < U_{22}$.

Since the voltages of units 13 and 23 are the same as those of units 21 and 31, while the voltage of unit-12 is equal to the voltage of unit-32, the highest DC voltage amongst all the units will be impressed upon unit-22. Therefore, it is better to avoid such bridge connections.

The example above used equal power outputs. Typically, wind speed decreases when some of its energy is extracted by rotor blades. But the speed recovers at some distance downwind. It indicates that the mean power outputs of wind power units tend to reduce from upstream to downstream branches. However, some branches might have similar mean power outputs depending on wind speed characteristics. The uncertainty of wind power implies that with the bridge connections excluded, various topologies are still possible with the selection of different switches. The optimum switching strategies under random fault conditions are yet to be determined.

VI. SIMULATIONS

To verify the modelling and control of the designed PMSG based WECS in PSCAD, detailed wind turbine models are applied for the series collection topology. Four wind power units are connected in series. Distinctly varied wind speeds are provided for different turbines to show the robustness of the system. Besides, a 6×4 series-parallel collection system is tested. Ideal power sources are employed to reduce the simulation burden with the large number of wind turbines.

The grids are modelled as ideal voltage sources. GSC output voltage references are set at 16 kV for the series collection model without considering faults and 24 kV for the series-parallel model. The rated DC voltage for each unit is 7.5 kV, which means the GSCs hold the total DC voltages of the series and series-parallel systems at 30 kV and 45 kV respectively. The steady-state voltage limit of each power unit is therefore

$$U_{lm} = 1.1\times 7.5kV = 8.25kV \tag{16}$$

A. Series Power Collection System with Fault

For this case, unit-2 is disconnected at 15 s upon a fault and IVRM is applied. The GSC output voltage reference is replaced by 15.156 kV according to (14). The simulation results are shown in Fig. 4. Wind speed inputs of unit-1 to unit-4 are denoted by V_{w1}, V_{w2}, V_{w3} and V_{w4} respectively and illustrated in Fig. 4 (a). It is clear that V_{w1}, V_{w2} and V_{w3} ramp up in different patterns, while V_{w4} decreases. Fig. 4 (b) shows that wind power outputs change following their corresponding wind speed curves with small fluctuation upon fault. P_2 becomes 0 after fault as unit-2 is removed. U_1, U_2, U_3, U_4 depicted in Fig. 4 (c) are distributed among the four units based on VDP. U_T is kept at 30 kV before fault and drops to around 23.7 kV after fault. It can also be seen in Fig. 4 (c) that the maximum DC voltage is limited at 8.25 kV after fault due to IVRM. Moreover, all voltages are far below the transient voltage limit.

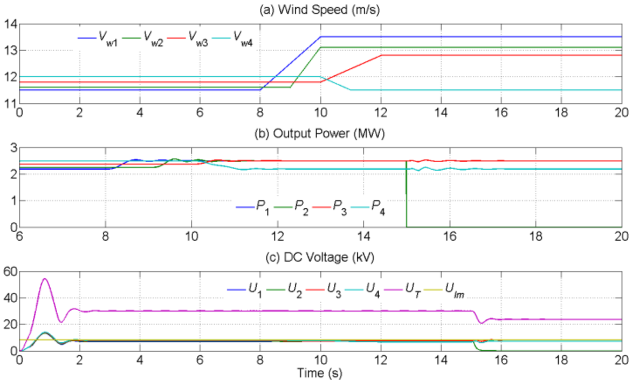


Fig. 4. Results with four series connected units.

B. Series-parallel Power Collection System with Fault

The 6×4 series-parallel collection model with power switches is shown in Fig. 5. Suppose the wind blows from the left to the right. It has been assumed that the rated power is 1 pu and power outputs of branches 1 to 4 vary randomly around 1 pu, 0.98 pu, 0.96 pu and 0.94 pu respectively.

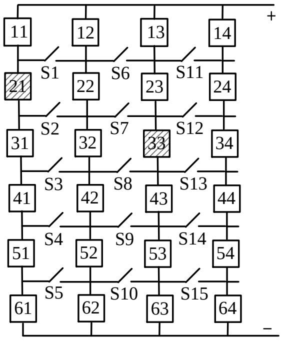
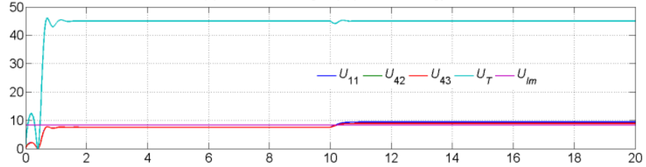


Fig. 5. Schematic diagram of series-parallel simulation model in PSCAD.

It is considered that unit-21 and unit-33 become faulty simultaneously at 10 s. The adjacent switches of unit-21 are S1 and S2. Therefore, to limit the DC voltages of non-faulty units in branch-1, these switches are closed upon fault. However, there are two pairs of adjacent switches of unit-33, which are {S7, S8} and {S12, S13}. Either pair of switches can be selected. Simulation results with two different switching strategies are shown in Fig. 6, where the switches {S1, S2, S7, S8} are closed under strategy-1, while the switches {S1, S2, S12, S13} are closed under strategy-2.

(a) Some DC Voltages (kV) under Strategy-1



(b) Some DC Voltages (kV) under Strategy-2

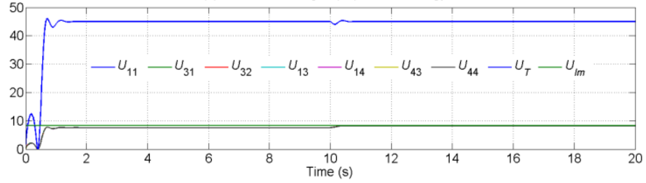


Fig. 6. DC voltages for series-parallel collection: (a) strategy-1 and (b) strategy-2.

To show better visibility of the control results, only relatively higher voltages by applying each strategy are plotted. It can be seen in Fig. 6 (a) that the highest voltage after fault is around 9.39 kV, which is above U_{lm}. Fig. 6 (b) shows that by applying strategy-2, the highest voltage amongst all the units is limited below U_{lm}. The simulation results demonstrate that different switching options after fault have different effects on voltage restriction. The total DC voltage is kept at 45 kV with both switching strategies regardless of fault. Besides, no transient voltage exceeds the transient limit.

VII. CONCLUSIONS

In this paper, the collection systems of PMSG based WECS are studied. Three collection topologies for offshore wind farms are discussed and compared. A series wind power collection topology is proposed. The input and output voltage references of the GSC are modified to avoid overvoltage occurrence when fault happens in series collection systems. Switches are applied between adjacent wind power branches for the series-parallel collection topology. Switching strategies that generate bridge connections are to be avoided amongst various switching options. The proposed voltage control strategy for the series collection system is validated through the simulation studies using PSCAD. Different voltage control effects with different switching strategies are simulated using a series-parallel collection model. Optimum switching strategy determination has not been studied here and will be reported in a future publication.

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APPENDIX

TABLE-I. SYSTEM PARAMETERS

	Parameters Names	**Parameter Values**
Wind turbine and PMSG	Rotor radius	58 cm
	Air density	1.225 kg/m^3
	Rated wind speed	12 m/s
	Rated apparent power	2.5 MVA
	Rated line-to-line voltage	4 kV
	Rated frequency	10 Hz
	Number of pole pairs	49
Pitch control	Proportional gain	100
	Integral time constant	0.001 s
	Maximum increase/decrease rate	1000/s
	Upper limit	60°
	Lower limit	0