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Design of DC Architecture for Large-Scale Non-Grid-Connected Wind Power Generation System

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Abstract: In this paper, a dc architecture for large-scale non-grid-connected wind power generation system (WPGS) is presented. Unlike the existed wind farms, the proposed structure has the merits of eliminated reactive power, low power loss, long transfer distance, and etc. With the purpose to overcome the effects of integrating large wind power plants into utility systems, a creative concept of direct integration of high energy consumption industry (HECI) with large scale WPGS where the fluctuant power or whole power is consumed by the HECI. A three-phase full-bridge high power step-up dc/dc converter is adopted to meet the implementation of the system. Compared to the traditional single-phase full-bridge dc/dc converter, the presented converter features strong power management ability, high efficiency, and flexible transformer design. With proper control strategy, both of the voltage level before and after the dc transformer can be stabilized with a closed-loop converter located at the receiving-end of the transmission system. Finally, a 200MW wind farm is simulated with the proposed dc architecture. The results verify the feasibility of the presented WPCS and system control method.

Keywords: DC Architecture, High Energy Consumptive Industry, Three-Phase Dc/Dc Converter, Rotor Speed Feedback Control, Large-Scale Non-Grid-Connected Wind Power.

I. INTRODUCTION

Wind power generation technology which exhibits the pioneer of renewable energy generation was explosive growth in the past decades, due in part to the renewed public support and maturing turbine technologies. Offshore wind farms have been particularly focused on some exclusive benefits, such as significantly higher wind energy resources, reduced issues of noise and ameliorated the impact on the landscape [1]. Several offshore wind farms, such as Dennark's 160-MW Horns Rev wind farm, the main European offshore pilot project, and Denmark's 165.6-MW Nysted wind farm have been constructed and run. As can be predicted, the power rating for future wind farms will be up to several hundred megawatts.

However, the inherent characteristics of wind power, such as its location-specific resource, intermittent output, and low capacity factor, has been demonstrating the potential effects of integrating wind power plants into utility systems and present. This work was supported by National Basic Research Program of China (973 Program) in contract number-2007CB210303.

Unique integration challenges, which limits the total power capacity of the large scale wind farm for the reason of power quality, active and reactive power flow, and infrastructure and system stability. Especially in the under-development country, the problems are more serious because of the power system is relatively weak and regional independency. With the purpose to eliminate the impact of large wind farms to the power system, many types of research have been carried out over the past decade [2, 3]. An innovative ideal of integrating large offshore wind farms with high energy consumptive industry (HECI) park directly is proposed in the literature [4].

In this paper, a novel High Energy Consumption Industry (HECI) integrated dc architecture large-scale offshore wind farm is proposed for the non-grid-connected WPCSs.

The proposed system has several characteristics, which can be summarized as follows.

- DC grid which has the merits of low transmission losses, long transmission distance, and high stability is adopted.
- Direct integration of high energy consumptive industry absorbs most of the wind power and feeds little power to the grid, and the passive impact on power system will be partly alleviated, even eliminated.

The paper is organized as follows: Section II describes the proposed dc architecture, and a simple comparison to AC architecture in carried out. The ideal of integration of HECI is introduced in Section III. In Section IV, a three-phase dc/dc converter is introduced for high-voltage high-power HVDC application. Then, the power control for turbine and system is discussed in part V. In Section VI, a 200MW WPCS simulation model based on dc architecture is built, and the results verify the feasibility of the proposed dc architecture based WPCS.

II. DC ARCHITECTURE

Wind farms that operate today are most constructed in ac architecture because ac structure is commonly used for its flexible in building and convenient in voltage conversion.

However, in some applications, such as the permanent magnetic synchronous generator (PMSG) application, the ac structure may not exhibit its superiority anymore. For example, a four-quadrant back to back converter for full-rated power conversion is necessary to connect the generator and ac collection grid in PMSG application.

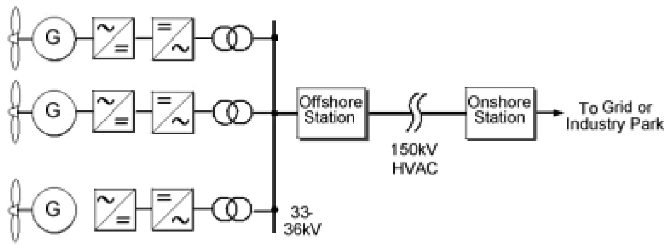


Fig.1 Traditional AC Architecture

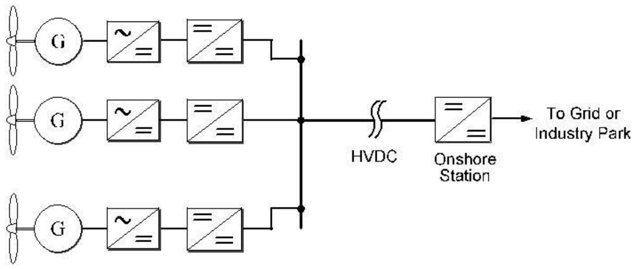


Fig.2 Proposed DC Architecture

Fig.1 illustrates the simplified diagram of direct-drive PMSG based ac architecture WPGS. Besides, the offshore wind farm has been paid widely attention with the purpose to obtain better wind profiles and large space demands, the distance between wind turbines is usually longer than the onshore wind farms and keeps growing capacity of offshore wind farms. Therefore, the conduction losses of traditional ac grid increase remarkably.

To overcome the drawbacks of conventional ac architecture, a new ideal of dc architecture is introduced, as shown in Fig.2. Only one PWM rectifier is used following the PMSG and the dc voltage is boosted up to several tens or hundreds of kilovolts with a dc transformer. The DC/AC inverter and bulky boost transformer existed in the traditional ac architecture are eliminated. Some publications have evaluated the cost and loss between ac grid and dc grid [5, 6].

In the system proposed in Fig.2, the sending-end converter is different from the general VSC-HVDC transmission system, where the AC/DC PWM rectifier is replaced with many independently high power isolated step-up dc/dc converters installed following each turbine. High frequency isolated transformer can be used instead of traditional 50/60Hz bulky low frequency transformer, which leads to a great reduction of weight and size. A detailed description of such converter will be given in Section IV.

III. INTEGRATION OF HIGH ENERGY CONSUMPTIVE INDUSTRY

In general, the power of an offshore wind farm is fed to the large utility entirely. However, with the increased capacity of the future offshore wind farm, the proportion of wind power in the utility increases remarkably. Although the effects of integrating large wind farms to the utility are greatly improved with VSC-HVDC technology and the stability of utility is enhanced to a certain extent. However, it has not solved the inherent problems that the wind farm features. The fluctuant power is still existed and flow into the utility and the large perturbation of wind energy will still threaten the stability of some relatively weak local grid, even large power system.

A. System Description

To overcome the above-mentioned problems, a new concept of integrating high energy consumptive industry with large-scale offshore wind farms is proposed here. The high energy consumptive industry which has a similar characteristic with battery is designed to absorb the fluctuant power. The fluctuant power is consumed by the HECI industry directly rather than fed into the grid, even the whole wind power.

Fig.3 depicts a typical configuration of dc architecture for the HECI integrated WPCS. The output of wind generators is gathered after a four-quadrant ac/dc rectifier and transferred to an offshore platform. After that point of common coupling (PCC), a high power dc/dc converter system is installed for stepping up the voltage from the distribution to the transmission voltage level. Afterward, the power is transferred via a submarine dc-cable to the onshore conversion station. Subsequently, the constant part of the power is fed into the grid while the fluctuant part is consumed with HECI directly or the whole power is consumed with the HECI if the stand-alone system is adopted. Since the difference between the output power of each turbine and the total power transmitted to the onshore industry park is huge, several voltage steps may be needed.

B. High Energy Consumptive Industry Park

The electric loads in the industry park are high energy con-sumptive industry, such as Chlor-Alkali industry, electrolytic aluminum and electrolytic copper industry etc. All of those electric loads have the same characteristic of nonlinear, tiny voltage variety could lead to considerable current change. Fig.4 and Fig.5 give the V-I characteristic of high energy consumptive load (HECL) and battery respectively. The characteristic of the high energy consumptive loads has the similar feature of the battery under charging condition. That is, the HECL has the ability of extraction fluctuant power as the battery. Therefore, the power supply for HECL can be designed as a controlled current source, and the capacity of storage equipment can be greatly reduced in the proposed WPCS.

Take the Chlor-Alkali industry as an example, the normal operation voltage of the electrolyzer is about 3.2-3.9Vdc, in other worlds, the permitted fluctuant voltage is about 0.7V. However, the variation of the load current is rather large if a tiny change of voltage occurs, as shown in Fig. 5, which leads to a wide range of power absorption ability within the normal operation state.

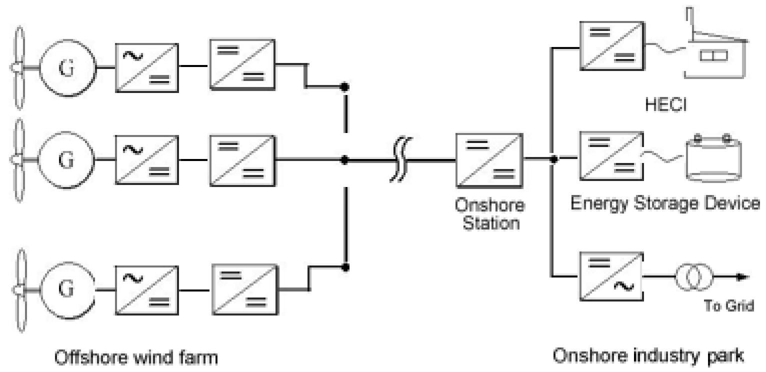


Fig. 3: The Typical Structure of HECI Integrated WPCS

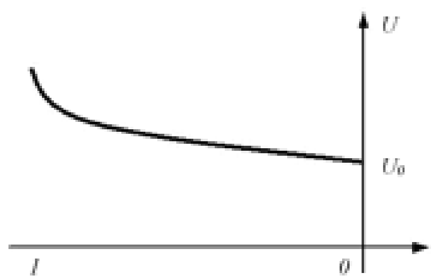


Fig. 4 V-I Characteristic of High Energy Consumptive Loads

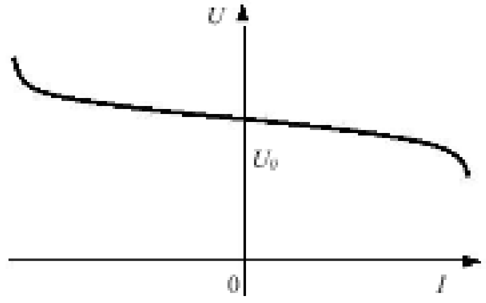


Fig. 5 V-I Characteristic of Battery

So the fluctuant power of wind power can be extracted by the HECI, leaving the steady power fed to the utility or the whole power is consumed with the HECI if the standalone system is adopted. The benefits of such ideal could overcome the impact of large offshore wind farms to the power system, and create a new area of wind power generation.

IV. HIGH-POWER DC/DC CONVERTER

A. Three-phase dc/dc Converter

Several dc/dc converters should be implemented to step-up or step-down the dc voltage in the proposed dc architecture WPCS. High power and high reliability are the essential requirements for the converters in such an application. The use of full-bridge converter is mandatory at high power. In this subsection, a simple three-phase full-bridge dc/dc converter is presented, where the conventional single-phase power transformer is replaced with a three-phase transformer, as shown in Fig.6. The introduced converter features higher efficiency as the root-mean-square (r.m.s) current at each leg and transformer windings are remarkably reduced with the same power level.

The use of three-phase transformers has been investigated for high power application [7, 8]. However, the most attractive applications of these solutions are for low-voltage systems, such as fuel cell and photovoltaic generation. By far, no report has been found for the high power HVDC transmission application in WPCS.

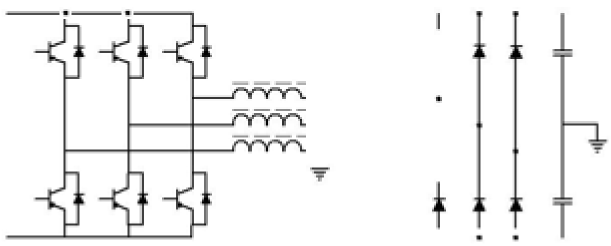


Fig. 6 Three-phase High Power dc/dc Converter

The three-phase topologies have much smaller input and output current ripples due to an increase of ripple frequency. Also, the weight and volume of the isolated transformer are reduced due to the reduced yoke volume and reduced voltage and magnetic stresses.

B. Three-phase Transformer Design

Different connection types of the three-phase transformer were available by connecting the windings at primary or secondary in delta (ấ) or wye (Y) structure. The transformer topology given in Fig.6 is designed in ấ-ấ structure. In this section, four different kinds of transformer topologies are analyzed and compared. Assume the turns-ratio of the transformer is a unit. The amplitude of the line voltages at the secondary is the same as the primary when the Y-Y structure of the transformer is designed. The ấ-Y connection of the three-phase transformer is depicted in Fig.7, this structure assures the amplitude of the line voltages at the secondary of the transformer twice the line voltages at the primary. This means that an inherent voltage gain is equal to two. Therefore, this configuration is extremely suitable for the step-up application in the WPCS. What's more, the ấ-Y connection ensures that the r.m.s current flowing on the primary windings is 3 which is lower than the line current at primary. On the contrary, the Y-ấ connection structure could be adopted for the step-down application. The amplitude of the line voltages at the primary is twice the line voltages at the secondary.

The fourth structure of the transformer is ǻ-ǻ connection, which has the same voltage ratio as the Y-Y structure. The drawback of ǻ-ǻstructure is the impracticability of neutral voltage, which is required by several applications such as bipolar HVDC transmission system.
According to the previous analysis, the transformer structure of voltage ratio as the ǻ-Y and Y-ǻ is an ideal choice for dc architecture WPCS.

Whichever structure of the transformer is selected, the winding currents at both primary and secondary in the converter are much lower than those flowing in the standard single-phase full-bridge dc/dc converter.

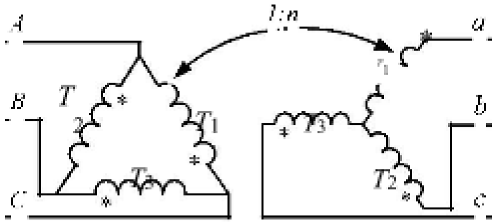


Fig. 7 Delta-wye Connection of the Transformer for Step-up Application

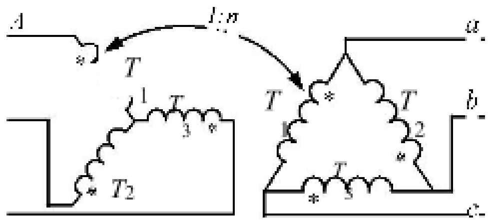


Fig. 8 Wye-delta Connection of the Transformer for Step-down Application

C. Combination Methods
While for extremely high voltage high power applications, such as HVDC transmission application, the dc bus can be as high as several hundred kilovolts, remember that the parallel or series connection of several dc/dc modules is a practical way. Fig.9 gives an example of a high output voltage step-up integrated dc/dc converter, two three-phase dc/dc converters operate with an input connected in parallel and output connected in series, and the ǻ-Y structure of each three-phase trans-formers is design. Therefore, the voltage gain of this topology is four, assuming the turns-ratio of T_1 and T_2 is unity. Vice versa, two converters with an input connected in series and output in parallel is suitable for the step-down application.

V. POWER CONTROL

A. Turbine Control
The mechanical output power at a given wind speed is drastically affected by the turbine's tip-speed-ratio (TSR), which is defined as the ratio of turbine rotor tip speed to the wind speed. The maximum energy conversion efficiency occurs at an optimal TSR at a given wind speed. Therefore, as wind speed changes, the rotor speed of the turbine needs to change accordingly in order to maintain the optimal TSR and thus to extract the maximum power form the available wind resources. To data, several maximum power tracking algorithms for wind generation have been developed over the past decades, namely TSR control, rotor speed feedback (RSF) control, hill-climb searching (HCS) control [9, 10]. In the following study, the PSF control algorithm is adopted if there is not special noted.

B. System Power Control
Based on the analysis carried out before, the system configuration of chosen as practical design for its overall high efficiency and reliability.

In an ideal case, the instantaneous power form the wind farms should be equal to the power dissipation at the high energy consumptive industry park or fed to the grid. However, considering the delay and detection times together with power fluctuations within the wind farm, this cannot be achieved for transient operations. The dc bus voltage may have some small perturbation for the transient power dismatch and the line resistance. In order to provide relatively steady power for the industrial park or grid, energy storage equipment's, such as flow battery, flywheel, can be implemented to absorb the fluctuant power.

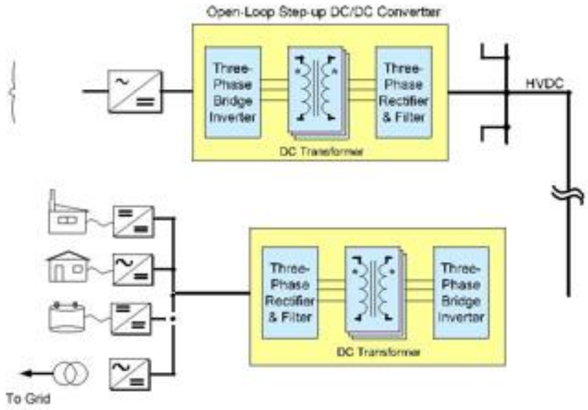


Fig. 10 Power Control of the proposed WPCS

Fig. 10 gives the power control and transmission process. The step-up dc/dc converter operates with a constant duty ratio to boost the medium dc voltage to HVDC. The voltage level is controlled with the step-down dc/dc converter or dc/ac inverter at the receiving-end. Namely, the voltage level before the boost dc transformer has a constant ratio to the HVDC bus and is indirectly regulated by the converter located in receiving-end.

VI. SIMULATION RESULTS

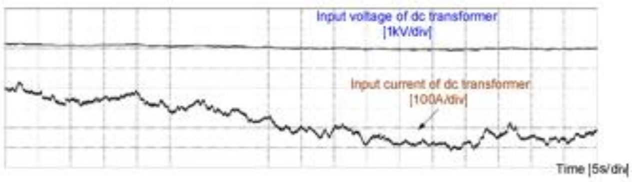
In order to verify the validity and feasibility of the proposed dc architecture based WPCS and the corresponding power control method, a simulation model of a 200MW offshore wind farm is built in Saber environment referring to system structure depicted in Fig. 10. The simulation results are given in Fig.11 and Fig.12.

Fig.11 shows the current and voltage variation before and after the step-up dc/dc transformer within 90 seconds. Obviously, the voltage level of those two points is stabilized with the converter located at receiving-end. However, the voltage level before the step-up transformer appears a slight variation, that's because the voltage drop across the line resistance and power switches vary with the line current.

Fig.12 gives the transient variation of transmission bus under a power step about 25MW. The voltage level of transmission bus has only about 0.1% variation.

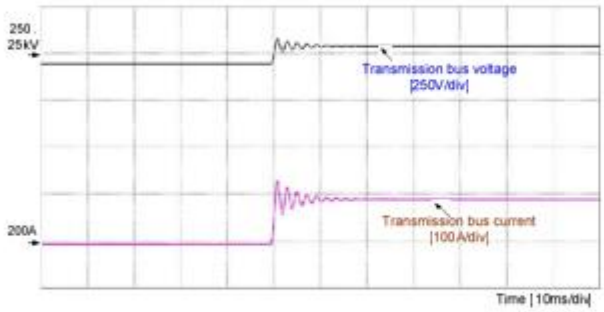
VII. CONCLUSION

In this paper, dc architecture for future large-scale offshore wind farms is proposed, which eliminates the total power capacity limitation of large scale wind farm for the reason of power quality, active and reactive power flow, infrastructure, and system stability. The creative concept of integration wind power generation system with HECI to construct a large-scale non-grid-connection WPCS is introduced. Which could further overcome the drawbacks of directly fed the wind power to the power system? A three-phase high power dc/dc converter is then introduced to step-up medium dc voltage to HVDC or step-down the HVDC to medium voltage. At last, the simulation is carried out, and the results verify the feasibility of the proposed dc architecture.



(a)

(b)



(c)

Fig.11 Voltage and Current Variation of the Dc Grid
(a). Before dc Transformer. (b) HVDC Transmission Bus.

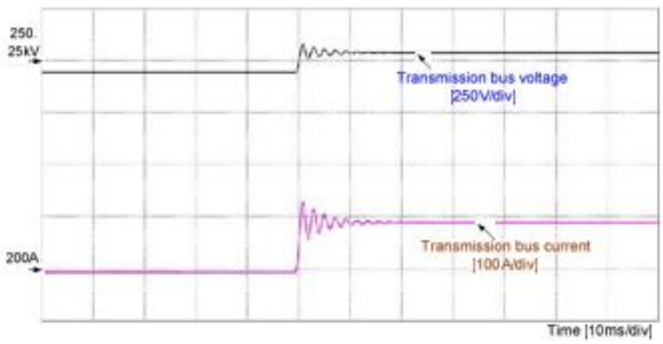


Fig.12: The Transient Characteristic of HVDC Transmission Bus

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