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A Modular Series Connected Converter for a 10 MW, 36 kV, Transformer-Less Offshore Wind Power Generator Drive

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Abstract

In the future, large offshore wind turbines are expected to reach a rating of 10 MW. To reduce the corresponding weight increase of the nacelle, research has started to focus on solutions to omit the step-up transformer in each turbine. Therefore this paper investigates a modular converter suitable for a special high power, transformer-less generator drive with 36 kV output DC-voltage. The drive consists of nine converter modules connected in series on the DC-side to obtain a high output voltage. Due to the series connection, extra care has to be taken to achieve equal voltage division between the converter modules. Therefore, a DC-voltage balancing scheme based on a droop control is proposed. The performance of the system will be demonstrated through simulations in EMTDC /PSCAD.

Keywords: Offshore wind power, power electronic converter, transformer-less drive, high voltage, redundancy

1. Introduction

Wind power has been pointed out, together with solar power, as the most promising energy resource for the future. Especially in the aftermath of Fukushima, where countries like Germany have announced plans to abandon their nuclear power plants [1]. Nuclear power was by many considered to be the most realistic alternative to fossil fuels in the struggle to reduce emissions of green house gases. But Fukushima reminded the world of the consequences of an accident at a nuclear power plant.

In the wind power research and industry, the focus has gradually been shifted from onshore to offshore development during the last decade. The main driver for the specific focus on the offshore segment is the wast, unexploited potential. While the access to good sites on land is becoming sparse and those available become more and more controversial due to conflicting interests, few sites are so far developed offshore. This is well illustrated by the UK Round 3, which may, alone, make available a theoretical potential of 33 GW wind power offshore [2].

However, this shift is carried out despite the fact that offshore wind power is not economically viable - at least not in today's energy market and with the present technology. Even onshore wind power is still relying on governmental support schemes, and offshore faces even more challenges. Some of theser are listed below:

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- Harsh weather conditions
- Increased electrical infrastructure cost
- Increased foundation cost
- Operation and maintenance difficulties

As conclusion, it has been assumed that it will be beneficial with offshore wind turbines larger than those installed on land ([3]). This is mainly due to the costs being highly related to the number of turbines. Another reason to consider larger turbines is because the size is no longer limited by the size of roads for transportation or visual pollution related problems. But when turbine ratings reach 10 MW and beyond, new problems occurs. One of these problems is the nacelle weight. The component size will increase significantly, both for the electrical as well as the mechanical parts. It is also necessary to move the distribution transformer from ground level up in the nacelle, in addition to the component weight increase. Bulky cables and high losses at low voltages are the reasons for that. As a result, even more weight is added to the nacelle. This weight is again increasing the loadings on the tower, which increases the demands on, and hence the cost of, this.

Therefore, recent research has focused on solutions which will reduce the weight. The main focus on the electrical part has been to make the 50 Hz distribution transformer superfluous. This research on transformer-less drives can be divided in two major directions: The first proposed solution is to createae a series connection of turbines, such as in [4], [5]. The solution is built around a matrix converter based generator drive. The drive train is not truly transformer-less, but uses an high-frequency transformer to step up the voltage before it is rectified. The advantage is that the high frequency transformers can be much more compact than those operating on 50 Hz. The outputs of several turbines are connected in series to generate a sufficiently high voltage to transfer power directly to shore.

The second direction aims at achieving higher voltage output from each turbine by application of series connection of converter modules. [6, 7, 8, 9, 10] are all based on special generator solutions. The generator windings are connected to a set of single-phase converter modules. These again are connected in series on the grid side achieve distribution level voltage output from each turbine. The same principle is applied in [11], but here, three-phase converters are connected in series on the DC-side and a total DC-voltage of 23.6 kV is achieved. The application of three-phase converters means less components than the single-phase solutions. The work presented here is following up some of the ideas presented in [11].

In this paper, a generator with nine three phase winding segments is combined with a converter configuration which takes advantage of the possibilities offered by the generator design. The generator can withstand high voltages between each three phase group. The aim is to achieve a voltage in the high end of the medium voltage range, i.e. 36 kV DC, without transformer. This is in the range of the standard AC-distribution grid voltage. Therefore, it is assumed that no further transformation is necessary before the offshore node of the wind farm.

The work is a continuation of that presented in [12], and will focus on converter configuration details and control. The main contribution of this paper is to propose a droop based balancing control to achieve equal voltage sharing between the DC-bus capacitors of the different converter modules.

2. Converter

2.1. Generator drive configuration

The generator drive configuration investigated in this work is presented in fig. 1. The drive train is constructed based on a generator with 9 segments. Each generator segment is equivalent to a standard three phase generator, and electrically isolated from the other 8 generator segments. The output voltage from each generator segment is at the level of industrial medium voltage drives (e.g. [13]). The converter modules contains three phase voltage source converters (VSC) (described in [14]). One converter is connected to

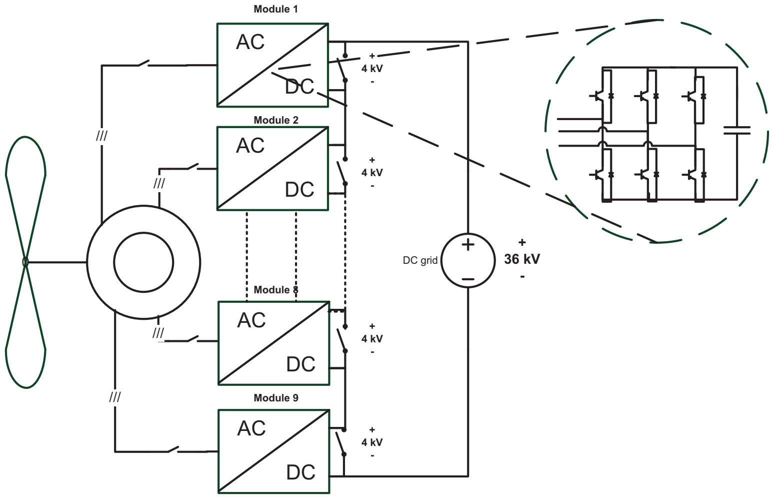

Fig. 1. Principal overview of the modular series connected converter generator drive

each of the segments, and the DC-buses of the converters are connected in series. This yields here a 36 kV DC-output voltage without the transformer.

The benefits from such a converter configuration are several. The most evident being the medium voltage rating of each module in combination with a distribution level voltage output without transformer. In addition comes:

- Converter module rating of only $1/9^{th}$ of the total power rating.
- Modular construction with standard building blocks.
- Easier maintenance.
- Redundancy.

The modular construction makes it possible to standardize the content in each module. Also, the type of converter in each module can be adapted with varying voltage levels and demands on voltage quality. This is believed to contribute to lowering prices of the system. A modular converter system will also contribute to facilitate the maintenance work - In the case of a failure, only faulty modules have to be replaced.

Redundancy can also be achieved in the proposed generator drive. This is a direct result of the way the modules are connected together and the amount of converter modules utilized in a turbine. That is, the turbine can continue to run even if a generator segment/converter module fails. There are, however, two limitations. The first is on the voltage rating: since the output voltage is set by the grid, the remaining converters must be able to support a DC-bus voltage 11 % higher than the nominal. Hence, the voltage blocking capability of the semiconductor devices must be increased. The second limitation is on power. The turbine can be temporarily de-rated to fit the new power capability in case of a failure, or there can be an overrating of the converters so that the remaining can take the full load. The level of redundancy should be subject to a trade-off between expected downtime before maintenance and increased converter cost.

On the downside for this system comes the increased complexity which results in decreased reliability. The total component count is high, both concerning semiconductors and control related electronics. Also, the series connection of several power electronic converters demands for careful operation and coordination of the module control. And although a large part of the control system can be modular, some communication between the module controllers and a turbine master controller is needed. This will be described further in sec. 3.

An additional, possible weakness of the system is introduced by the series connection and demand for same current in all converter modules. This implies that if, for some reason, a converter module has problems and must decrease its current limitations, the other modules will have to be subject to the same limitations. As a consequence, the nominal working point of the turbine will have to change accordingly, and possibly, energy is lost.

3. Control system

3.1. Main structure

As was stated in sec. 2, the entire system is constructed with an aim to make everything as modular as possible. So also the control structure. But although the control system is modular to a very large extent, there has to be a two-way communication between the master turbine control and the slave controller in each VSC-module. The current reference, $i_{q,ref}$ is common for all 9 modules. It is generated in the master before being transferred to the slaves. So is the case for the DC-bus voltage reference, $v_{dc,ref}$. In addition, each module controller needs information about settings for the slave controller state. The feedback signals to the master (sysmon[1:9] in the figure) contains the status of each slave (temperature, DC-bus voltage, current measurements, warnings, errors etc). The organisation of the proposed system is presented in fig. 2.

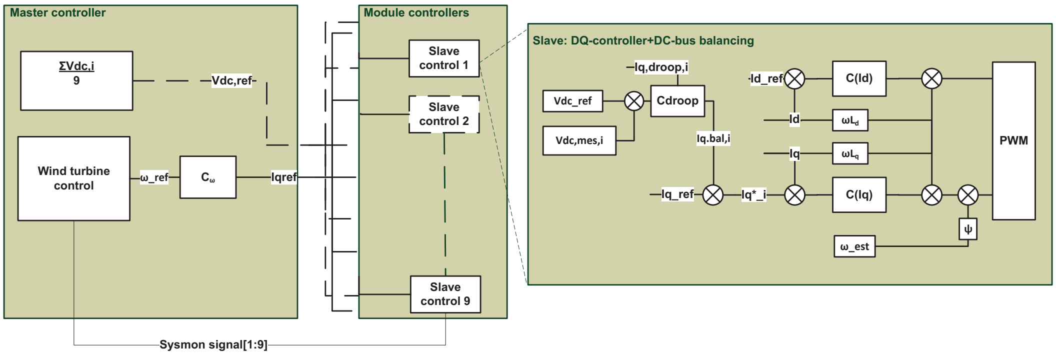

Fig. 2. Control system structure with master controller, slave controller organization and content in each slave

The turbine master controller regulates the turbine set point according to the preferred control strategy, for example maximum power point tracking (MPPT) [15]. The output of this is the turbine speed reference, ω_{ref} to the master speed controller. This controller generates the torque producing current reference, $i_{q,ref}$, which is common input to all the module controllers. $v_{dc,ref}$ is generated by filtering and averaging the measured DC-bus voltages of the modules.

Each module controller is synthesized based on the standard DQ-current control scheme [16] with a traditional sinusoidal three phase pulse width modulation. The current controllers C(Id) and C(Iq) in fig. 2 are PI-regulators tuned according to the modulus optimum criterion as described in [16]. A DC-voltage controller is included in each slave in addition to the current control scheme. The output of this balancing control, $i_{q,bal,i}$ is added to the main current reference ($i_{q,ref}$), resulting in a specific current reference, $i^*_{q,i}$, input to each current control. The effect of the change in current reference is a resulting change in the power take-off in that generator segment. Since the DC-link current is set by the chain of converters, a small change in power across one module will result in an excess(deficit) of power which will result in a charge (discharge) of the DC-bus capacitor of that module. Hence, the output voltage of that module will change.

3.2. DC-bus voltage balancing - Droop

In [12], a PI-controller was employed to achieve balancing of the DC-link voltage between the DC-buses of the different converter modules. This yielded an acceptable dynamic performance, but it would

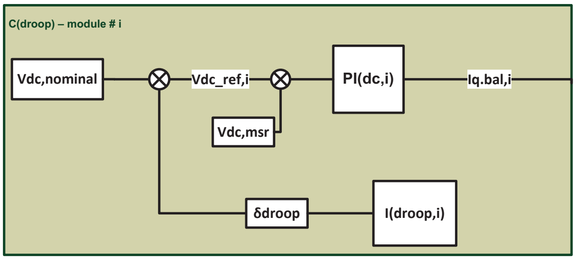

Fig. 3. Droop control scheme for DC-bus balancing

cause problems in steady state. The reason is that the difference in DC-bus voltages over different modules will charge the integrators differently. The result is that the average of the balancing current references is different from zero. This average balancing current will affect the working point of the main controller chain, as will be showed by simulations in sec. 4.2. To avoid this, a droop control scheme based on the DC-voltage droop presented in [17] is introduced. Fig. 3 shows the block diagram for such a controller.

The droop controller works as following: The core is one PI-controller per converter module, which generates $i_{q,bal,i}$ based on the the reference and measured DC-bus voltage. The droop control itself adjusts the set point of the DC-voltage reference in each slave: The difference between the droop and nominal current is multiplied with the droop constant δ_{droop} and subtracted from the nominal voltage reference.As a result, the PI-controller dynamics are decoupled and PI(dc) can be tuned according to the desired dynamic response. The droop is described by the following equation, eq. 1.

$$v_{dc,ref,i} = v_{dc,n} + \delta_{droop} \cdot (i_{q,nominal} - i_{q,droop,i}) \tag{1}$$

However, since the default situation for the balancing control should be zero current, $i_{q,nominal}$ can be set to zero, and the droop can be expressed as in eq. 2.

$$v_{dc,ref,i} = v_{dc,n} - \delta_{droop} \cdot (i_{q,bal,i}) \tag{2}$$

The droop constant, δ_{droop}, is in a parallel connection chosen based on the power rating of the different paralleled modules. The same is valied here, and since all generator segments/converter modules have the same nominal power, all δ_{droop} are set equal. This will assure equal power sharing between the modules. By choosing $\delta_{droop} = 0.1$ is the droop characteristic given by fig. 4.

At the limits of the current capability, the voltage will increase (decrease) abruptly. In such cases, other protection mechanisms such as DC-choppers must be activated in order to protect the converter.

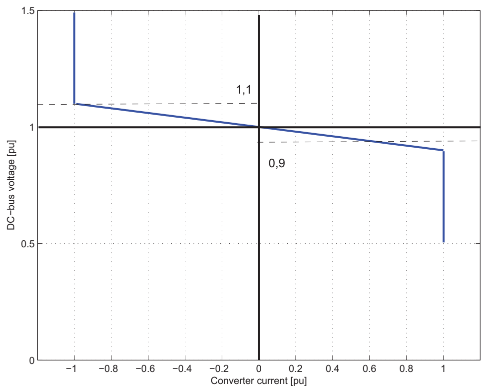

Fig. 4. Characteristics of the DC-bus balance droop control

4. Simulation

4.1. Simulation model

The simulation model was constructed using the simulation software EMTDC/PSCAD [18]. As was explained in [12], it can be assumed that each generator segment can be represented by a standard 3 phase synchronous generator model. This is due to the weak magnetic coupling between the segments. The rotor excitation voltage in the model was fixed to 1.0 per unit to emulate permanent magnets. The converters were connected together according to fig. 1, and simulated with ideal semiconductor components. As grid model was a stiff DC-voltage source of 36 kV employed. This corresponds to a system were the offshore node converter controls the voltage.

The wind turbine was simulated using model shipped with PSCAD. The input to this model is the shaft rotational speed in rad/s and wind speed in m/s. The input wind speed was increased in three steps. The cut in wind speed was set to 4 m/s, then increased to 8 m/s and ending at rated wind speed, 13 m/s. This to avoid the pitch controller masking the effect of the proposed control system. The speed reference was set manually in the simulation. The start-up speed was set to 0.25 pu, then ramped up to 0.4 pu and in the end increased to 0.8 pu. Hence, no MPPT-algorithm was implemented.

Table 1. Simulation parameters

Generator parameters	Value, unit
Generator rating	10 MVA
Stator resistance, r_s	0.045 pu
Stator reactance, x_s	0.33 pu
Generator frequency, f_n	30 Hz
Nominal line voltage, v_n	2.45 kV (rms)
Nominal generator current, i_n	262 A (rms)
Converter Parameters	
Converter module DC-bus voltage $V_{dc,i}$	4.0 kV
Nominal converter current, $I_{n,conv}$	325 A (rms)
DC-bus capacitance, C_{dc}	2150 uF
Switching frequency, f_{sw}	1.5 kHz
Nominal modulation index, m_a	0.95
Grid parameters	
Total DC-grid voltage, v_{dc}	36 kV
DC-grid inductance, L_{grid}	25 mH
DC-grid resistance, R_{grid}	1.49 Ω

4.2. Droop controller simulation

In this section,the effectiveness of the droop controller is demonstrated through simulation. The system was first simulated without the droop to establish a case for comparison. That is, with pure PI-controller and with common, constant $v_{dc,ref}$ for all modules. The resulting DC-bus voltage and the corresponding balancing current references are given in fig. 5.a and fig 5.b respectively. It can be observed that from DC-bus balancing objective, the PI-controller fulfils its purpose. But the average PI-controller output is not zero in steady state. This indicates that the balancing will affect the performance of the main controller loop, which should be avoided. The consequence of this can be observed in fig. 5.c, where the rotational speed is given. During the ramp-up of the turbine is the wind input speed increased, and this leads to the speed controller output going into saturation. However, if inspecting the current controller input $i^*_{q,i}$ (fig. 5.d), it is observed that there is more current capability left in the converter. This is, however, not seen by the speed/torque-control of the main converter chain.

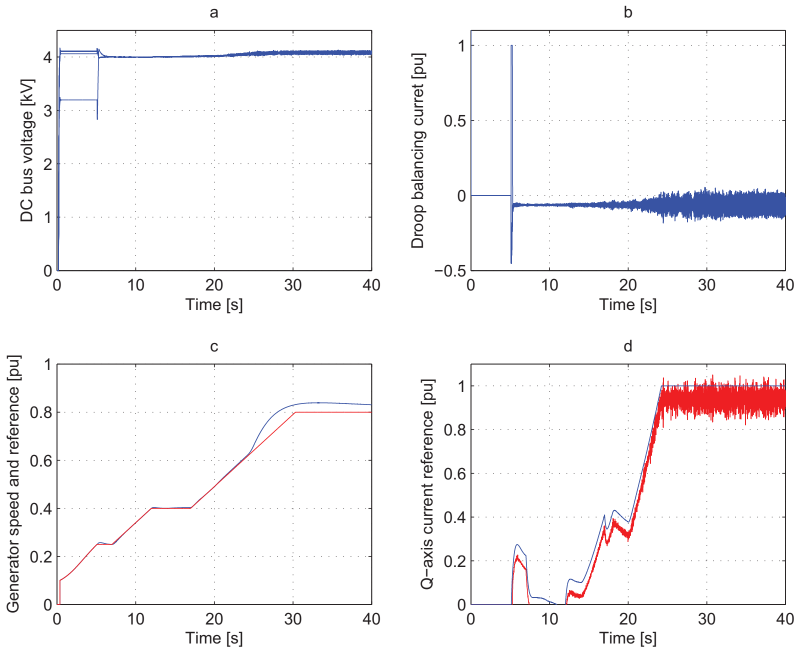

Fig. 5. a) DC-bus voltages. b) Balancing current references. c)Turbine rotational speed.(red: reference, blue: measured) d) blue: Q-axis curent current reference, red: Measured q-axis current

In fig. 6 are the simulation results with the droop controller activated given. The δ_{droop} was set to 0.1 as described in sec. 3.2. Except for this were the two simulation cases identical. In fig. 6.a, it can be observed that the DC-bus balancing is achieved as with the PI. The difference can be seen in 6.b, where the balancing output currents are given. Their average are going to zero steady state value. This means that the introduction of the droop controller eliminates the problem introduced by the PI-controllers. The corresponding rotational speed with reference is given in fig. 6.c. An overshoot is also present in this case, but here the control system is capable of regulating the turbine speed back to its reference. In fig. 6.d is $I_{q,ref}$ and $I_{q,*,i}$ given. From this plot, it can be observed that these are equal in steady state. Hence, the balancing controller is not affecting the turbine main control chain operation point.

5. Conclusion and further work

In this paper, operation and properties of a modular series connected converter has been presented. The converter has been developed for a 36 kV transformer-less offshore wind power generator drive. The emphasis was on the modularity of the converter solution, and the control system. A droop controller was proposed to assure balanced DC-bus capacitor voltages in the converter and to separate the dynamics of the PI-controller. Simulations in PSCAD have been presented to demonstrate the functionality of the droop, and the control system as such. The simulations showed the droop controller's capability to bring the DC-capacitor voltages back to a balanced state. That is, zero average balancing current references.

In the further work will more stability issues related to the droop controller be addressed, In addition will design of DC-filters for the converter modules will be treated, and the redundancy possibilities will be explored more in details. To verify the simulation model is a 50 kW laboratory prototype with three generator segments/converter modules under construction.

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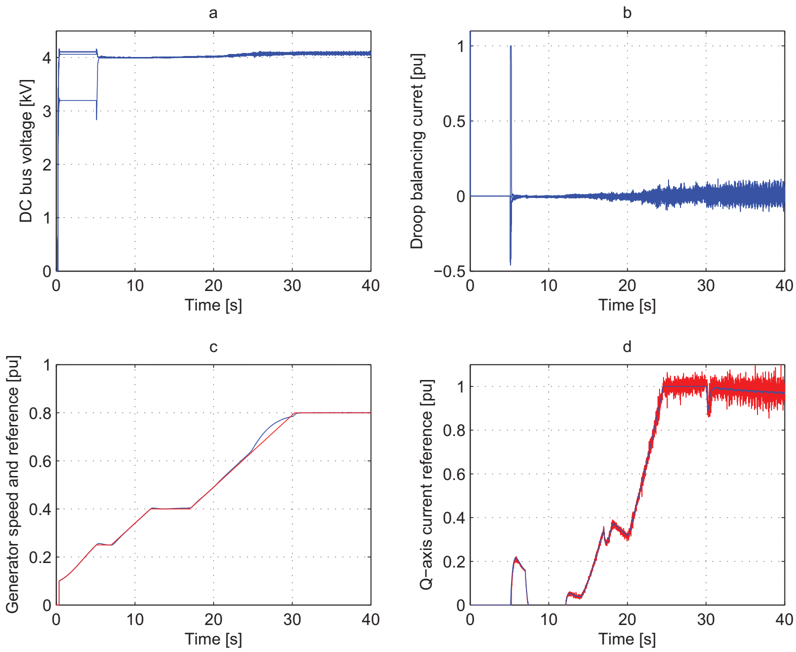

Fig. 6. a) DC-bus voltages. b) Balancing current references. c)Turbine rotational speed. (red: reference, blue: measured). d) blue: Q-axis curent current reference, red: Measured q-axis current

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