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Dynamic Performance of Grid Converters using Adaptive DC Voltage Control

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Keywords

<<Converter control>>, <<Efficiency>>, <<Grid converter>>, <<Adaptive control>>.

Abstract

This paper investigates a controller that ensures minimum operating dc-link voltage of a back-to-back converter system. The dc-link voltage adapts its reference based on the system state, reference given by an outer loop to the dc-link voltage controller. The operating dc-link voltage should be kept as low as possible to increase the power conversion efficiency and increase the reliability of converters. The dynamic performance of the proposed controller is investigated by simulations and experiments.

Introduction

Wind power generators need to slowly replace the conventional fossil fuelled based generators. The installation of onshore and offshore wind farms is emerging worldwide, with the rated power per wind turbine of up to 8 MW [1]. Induction generator was at the ground of the wind turbines development, and the synchronous generators are gaining significant attention in recent years. For most of the generator technologies, the controllability and power processing is realized with a back-to-back converter. The efficiency and reliability of the wind turbine converter are very important for the entire system, and new ways to improve these factors are always welcome [2].

The generator is decoupled from the grid in the dc-link of the wind turbine converter. The grid converter is the component that controls the voltage level of the dc-link in order to maintain the energy balance between the two power sources, generator and grid. The general state-of-the-art wind turbine structure is shown in Figure 1. The grid converter synchronizes with the grid voltage, controls the dc-link voltage and the grid currents according to the references given to the current controller [3]. The active current reference is given by the dc-link voltage controller, and can be also influenced by the ancillary services such as frequency control. Normally the dc-link voltage reference is fixed, and setup to a level that allows the converter operation over the entire power range and can achieve certain dynamics of the current controller.

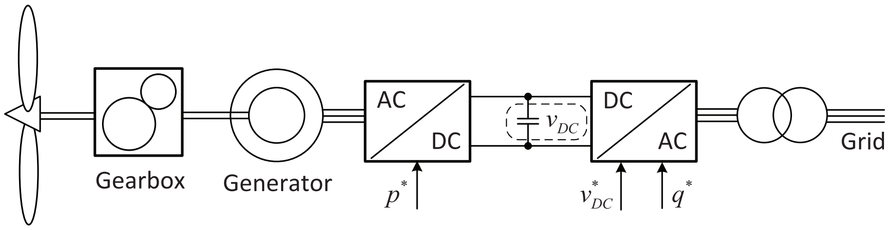

Figure 1: Wind Turbine System with Full Scale Converter

Reducing the energy stored in the dc-link can bring benefits in efficiency and reliability of both the grid and the generator converter. The energy storage can be reduced depending on the system state, by adaptively adjust the dc-link voltage reference. A method that calculates an offline table for the dc-link voltage, based on the operation of both grid and generator converters was introduced in [4]. It was also shown that the reliability can be increased due to the reduced failure rate based on cosmic rays. This method is however dependent on the model of the grid and generator, which include parameters that can change depending on various factors like operating temperature of the generator, grid voltage, grid impedance and grid filter impedance.

Adaptively adjusting the dc-link voltage reference online can eliminate the calculation errors based on the involved systems modelling. Improvements in the wind turbine converter were shown in [5], such as a slight increase in efficiency and increased reliability due to reduced thermal cycling. For installations at high altitude the effect of reduced operating dc-link voltage improves more the reliability by decreasing the failure rate based on cosmic rays [6].
An additional control loop as outer loop to the dc-link voltage controller, which adapts the dc-link voltage reference by controlling the maximum modulation index (M_{Max} controller), was introduced in [5]. The reduction of power losses was proven, however without the experimental validation of the controller. This paper validates the M_{Max} controller by simulation of a 6 MW converter and experimentally testing on a downscaled prototype.

Adaptive DC Voltage Control

A controller that is to be used in normal operation mode of the wind turbine is described in the followings. To achieve an online adaptation of the dc-link voltage reference, a control loop can be implemented as shown in Figure 2. Instead of setting a fixed dc-link voltage reference, the maximum modulation index reference is controlled taking the feedback from the input modulation index to the modulator.

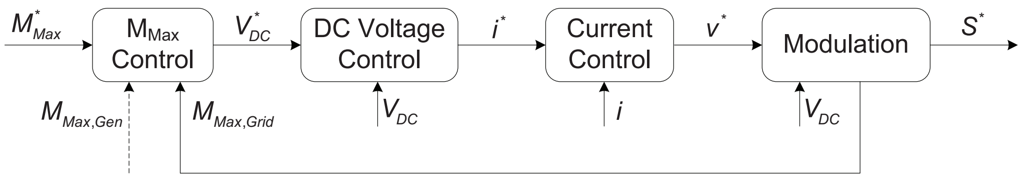

Figure 2: Proposed adaptive dc-link voltage controller

A maximum modulation index reference is given instead, and the output dc-link voltage reference will adapt to the converter system state. In this way the operating dc-link voltage is reduced significantly at all power levels, and more consistently at light load. The maximum operating modulation index, or the minimum operating dc-link voltage depends on all the following factors: grid voltage, grid current, grid impedance, filter impedance, generator voltage (in case of a turbine), modulation strategy, minimum pulse width of the used power devices, harmonic limits from the applied standard [5]. Most the enumerated factors are changing during the operation depending on the grid state, transferred power and temperature. Therefore it is very difficult to implement an offline calculated/measured look-up table to optimize the operating dc-link voltage during operation.

Ideally the maximum modulation index reference should be unity, but a small reserve should be kept to allow operation with changes in power for a given maximum dP/dt. The dc-link voltage control dynamics can be improved with a feed-forward from the generator control, to allow fast power ramps. The power devices in the converter will set further limitations on the minimum pulse width. Setting a maximum modulation index reference above the voltage reserve for the minimum pulse width filter can introduce additional distortion on the output current. Therefore the maximum M_{Max} reference should be experimentally determined in order to comply with the harmonic standards.

M_{Max} Controller Performance

A possible implementation structure is shown in Figure 3. The current control can be implemented in a standard decoupled dq rotating reference frame [7], [8]. The input to the control structure is the maximum modulation index reference M^*_{Max} and taking the feedback from the modulator, the error is regulated by the modulation index controller.

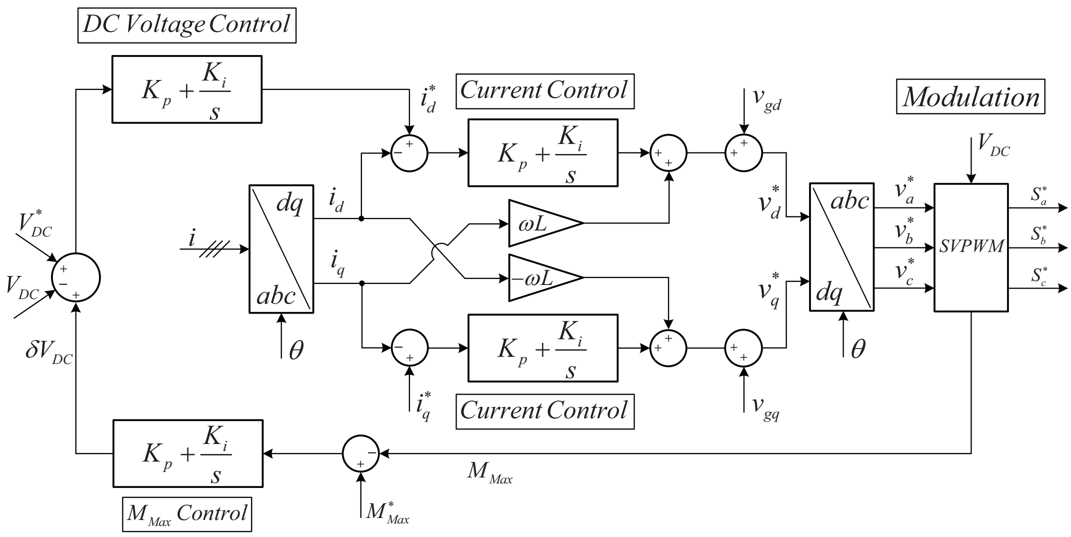

Figure 3: Grid converter dq adaptive control structure

This case assumes that the wind turbine generator rated voltage is smaller as compared with the grid voltage, and the modulation index of the grid converter is always smaller compared with the grid converter. The output of the modulation controller is the dc-link voltage reference adjustment δV_{DC} , added to the feed-forward reference V^*_{DC} , regulated by the DC voltage controller having the measured dc-link voltage V_{DC} as feedback. Proportional integral (PI) controllers are used for all control loops in this example.

To investigate the operation of the proposed controller, a simulation model was implemented with the control structure sown in Figure 3. The converter topology is the classical two-level converter connected to a low voltage 690 V transformer, with the rated power of 6 MW. The model of the output L filter and grid impedance was assumed to be 70 μH and 2 mΩ in total, and the total installed dc-link capacitance of 10 mF. The controller operation is shown in Figure 4, enabled at 1.5 s with converter operating in steady state at 50% of the rated power. The maximum modulation index reference was set to 0.999.
After enabling the controller, the detected maximum modulation index is increased and controlled to the reference value with a time constant of 1 s. The operating dc-link voltage is therefore reduced to around 1000 V, with 50 V less as compared with the fixed reference that is classically used to operate the

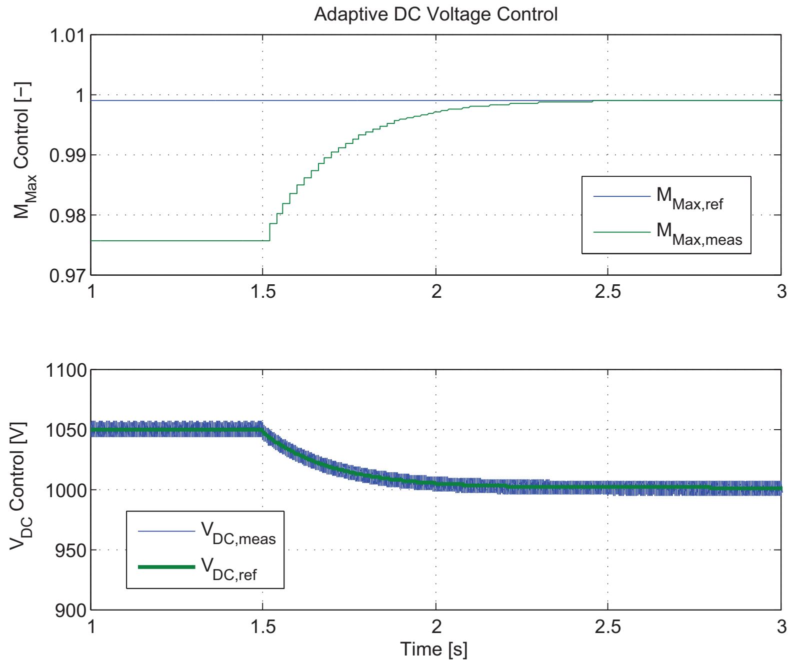

Figure 4: Controller operation at 50% load (3 MW)

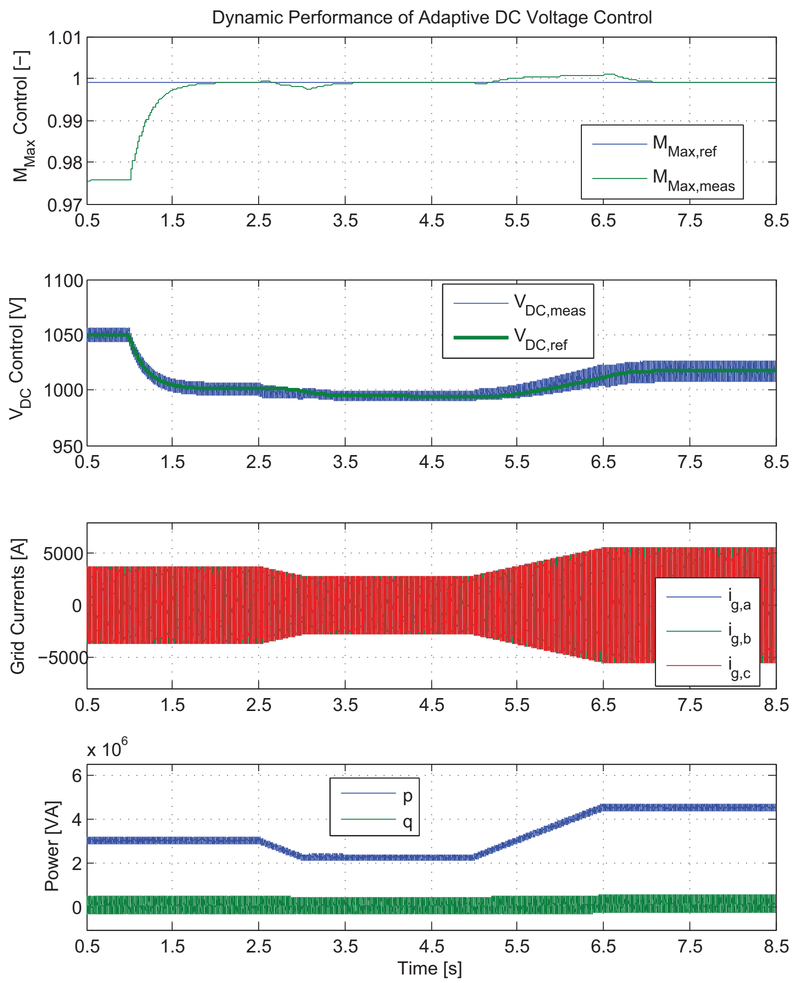

Figure 5: Dynamic operation of the proposed adaptive control

converter over the entire power range. The aforementioned improvement using reduced dc-link voltage also comes with restrictions regarding dynamics of the control. The proposed controller is designed to operate in a mode where no fault is present in the grid. Moreover the dynamics of the generator control should meet the imposed maximum power variation in time, limit that will ensure the back-to-back system stability. Therefore the dynamic operation will be considered in the followings.

In Figure 5 the controller response to positive and negative power gradients is shown. At 0.75 s the M_{Max} controller is enabled and brings the voltage to the reference value as in Figure 4, for a power flow of about 3 MW. The magnitude of the grid currents and injected powers into the grid are shown also. The injected power is positive meaning that is injected into the grid, generated by the wind turbine. Having the power gradient fixed to 1.5 MW/s, the dynamic operation is seen from second 2.5.
At negative gradient the M_{Max} controller has a positive feedback error and decreases the voltage reference, following the imposed maximum modulation index. During positive gradient at 5 s the power is 2.25 MW, and ramped up to 4.5 MW. It can be seen that a slight overmodulation is present in the case of positive gradient with the chosen dP/dt and controller gains, however maintaining the stability.

Experimental Investigation

The simulated control from Figure 3 was implemented in a dspace1006 control platform. The converter prototype is a two-level 2.2 kW, grid connected to the 400 V grid. The test setup is shown in Figure 6. The used grid LCL filter had a total inductance of 4 mH and a delta connected capacitor bank of 9 μF.

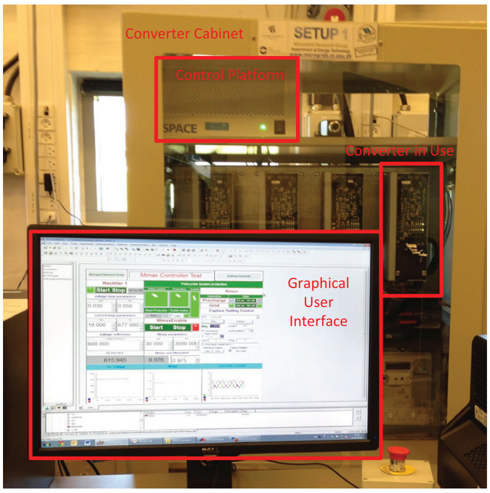

Figure 6: Experimental test setup

The converter is modulated with continuous space vector pulse width modulation, switching and sampling at a frequency of 10 kHz. The deadtime between the low side and high side transistors was 1 μs while the minimum pulse width filter is set to clamp the output voltage for a dutycycle less than 2 μs. The M_{Max} controller is implemented with a PI controller, with the feedback of the maximum modulation index detected at each fundamental frequency.

The operation of the proposed M_{Max} controller is shown in Figure 7. The converter starts operating at a fixed dc-link voltage reference of 600 V, operating at light load. The M_{Max} controller is disabled at this time. The power direction in this case is from the AC to DC, operating as an active rectifier using a fixed resistive load in the dc-link. At around 1.9 s the M_{Max} controller was enabled, moment at which the maximum modulation index is regulated at its reference of 0.985. It can be seen the response time is around 1 s. The dc-link voltage is regulated at an adaptive reference of around 565 V. The operating dc-link voltage is reduced by 35 V, for the given load, grid condition, and converter configuration and operating parameters.

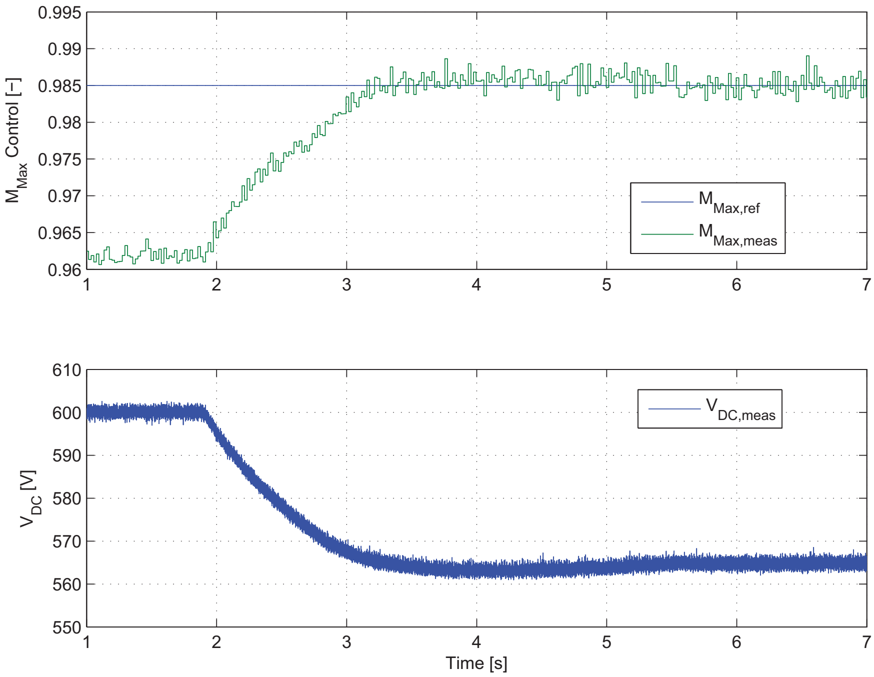

Figure 7: Experimental operation of the M_{Max} controller

The dynamic operation of the M_{Max} controller is shown in Figure 8. In this case, there is no load in the dc-link and the power flow is from the dc-link to AC grid. A current controlled power supply is installed in the dc-link to emulate the generating power. At time 0 s the controller is already enabled.

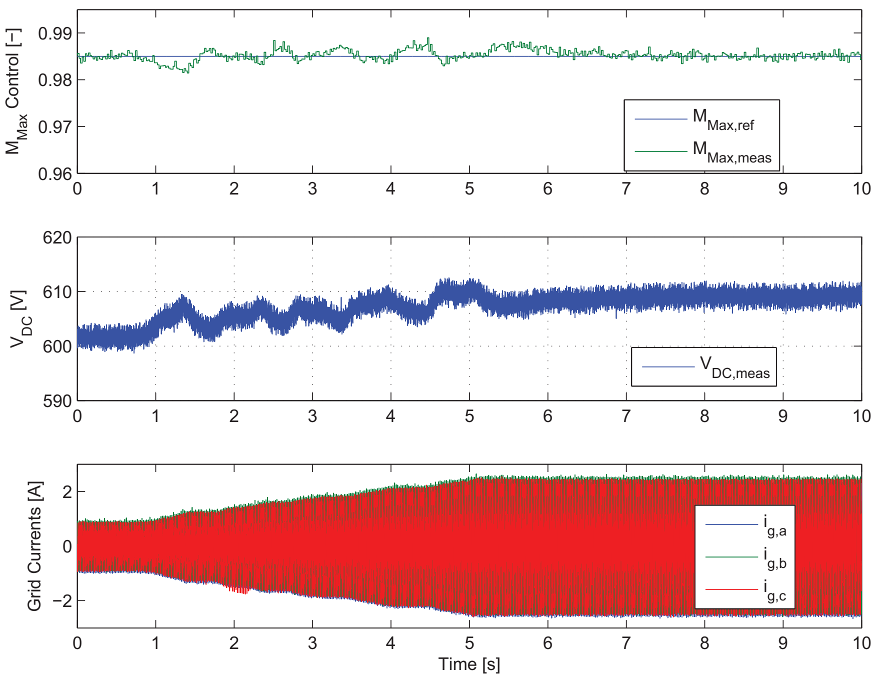

Figure 8: Experimental dynamic operation of the M_{Max} controller

After 1 s, the power is increased in a number of arbitrary steps up to 5 s. Having the steps of power and not a power ramp, and the steps are faster than the controller response the steady state cannot be achieved between steps. At around 7-8 s in time the controller reaches steady state and the operating dc-link voltage is increased to around 610 V. The dc-link voltage is increased due to the increased power flow, maintaining the control over the maximum modulation index.

Conclusion

A controller that optimizes the wind turbine converter operation with respect to the switched DC voltage was evaluated. The dc-link voltage is adaptively controlled depending on the system state. The control is simple, implemented with a PI controller, designed for normal operation modes without any faults. The dynamic operation was investigated, and it is concluded that the wind turbine controller robustness it not affected when the maximum power gradient complies with the limits required by the proposed controller. The controller was experimentally validated on a downscaled prototype. Operation with power flow in both directions is valid, with a higher reduction in dc-link voltage in case of an active rectifier. Having a control over the required operating dc-link voltage, the losses and stress of the converter can be optimized.

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