Effective capture of wind gusts in small wind turbines by using a full active rectifier

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Abstract

Small wind turbines have difficulties to start rotating at low wind speeds due to their relatively large rotor inertia and small starting torque. In case a permanent magnet generator is used, the rotor magnets will cause an additional cogging torque which makes starting even more difficult. By using the generator as motor from the moment a wind gust is detected, the turbine is able to accelerate much faster to reach the maximum power point. A maximum power point tracking algorithm is used to locate the optimal working point. At sufficiently large rotor speeds, the controller switches to the generator mode where the energy used for acceleration is recuperated, together with the additional energy captured from the wind gust. To control the generator power in both directions, an active rectifier is used in a back-to-back converter topology. In this paper, this wind capture strategy is simulated. The results show that the power output during a wind gust can be largely increased compared to common MPP-tracking.

1 Introduction

During the last few decades, wind turbines have become one of the most popular methods for renewable power production. At the end of 2013, the global installed capacity of both on-shore and off-shore wind turbines was equal to 318 GW, which is an increase of 12% compared to the year before [1]. Most of these turbines have a rated power of a few MWs.

Small wind turbines with a rated power in the range of 1 to 30 kW are less popular. The main problem of these turbines is the low height of their nacelle. At heights of only 15 m, the wind speed is less stable due to disturbances from the surroundings. In order to maximize the power output, variable speed wind turbines are necessary which have an adequate maximum power point tracker (MPPT) for fast control of the rotor speed towards the maximum power point (MPP). Today, commercialised systems are already available with a cost-performance ratio that is comparable with photovoltaic systems. However, research has shown that there is still an opportunity for improvement because this market segment is not mature yet [2].

Small wind turbines have a great potential because they are ideal to be used as distributed generation units (DGs) in densely populated regions, on top of residential or industrial buildings and in microgrids.

A problem however is that there is still very little known about the start-up behaviour of these small turbines. Because most of them do not have pitch control, the initial angle of attack is near to 90°. In combination with the corresponding low Reynolds number, very little data is known about the lift and drag coefficients in this scope [3]. In [4], the start-up sequence of a small 5 kW turbine is described. They noted that during start-up 'idling' periods of 30 to 50 seconds with slow rotation exist, in which the rotor blades are stalled due to the high flow angles and produce little torque. When a new increase in wind speed occurs, the angle of attack gets large enough in order to produce sufficient torque and accelerate the turbine further on. In general, it can be concluded that the starting torque of a wind turbine is very limited and will result in a long start-up.

In the latest generation of wind energy conversion systems (WECS), the use of permanent magnet synchronous machines (PMSM) has become popular. Due to the absence of any rotor windings with corresponding copper losses, they offer high efficiency and reliability in a compact machine. Because a large number of poles can be installed, the PMSM rated speed can be chosen near the rated speed of the wind turbine. The usual reducing gearbox can be omitted, which results in a direct drive. The disadvantage of the PMSG is the cogging torque which tries to align the magnets with the stator slots in positions of minimal reluctance. The cogging torque impedes the turbine to start rotating until the static magnet forces are broken. This phenomenon makes the turbine starting even more difficult.

If a wind gust with a duration of a few seconds occurs when the rotor stands still, the turbine will hardly react due to the low starting torques. Almost none of the energy that was contained in the wind gust will be captured and converted into electricity. In this paper, a strategy is described which increases the rotor acceleration from the moment a wind gust is detected. In the usual situation, the generator is driven by the turbine and electric power is injected in the distribution grid. For the improved start-up and acceleration, electricity is used from the grid by which the PMSM operates shortly as a motor to produce a torque in the same direction of the turbine torque. The rotor starts immediately and is driven towards the optimal rotor speed. When the MPP is reached or the wind speed starts decreasing again, the controller inverts the power direction and the PMSM starts again producing electricity to the grid. The energy used for the initial acceleration will be largely recuperated (some of it will be dissipated due to the limited efficiency) together with the part of the wind gust energy that was captured by the wind turbine. The result is a net production of electricity by the WECS.

2 Wind gust definition

The definition of a wind gust in this paper is based on the gust front loading factor that is used in civil engineering. In [5], the rapid changes of the wind speed during a short period of time are discussed. A non-stationary wind model is introduced which describes a wind field varying over height and in time:

$$v(z,t) = v_{\mathrm{g}}(z) \cdot v_{\mathrm{g}}(t) \tag{1}$$

in which $v(z,t)$ is the wind gust field, $v_{\mathrm{g}}(z)$ the vertical profile and $v_{\mathrm{g}}(t)$ the time function. Because the rotor diameter of small-scale wind turbines is limited to a few meters, the wind speed variation across the height of rotor front area can be neglected. The interesting part is the time function of the gust which can be described as:

$$v_{\mathrm{g}}(t) = v_{\max} \sin\left(\frac{\pi}{t_{\mathrm{g}}} t\right) \tag{2}$$

where $v_{\max}$ is the maximum wind speed value of the wind gust and t_{g} is the duration. This wind gust profile will be used in the simulation model and is illustrated by Fig. 1. By adapting the two parameters, different types of gusts can be simulated.

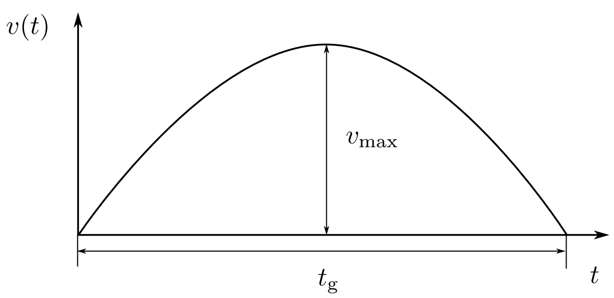


Fig. 1: Wind gust profile in function of time.

3 Back-to-back converter

The considered WECS is the back-to-back converter topology [6], illustrated by Fig. 2. The wind turbine drives a PMSM which generates an ac current with variable frequency and amplitude. An active rectifier converts this 'wild' ac into a dc current which is directed to the dc-bus with voltage V_{dc}. A grid-coupled inverter converts the dc-power back into an ac current of fixed frequency. The inverter is able to control the injected active and reactive power independently and controls the dc-bus voltage to balance the active power.

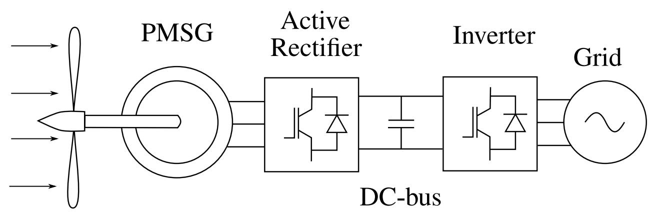


Fig. 2: Back-to-back converter

The active rectifier is a three-phase IGBT voltage source converter which controls the generator current by using field oriented control (FOC): the stator current is in phase or anti-phase with the electromotive force (EMF) [7]. This way, the machine torque can be easily controlled as it is proportional with the stator current amplitude in the q-axis:

$$T_{\mathrm{g}} = \frac{3}{2} N_{\mathrm{P}} \Psi_{\mathrm{PM}} i_{\mathrm{q}} \tag{3}$$

in which N_{P} is the number of pole pairs, Ψ_{PM} the flux linkage of the permanent magnets and i_{q} the stator current in a synchronous reference frame. The FOC control scheme is presented in Fig. 3. Two PI current controllers are used: one to control the d-axis current to zero for implementing field orientation and another PI-controller to control the q-axis current to a reference value which corresponds with a reference torque according to Eq. 3. The resulting stator voltages are applied by using pulse width modulation (PWM).

In order to track the MPP, the rotor speed needs to be controlled to a certain reference value determined by the MPPT-controller. A third PI-control loop is placed outside the current control loop. The output of this PI-controller contains a saturator to limit the current reference to the positive $I_{\mathrm{q,max,gen}}$ and negative $I_{\mathrm{q,max,mot}}$ limit [8]. In the generator reference frame, a positive q-axis current results in a generator torque opposite to the turbine torque.

As MPPT-strategy, the TSR-control is used to explain the principles of wind gust capturing ([9], [10]). Each wind turbine has its own $C_{\mathrm{P}}(\lambda)$-curve, illustrated by Fig. 4, in which the power coefficient C_{P} determines the turbine power P_{t}:

$$P_{\mathrm{t}} = \frac{1}{2} \rho \pi r^2 C_{\mathrm{P}}(\lambda) v^3 \tag{4}$$

with ρ the air density, r the turbine radius and v the wind speed. λ is the tip speed ratio (TSR) and is the dimensionless rotor speed:

$$\lambda = \frac{r\Omega}{v} \tag{5}$$

The MPP is determined by $C_{\mathrm{P,max}}$ at the optimal TSR λ_{opt}. The TSR-control measures the wind speed and calculates the

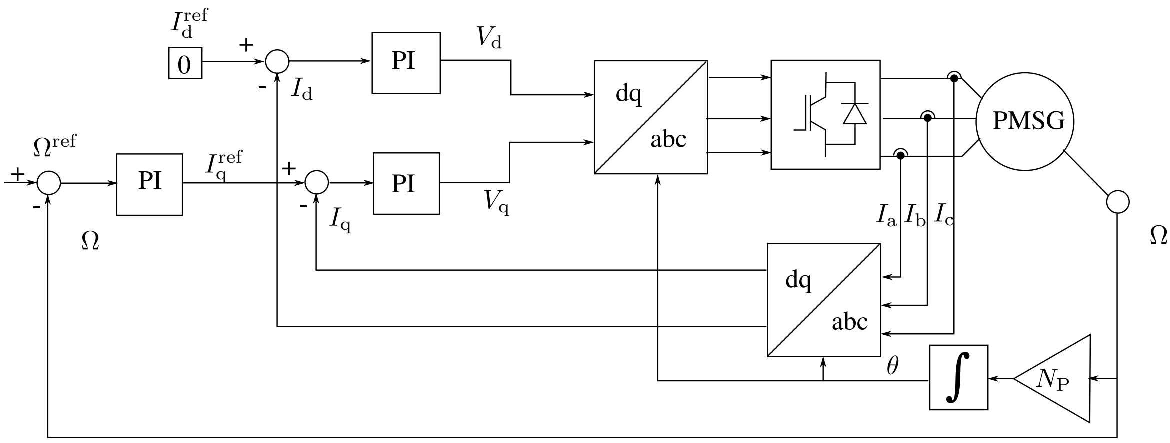


Fig. 3: Field oriented control scheme.

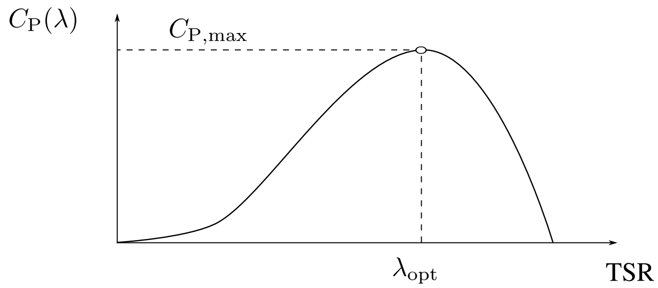


Fig. 4: $C_P(\lambda)$ wind turbine characteristic

optimal rotor speed Ω_{opt} by using λ_{opt}:

$$\Omega_{opt} = \frac{v\lambda_{opt}}{r} \tag{6}$$

At this optimal speed, the maximum possible power for that wind speed is captured by the wind turbine. The TSR-control is the fastest possible MPPT but it requires a correct value of the wind speed. Of course, the discussed wind gust capture strategy is also valid for other MPPT-strategies.

The wind turbine, the PMSG and the active rectifier with the MPPT-controller are all implemented in Matlab Simulink®, with which the following results are obtained.

4 Wind gust capture

To investigate whether using the PMSM as motor improves the energy output, a clear definition must be given of a variable which describes the relative captured amount of wind energy. First, the kinetic energy contained in the wind gust E_{gust} is calculated by integrating the wind flow power:

$$E_{gust} = \int_0^\infty P_0 \,\mathrm{dt} = \int_0^\infty \frac{1}{2}\rho\pi r^2 v^3 \,\mathrm{dt} \tag{7}$$

Also the electric energy E_{elec} generated by the PMSG is calculated by integrating the generator power:

$$E_{elec} = \int_0^\infty P_g \,\mathrm{dt} \tag{8}$$

The ratio of these two values gives the capture coefficient ξ:

$$\xi = \frac{E_{elec}}{E_{gust}} \tag{9}$$

First, the situation is simulated in which a wind gust occurs and the PMSM only operates as generator. $I_{q,max,mot}$ is thus set equal to zero. The considered wind turbine produces a nominal power of $360\,\mathrm{W}$ at $500\,\mathrm{rpm}$. The used wind turbine characteristic has a wind turbine torque of zero around stand-still. An offset value must be added to the turbine torque such that the turbine is self-starting. From data in [4], an illustrative starting torque could be calculated, equal to $0.095\,\mathrm{Nm}$. This is a very small value compared to the rated turbine torque of $6.9\,\mathrm{Nm}$. The simulation result for a wind gust of 5 seconds with a peak value of $3\,\mathrm{m/s}$ is presented in Fig. 5. Due to the small starting torque, the rotor speed gets not higher than $0.2\,\mathrm{rad/s}$. The turbine remains quasi at stand-still. In general, it can be stated that no significant amount of power can be captured during short wind gusts when the PMSM only works as generator.

In the next simulation, $I_{q,max,mot}$ is set to the rated motor current. The same wind gust profile is applied and the result is shown in Fig. 6. At the start of the gust, the generator power first becomes negative. This indicates that the PMSM is working as motor. The turbine rotor accelerates significantly and the rotor speed tries to follow its optimal value determined by the measured wind speed. When the rotor reaches its MPP, the generator power increases and becomes positive. The active rectifier is switched to the generator mode and power is generated until the rotor has been returned to stand-still. The capture coefficient ξ is calculated from the wind speed and generator power responses and is equal to 0.18. A generator efficiency of 90% has been taken into account.

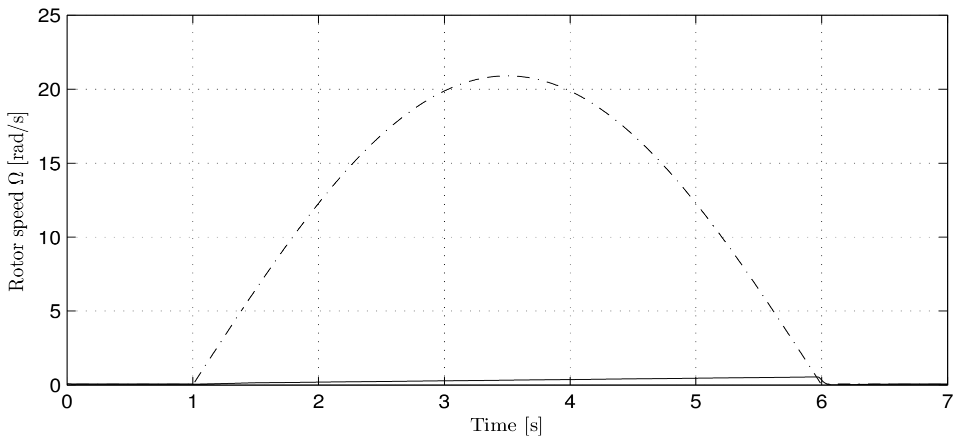


Fig. 5: Rotor speed (full) and optimal rotor speed (dotted line) in function of time for wind gust without motoring.

5 Influence of maximal motor current

The capture coefficient depends on the wind gust profile and the maximal allowed motor current. The previous simulation has been repeated many times for different values of the wind gust duration, the wind gust peak value and $I_{\mathrm{q,max,mot}}$. The results for three different values of $I_{\mathrm{q,max,mot}}$, where the capture coefficient is expressed in function of the wind gust parameters are presented in Fig. 7. Missing values indicate that the capture coefficient is smaller than zero and thus more power is used to accelerate than could be recuperated to the grid.

First, it should be noted that ξ is largely influenced by the maximal motor current. It can be concluded that the larger $I_{\mathrm{q,max,mot}}$ is, the higher the amount of generated electricity will be. The highest capture coefficients are obtained when the maximal value of the current limiter is set equal to the maximal allowed stator current in the PMSM. This current is normally two to three times higher than the rated current. This operation is allowed for only few seconds because otherwise the machine would overheat due to the excess Joule losses.

Second, the controller is able to capture most power from long and large wind gusts. The longer the wind gust, the more time the MPPT-controller has to reach the optimal rotor speed. The explanation is that the rotor inertia is the most important factor which impedes the MPP-tracker of being at any moment at the optimal rotor speed. The larger the wind speed, the larger the turbine torque is. This helps the PMSM motor torque to accelerate the rotor and reach faster the MPP. The capture coefficient can never become larger than the maximal power coefficient $C_{\mathrm{P,max}}$ equal to 0.44 (for this turbine). No more energy can be converted by the rectifier than could be captured by the turbine. The capture coefficients from the simulations however saturate at a lower value because the generator efficiency has been taken into account.

At last, it is observed that some wind gusts with a small duration or peak value result in negative capture coefficients. For these gusts, the active rectifier may not be started, because this would otherwise result in a net consumption of electric energy.

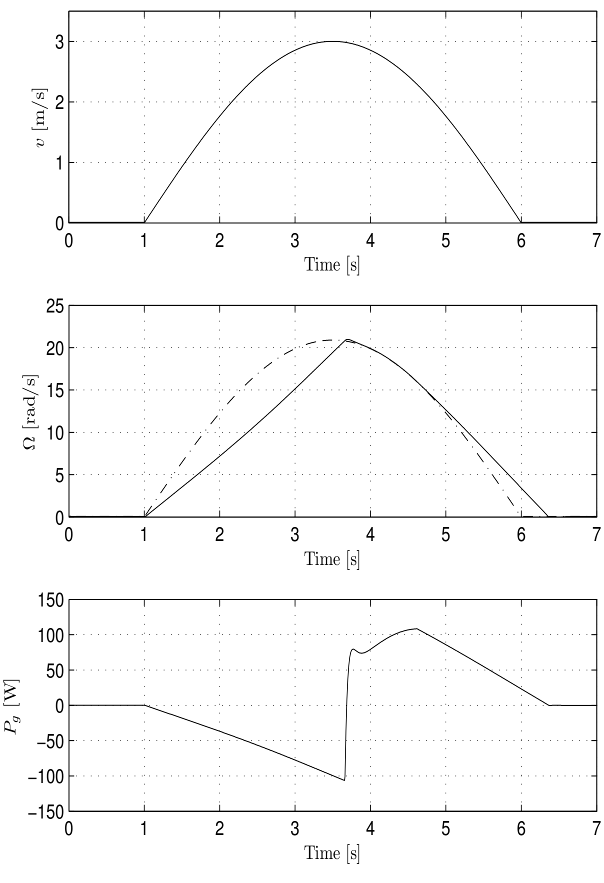
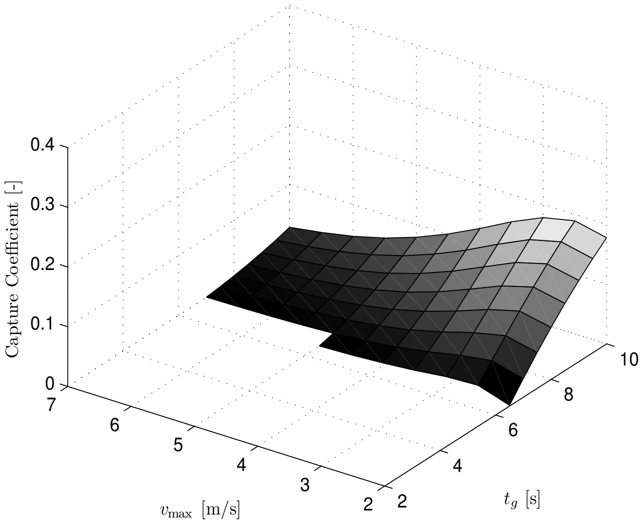
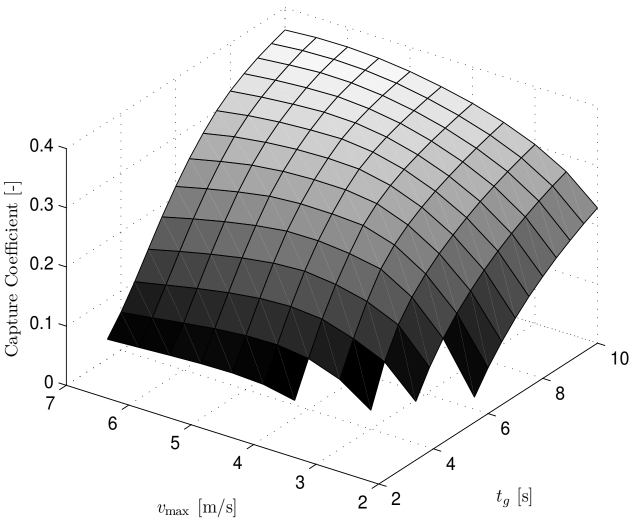


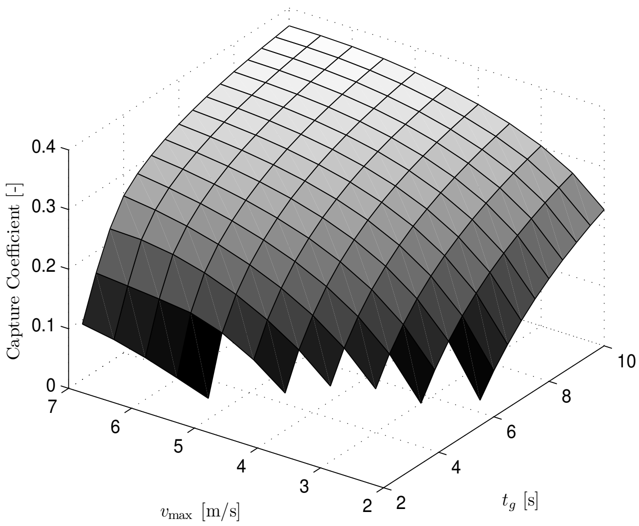
Fig. 6: Wind speed, (optimal) rotor speed and generator power in function of time during wind gust capture with rated motor current.



(a) $I_{\mathrm{q,max,mot}} = 0.3\ I_{\mathrm{nom}}$



(b) $I_{\mathrm{q,max,mot}} = I_{\mathrm{nom}}$



(c) $I_{\mathrm{q,max,mot}} = 3\ I_{\mathrm{nom}}$

Fig. 7: Capture coefficient in function of wind gust parameters and maximal motor current.

6 Wind gust detection

To prevent the active rectifier to start operating for small and short wind gusts, a detection algorithm is proposed which can distinguish appropriate from inappropriate wind gusts. For this purpose, only wind speed measurements can be used which are obtained during the very beginning of the gust. Otherwise, too much energy would already be consumed before the rectifier would be shut down again.

To make the distinction, not the wind speed itself but its first derivative is used. This value is determined twice: at the beginning of the wind gust (t=0) and 0.5 seconds after the start. The detection algorithm can be illustrated by the decision tree in Fig. 8. The result value ϵ indicates whether the detected wind gust is an appropriate (1) or inappropriate (0) one.

The initial wind speed derivative $\dot{v}(0)$ is compared with a minimal and maximal value to make a first separation. If the condition is not fulfilled, the rectifier won't start up and the wind gust will be passed. In the other case, the rectifier will start tracking the MPP by applying the maximal motor torque.

Next, a second separation is necessary which uses the value κ, corresponding with the product of t_{g} and $v_{\max}$. This value can be calculated after 0.5 seconds:

$$\kappa = \frac{\dot{v}(0)}{\arccos^2\left(\frac{\dot{v}(0.5)}{\dot{v}(0)}\right)} \tag{10}$$

If the second condition is fulfilled, the rectifier operation will be interrupted. Some energy will be lost, but the amount is limited because the half of a second is a small time in which the turbine will be hardly accelerated due to its inertia.

These two conditions are tested for the same array of wind gust parameters of which the result is presented in Fig. 9. When it is compared with Fig. 7c, it is observed that the wind gusts with negative capture coefficient are effectively rejected. Also some profiles with small duration and high peak value are omitted, but this is acceptable because these gusts are quite rare and their capture coefficients are limited.

7 Conclusions

Small wind turbines encounter difficult start-ups due to their large rotor inertia and low starting torques. Especially, when wind gusts occur at the moment the rotor stands still, quasi none of the wind energy can be captured. By using a PMSM with an active rectifier, this machine can be used to apply a motor torque which helps the turbine starting and accelerating towards the MPP. By applying the maximal allowable current, the capture coefficients are maximized. Some small, short gusts result in a negative power output and should be rejected. For this purpose, a wind gust detection algorithm is proposed which uses the measured wind speed's first derivative.

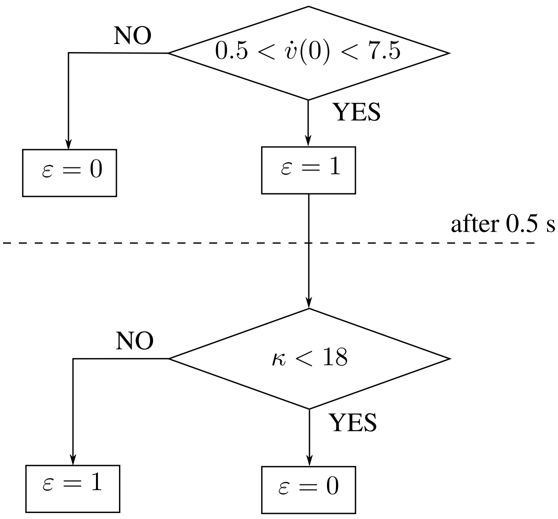


Fig. 8: Decision tree for wind gust detection.

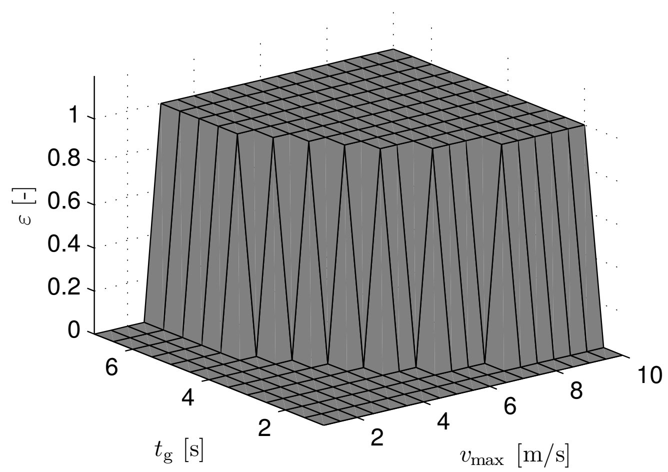


Fig. 9: Wind gust detection in function of wind gust peak value and duration.

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