

LOAD LEVEL COMPARISON VARIABLE SPEED WIND TURBINE

G. Adema, E.J.H. Kuipers *
R. Scherer **

* CTC, Bedrijvenpark Twente 301, 7602 KL Almelo, The Netherlands,
Tel.: +31(0)546-633304, g.adema@ctcgroup.nl

** NOI Rotortechnik GmbH, Kohnsteinbrücke 10, 99734 Nordhausen

Summary

Performance and fatigue loads of pitch, stall and active stall control methods are compared. With the given control curves the annual energy yields are calculated and compared for different wind classes. Fatigue load levels and equivalent 10 million cycles fatigue loadings (damage) are calculated for the three control strategies. The annual energy yields are related to the pitch case. The relative energy yield from stall increases with higher average annual windspeed (AAW). The relative energy yield for active stall control decreases and seems to get constant with increasing AAW.

With respect to the equivalent 20 years loading, the AS variant seems to give prospective results for the 20%TI spectrum comparison. Despite an increase in rotor torque and generator overloading level, which is also seen at the stall configurations, its advantage is seen in the absence of pitch adjustments, which can introduce additional edgewise and side to side tower responses.

1. Introduction

Performance and load cases for three kind of turbine control methods are compared:

- PD-controlled variable pitch and rotorspeed
- Conventional stall control with fixed pitch and fixed rotor-speed, with 0.5% slip
- Active stall with fixed pitch and variable rotorspeed

Generalized dimensionless quantities Power*, RPM* (rotor-speed), Torque* and Trust* are defined:

$$\text{Power}^* = \text{Power} / \text{Rated Power}$$

$$\text{RPM}^* = \text{RPM} / \text{RPM-max}$$

$$\text{Torque}^* = \text{Torque} / (\text{Rated Power}/\text{RPM-max})$$

$$\text{Trust}^* = \text{Trust}/\text{Trust-max}$$

The tip speed, V_{tip} , is restricted due too noise production, this gives the maximum for the rotorspeed: $\text{RPM-max} = V_{tip-max} / R$. The maximum trust, Trust-max, is reached in the pitch case, without application of peak shaving. The annual energy yield is compared for different wind classes, defined by GL, based on the average annual windspeed, AAW:

- GL wind class 1: AAW = 10 m/s
- GL wind class 2: AAW = 8.5 m/s
- GL wind class 3: AAW = 7.5 m/s

Fatigue load cases are calculated according GL regulations, with TI = 20%. From these, equivalent 10 million cycles fatigue loads (damage) are calculated for the three control strategies of scope. The strategies are modeled using Visual Fortran written routines. The simulation's output gives a qualitative view as the strategies were not direct related to a turbine manufacturers control system.

2. Turbine Control**2.1. Pitch Control**

Regarding the windspeed, the pitch control is based on three sections; design TSR till maximum tip speed is reached, maximum tip speed till rated power and pitching at rated power. A general PD-controller was used.

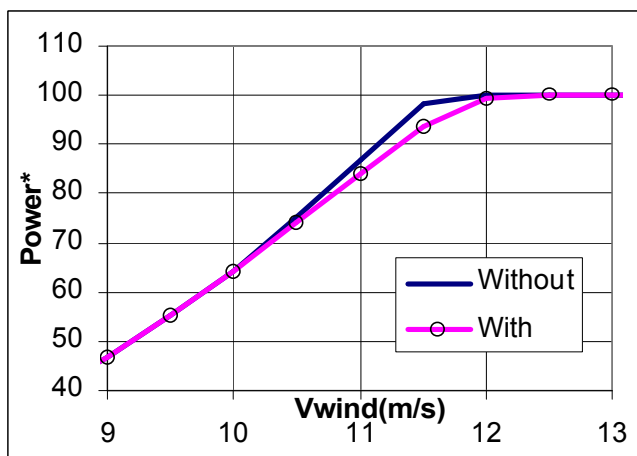


Fig. 1. Power for Peak Shaving at Pitch Control

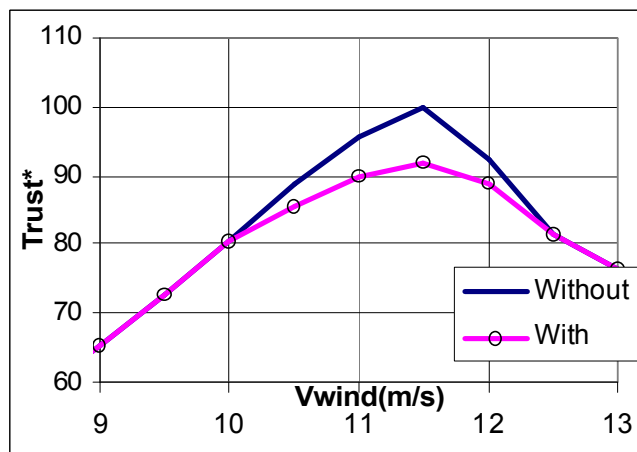


Fig. 2. Trust for Peak Shaving at Pitch Control

The aerodynamic optimum of the blade can be followed in this case. But the trust loads gives a sharp maximum peak in the second section, between design TSR and rated power. High trust fatigue loads can occur due variation in windspeed around the trust peak. Peak shaving is applied by decrease of the trust peak by reduction of the rotorspeed.

The turbine will not run at its design TSR for this section and will lose some performance. The trust is set at $Trust^* = 92$.

The proportional and differential gain parameters in the Fortran routines were tuned such that the wind speed and rotor speed harmonised without too many pitch actions.

2.2 Stall Control

To gain stall properties at rated power the blade is set on a constant pitch angle and a constant RPM^* . At low windspeeds the turbine is not at design TSR and a second RPM^* is applied. Vortex generators on the blades are applied to increase the performance for wind speeds just below rated power. When rated power is reached, the power will still increase with increasing wind speed, till the blade comes in stall and the power will decrease to rated again.

In the loads examination values of 2.5% and 5% slip were examined, next to 0.5%. For the fatigue production cases the amount of blade loading deviation versus slip was found to be little. The choice for synchronous speed was depending on the stall features of the rotor blades, rated power, overshoot, annual yield, noise level, and tip-angle for adding aerodynamic damping. The settings are tuned for a maximum power overshoot with $Power^* < 150$. Setting the tip angle more negative, with one degree, as in the pitch case gives 3% additional edgewise load reduction.

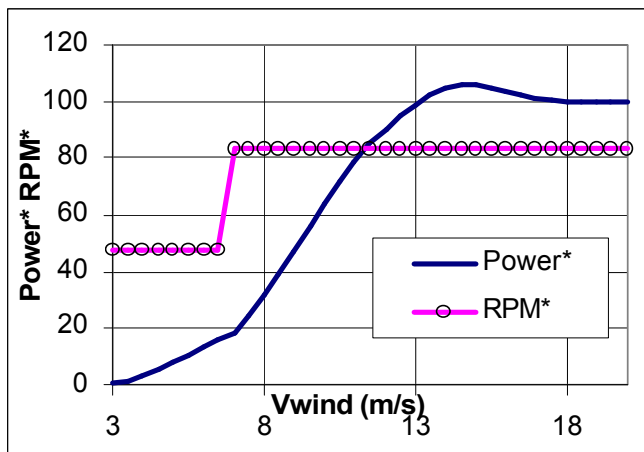


Fig. 3. Stall Control

2.1. Active Stall Control

Active stall control makes a combination of the pitch and stall control, with use of variable rotorspeed and fixed pitch. Below rated power the design TSR can be followed like pitch control, till its maximum allowable RPM^* . Then the rotorspeed decreases till the stall RPM^* . The power reaches rated at this rotorspeed with application of vortex generators. At rated power stall will occur and the power can be tuned with use of the variable rotorspeed.

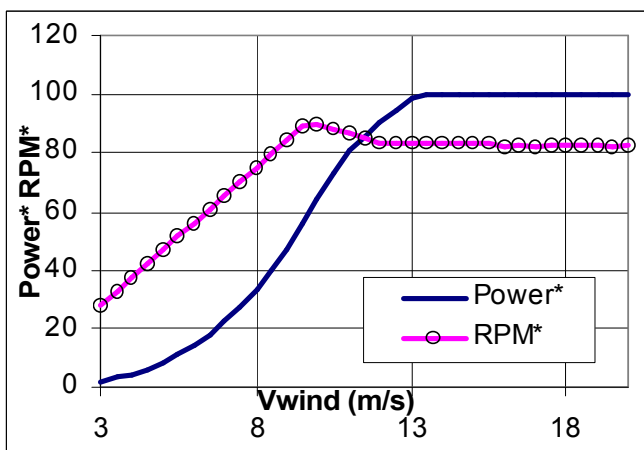


Fig. 4. Active Stall Control

The allowable RPM^* is restricted by the allowable power overshoot, which is taken equal as in the stall case, with $Power^* = 150$, this gives allowable $RPM^* = 86$; "AS_0.86". This RPM^* level is still about 5% higher than the synchronous speed of the stall rotor.

In the Fortran routine, the required reduction in rotor efficiency beyond RPM^* was achieved by adaptive power control. Hence, amplification of the electrical power discrepancies. The power set point to lower RPM^* values was adapted with amount of measured generator overload and vice versa. No input data was taken from wind speed measurements which resulted sometimes in too much generator overshoot e.g. at starting-up case.

3. Control Curves

For the three cases the calculated RPM^* - $Power^*$ curves are given in figure 5. Pitch control follows the optimal RPM^* curve till peak shaving. At rated power the rotorspeed increases till $RPM^* = 100$. In general, stall control uses only two rotorspeeds and active stall follows the pitch curve till its allowable RPM^* , then the RPM^* decreases to the stall level. At sections where the control curve does not follow the design TSR, decrease in $Power^*$ occurs, see fig. 6.

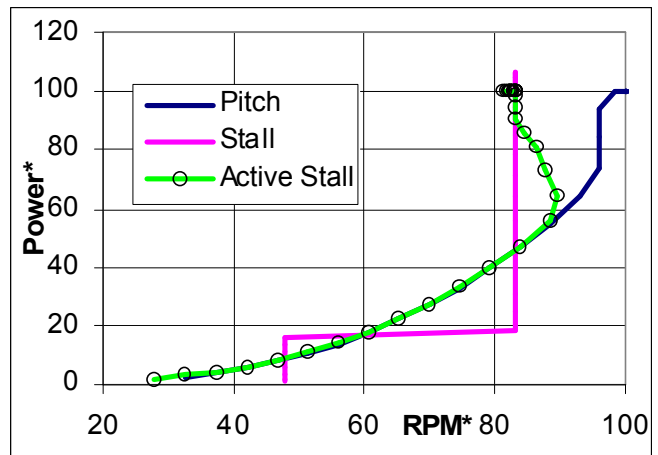


Fig. 5. Control Curves

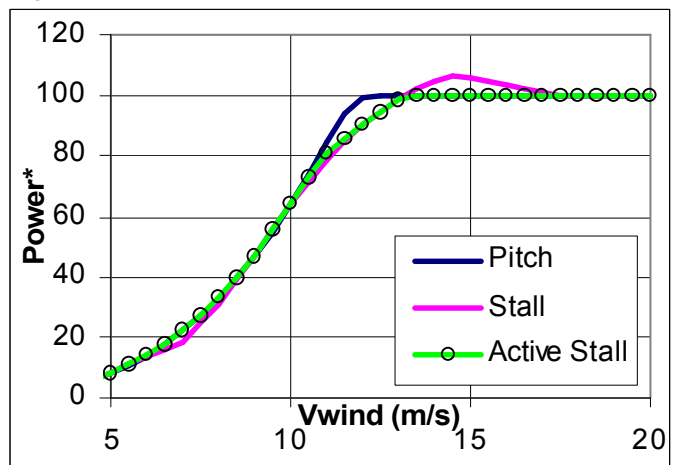


Fig. 6. Power Performance

Lower RPM^* at rated power gives higher torque, so the torque will be lower in the pitch case than in the stall and active stall cases for rated power. The power overshoot for stall will increase the torque for this section. The effect of the two RPM^* settings from stall control, before rated power, can be seen in fig. 7. Pitching of the blade at rated power gives a decrease of the trust, this does not occur in the stall and active stall cases. Decrease of RPM^* before rated power gives decrease of trust, applied with peak shaving for a pitch turbine. Relative low RPM^* before rated power in the stall and active stall cases gives relatively lower trust, see fig 8.

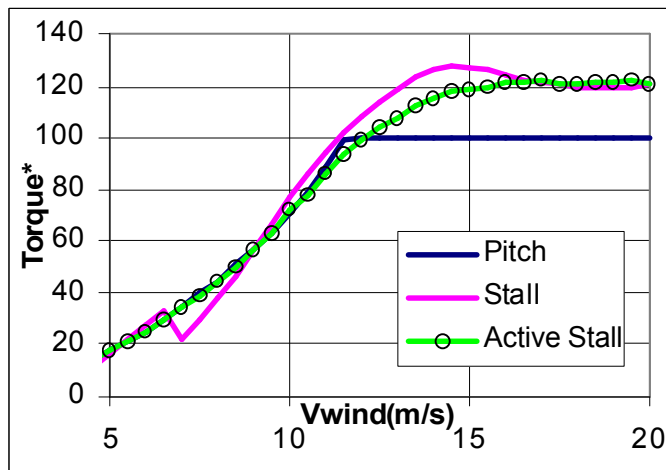


Fig. 7. Torque

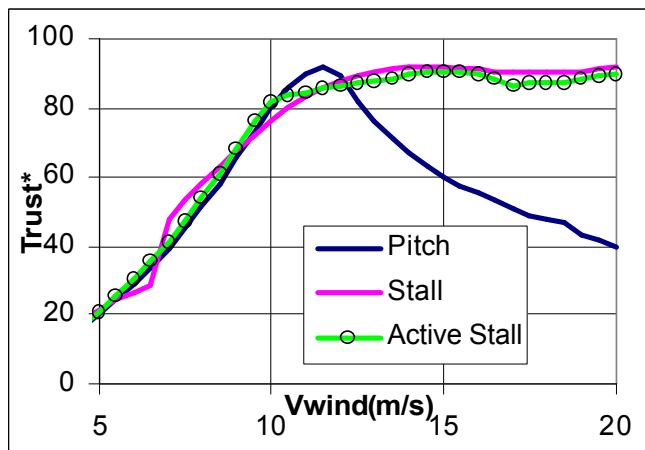


Fig. 8. Trust

4. Annual Energy Production

With the given control curves the annual energy yield can be calculated for different AAW's, with use of the Weibull ($k=2$) distribution. The energy yield for a wind bin is normalized on the maximum yield for the 8.5 m/s bin, see fig. 9. In this figure the effect of the deviation from the optimal RPM* for the stall and active stall control and the overshoot from the stall control can be seen.

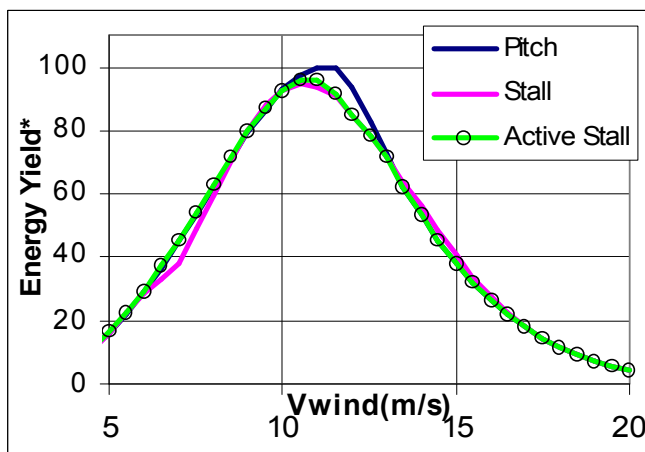


Fig. 9. Energy Yield for 8.5 m/s AAW

Summary of the bins gives the annual energy yield, this is calculated for the GL wind classes I, II and III, see figure 11. Pitch is set at 100%. The relative energy yield from stall control increases with higher AAW, partly due to the overshoot, assuming that it is transferred to the grid. The relative energy yield for active stall control decreases and seems to get constant with increasing AAW and reaches the stall level, due to reduction of the RPM* and stall properties.

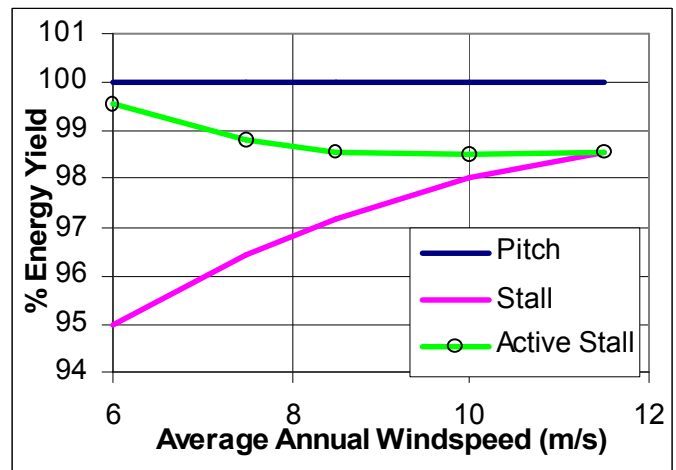


Fig. 10. Energy Yield for Wind classes

5. Fatigue Equivalent Load Levels

Fig. 11 shows the differences in flapwise blade root maximum load levels during each wind bin. The difference in lead-lag loading levels, inherently to power production and mass, between the 3 load series was small and not presented.

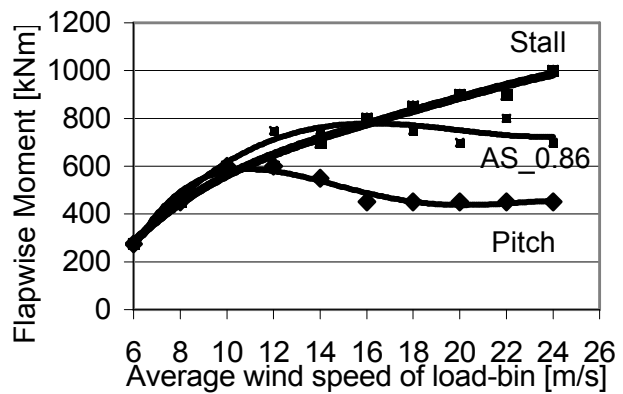


Fig. 11 Flapwise (non pitching rotor-co-ordinates) fatigue loading levels during normal operation fatigue cases.

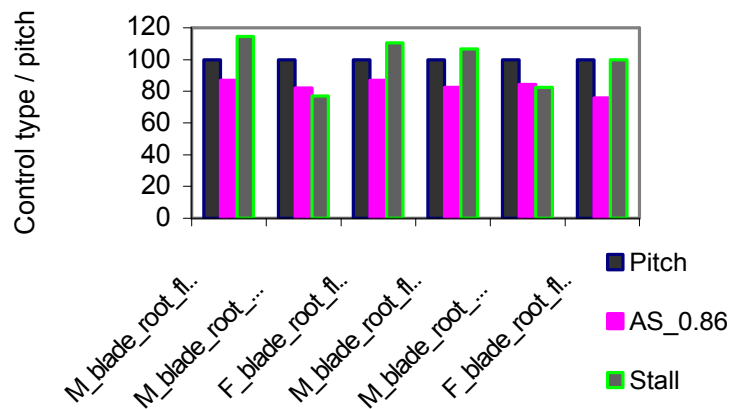


Fig. 12 GL 1 Equivalent fatigue loads blade in relation to pitch controlled equivalent loads.

A symmetric Goodman diagram is used for deriving the equivalent fatigue loads from the 20year spectrum. For the equivalent loads belonging to SN-slopes of 10 (SN10), applicable for glass-epoxy composites, the average load signal value was considered. This can elevate the level with 20% in flat-wise (perpendicular to local chord) direction. The SN-slope of 5 (SN5) indicates a level for steel parts, hence no mean value was taken into account.

Fig. 12 & 13 show the 10 million cycles equivalent fatigue loading for the GL-1 wind class fatigue spectrum. The values presented are all related to the pitch equivalent fatigue loads. This is also done for a GL-windclass 3 wind region. The relative effect for the change from GL 1 to GL 3 is shown in fig. 14.

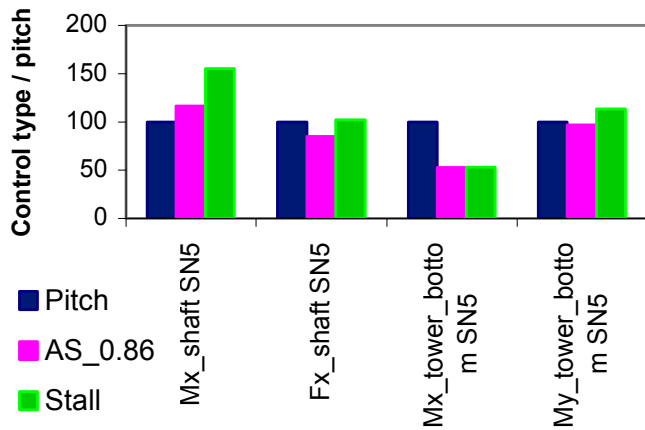


Fig. 13. GL 1 equivalent fatigue loads shaft and tower in relation to pitch controlled equivalent loads.

5.2. Pitch Control.

From the loads calculations, it was seen that the swift adjustment (higher number of occurrences) to external circumstances will make the edge wise blade fatigue damage higher for the pitch regulated blades. Further fine tuning of the used pitch controller probably could reduce these number of cycles slightly. This was not done in this analysis.

Flat-wise loading levels and equivalent levels (damage value) are lower due to the optimised inflow angle (drag reduction) .

The equivalent shaft load almost equals stall equivalent value. More energy capture is thought to be a reason despite the lower absolute load level of the pitch configuration. Further, shaft fatigue equivalent loading could be affected by the dynamic behaviour of the edgewise loading component of the blade.

5.3. Stall Control

The higher wind speed cases are responsible for the higher equivalent flapping loads. This as blade stall level increases with increasing wind speed above 18m/s.

The higher equivalent loading in shaft-torque is caused by the combination of rotor acceleration (mass and inertia) and higher torque performance (torque coefficients) of the blade at TRS from 7.5 towards 5.5.

5.4. Active Stall Control.

The low equivalent flapping loading is gained by the reduction of efficiency at the higher wind speed bins where the blade stall level tends to increase with wind speed.

Flat-wise loading levels of the AS version are higher than that of a pitch controlled turbine but the number of occurrences are lower which results in lower equivalent fatigue loading (damage).

Due to the absence of a pitch mechanism, no additional edge-wise cycles are introduces. This is beneficial for tower sidewise loading. However, an increase in shaft torque is applicable.

6. Conclusions

The relative energy yield from stall control increases with higher AAW. The relative energy yield for active stall control decreases and seems to get constant with increasing average wind speed.

From loads point of view, the AS variant gives prospective results for the higher GL turbulence class (20%TI). Despite an increase in rotor torque and generator overloading level, the advantage is seen in the absence of pitch adjustments. Latter can introduce additional edgewise and side to side tower responses.

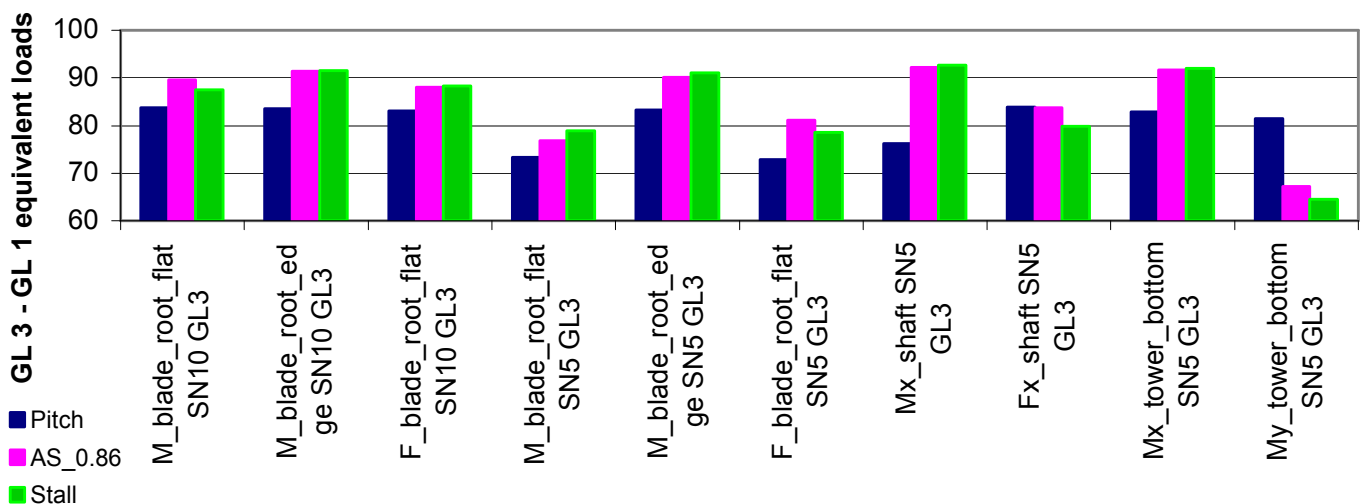


Fig. 14. Relative differences in fatigue equivalent loading between GL1 and GL3 wind classes.