UFSCKITE

TETHER TRACTION CONTROL IN PUMPING-KITE SYSTEMS

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Abstract

The machine speed control by FOC (Field Oriented Control) is suitable for many applications, but using it as the outermost control loop in a pumping-kite system might be problematic, especially when the kite is exposed to high levels of wind gusts. Keeping the machine speed constant in this scenario may cause the traction force and the airfoil angle of attack to fluctuate strongly, reaching values that may eventually lead the kite to a stall condition or to structural damage. In this work we have implemented an external loop to the FOC in a computer simulation of the pumping-kite system. This loop compares a given traction force reference to the instantaneous measured value and, based on this control error, generates a speed reference to the FOC. In this approach, the traction force control operates continuously and is capable of effectively rejecting high amplitude perturbations of the wind speed. A complete pumping-kite system was simulated to test the proposed control.

Introduction

Several companies and research groups around the world have already built prototypes to validate different configurations of AWE systems, all of which rely on the control of electric machines. An appropriate machine control can optimize power production and also allow for the tethered wing to fly robustly regardless of wind fluctuations while respecting system constraints such as the maximum tether traction force and reel speed. These machines should also be capable of operating both as a motor, during take off, landing and the retraction phase, as well as a generator during the traction phase.

Application and control

Speed control

Alternated current machines are commonly used in the industry mainly due to advanced features such as the well known Vector Control, also referred to as Field Oriented Control (FOC). In this scheme, the magnetic flux and electromagnetic torque currents are regulated in the inner loop, whereas the machine speed is controlled in the outer loop. In the ground station prototype of the UFSCKite team, a permanent magnet machine is used and its model can be summarized by three equations in the follow synchronous d-q frame:

$$u_{sd} = R_s i_{sd} + L_d \frac{di_{sd}}{dt} - \omega_e L_q i_{sq} \tag{1}$$

$$u_{sq} = R_s i_{sq} + L_q \frac{di_{sq}}{dt} + \omega_e L_d i_{sd} + \psi_m \omega_e \tag{2}$$

$$T_{em} = \frac{3}{2} n_{pp} (\psi_m i_{sq} + (L_d - L_q) i_{sd} i_{sq}). \tag{3}$$

The equations (1) and (2) represents the direct and quadrature voltages, respectively, whereas equation (3) models the electromagnetic torque. To complete the machine dynamic model, the motion is expressed as:

$$T_{em} - T_L = J \frac{d\omega_m}{dt} + B\omega_m. \tag{4}$$

The current and speed controllers were designed using a proportional-integral (PI) scheme, tuned with the root-locus methodology.

Tether traction force control

Based on the static model proposed by Fagiano [1], the main tether traction force is computed as:

$$F^{T_c} = \frac{1}{2} \rho A C_L E^2 (1 + \frac{1}{E^2})^{\frac{3}{2}} |\mathbf{W_{e,r}}|^2, \tag{5}$$

where the effective wind ($\mathbf{W_{e,r}}$) in the tether direction is:

$$|\mathbf{W_{e,r}}| = sin(\theta) cos(\phi) - \dot{r}_a \tag{6}$$

Replacing (6) in (5) we can note that the force on the tether depends on the reel-out speed ($\dot{r}_a$). So it is possible to achieve a desired value for the traction force by manipulating $\dot{r}_a$. We also know that the machine speed (ω_m) is related to the reel-out speed by a factor of r_d/k_{tr} (drum radius/gearbox transmission gain).

One characteristic of the UFSCkite prototype (as well as of several other AWE systems) is the measurement of the tether traction force by a load cell, which makes the control task easier. If we assume that the the speed dynamics achieved by the FOC is negligible in comparison to the traction force dynamics, the error between reference and actual traction force can be computed as:

$$e(F^{Tc}) = (F^{Tc^*} - F^{Tc}) \frac{r_d}{k_{tr}} = -J_L \frac{d\omega_m}{dt}, \tag{7}$$

where J_L is the load inertia. The machine load T_L is proportional to F^{Tc} by a factor of k_{tr}. Finally, the control law of the tether force is expressed as:

$$C_T(s) = -\frac{1}{J_L s} (F^{Tc^*} - F^{Tc}) \frac{r_d}{k_{tr}}. \tag{8}$$

This control can also be referred to a reference adjustment, since the gain is based on a system parameter (J_L). The proposed control scheme is illustrated in Figure 1, and it is a combination of the classical FOC speed controller with an additional loop aimed to control the traction force.

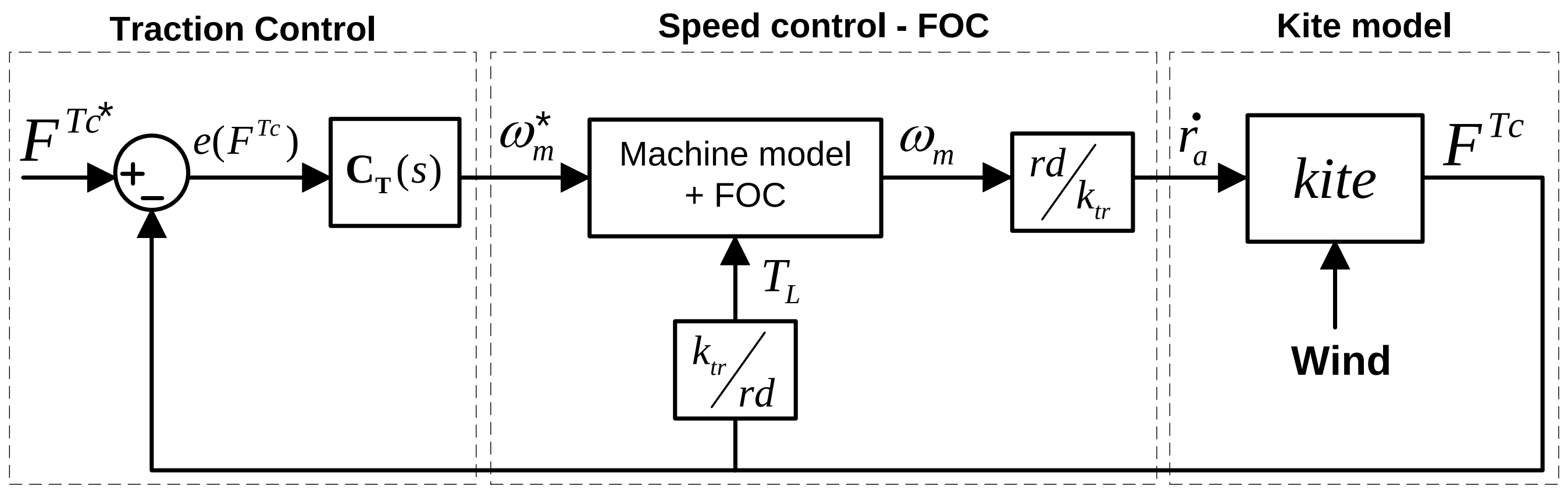

Figure 1: Proposed Traction Force Control.

Simulation Results

The simulations were parameterized to represent the ground station prototype under development by the UFSCKite team, which is based on a single permanent-magnet machine of 12 kW and designed to support up to 800 kgf of pulling force. The simulation comprises both the kite and electric machine dynamic models and also takes into account the wind turbulence using the Dryden model. In order to verify the impact of the turbulence on the angle of attack and on the traction force, we considered three wind scenarios: with no gusts, with moderate turbulence and with high level of turbulence. In Figure 2 it is illustrated the traction control performance achieved when the system is exposed to wind turbulence of moderate level. We can see that, as long as the maximum machine speed is not reached, the machine was able to manipulate its speed to properly regulate the tether traction force. When the speed reaches its saturation value, the tether traction begins to deviate from its reference, as highlighted in the figure. In this situation we are no longer able to limit the traction force only by manipulating the machine variables.

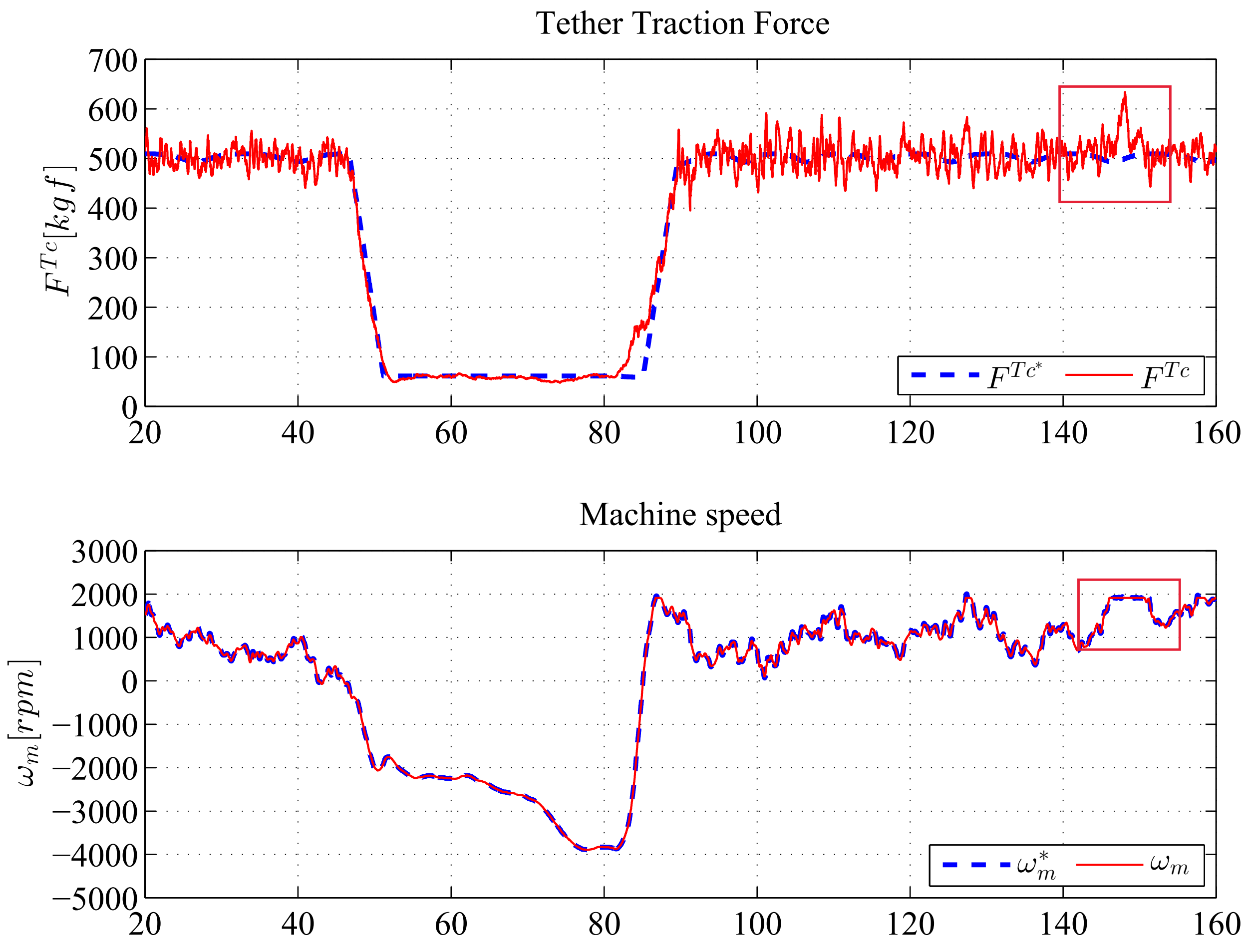

Figure 2: Tether force control in moderated wind gusts.

An interesting feature of the tether traction control, when compared to a situation where only the speed control is employed, is that in this way we are able to keep the airfoil angle of attack inside a desirable safe range. Thus, this strategy aids to avoid the airfoil from stalling due to wind speed fluctuations. This can be seen in Figure 3, where both strategies are compared under different wind turbulence levels.

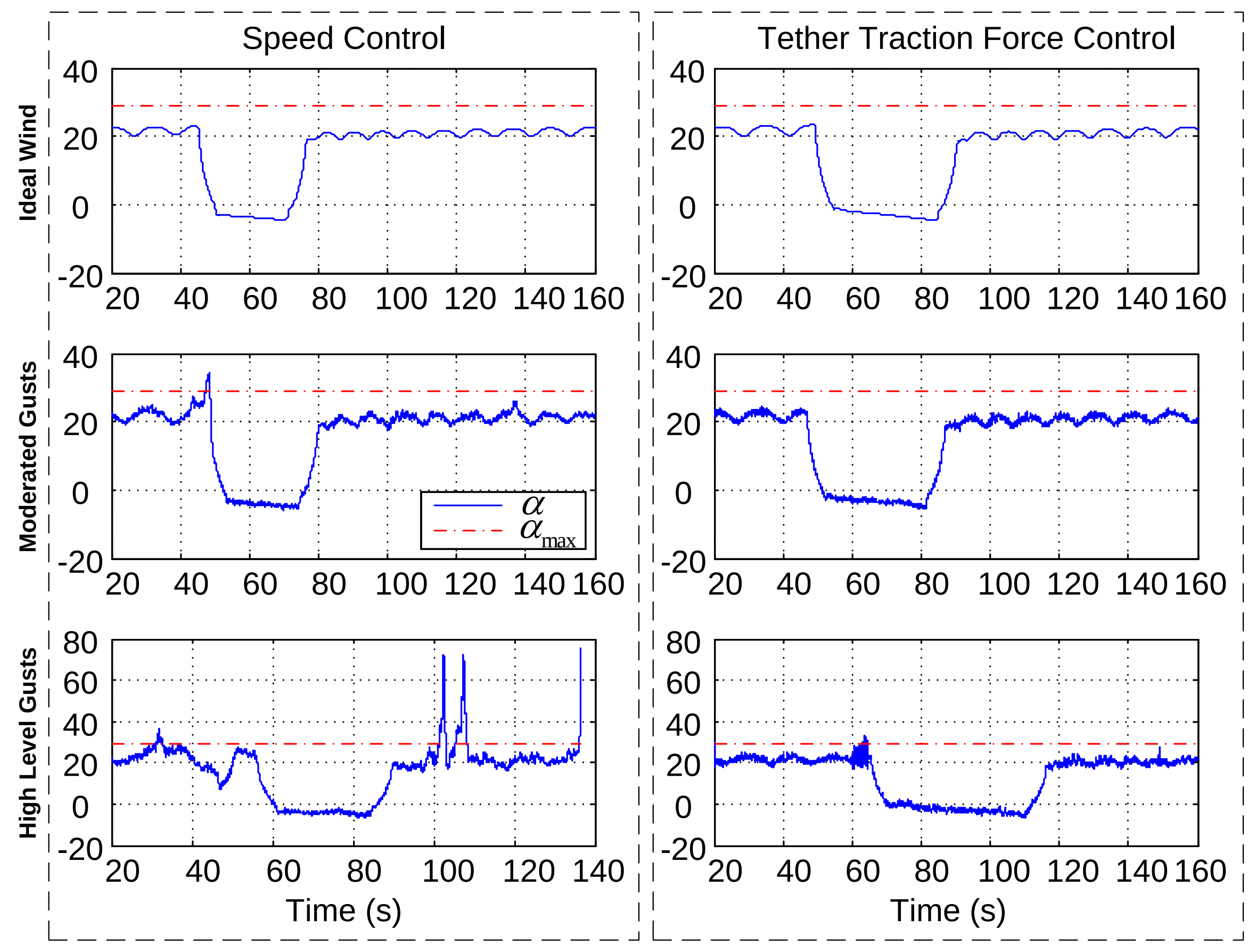

Figure 3: Effect of controllers on angle of attack.

Conclusions

In this work a tether traction force control strategy was proposed. According to our simulations, we can see that the system is able to effectively reject high amplitude perturbations of the wind speed as long as its frequency is lower than the cutoff frequency of the closed loop dynamics. The results show the effectiveness of the proposed control strategy, not only for tracking setpoints of the traction force but also to prevent the kite from stalling. For further work, we should develop a strategy, based on the current wind condition, to generate an optimum traction reference to the system. Moreover, we intend to improve the traction force control by using non-linear and robust design methodologies.

References

[1] L Fagiano. *Control of Tethered Airfoils for High-Altitude Wind Energy Generation*. PhD thesis, Politecnico di Torino, Torino, Italy, 2009.

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