Servo hydraulic actuator - V2

Start of a rewrite to make the system tfs a modular / re-useable library

Notebook for design of mechanism to provide control of pressure in a closed hydraulic system

Motor -> mechanical drive -> master cylinder

Components

Motor:

- Brushed DC motor
- Voltage limit on controller
- Simulation of transient thermal characteristics based off motor supplier data

Mechanical Drive:

- Gearbox
- Rotary to linear mechanism

Hydraulic system

- Stiffness represented as a linear spring based on master cylinder travel

Controller

- Simple PI controller controlling pressure by varying motor voltage

Assumptions

- Winding resistance change with temperature is ignored. This will over-estimate performance of motor at continuous / heavy use
- Non-linear (detailed entrained / dissolved air) behaviour of fluid ignored. Low pressure behaviour of fluid will be inaccurate

In [1]:

```
import sympy
from sympy import *
import control as ct
import matplotlib.pyplot as plt
```

```python
from math import pi
import numpy as np
import scipy as sp
init_printing()
plt.style.use('style.mplstyle')
```

Parameters

In [2]:

```python
#Mechanical parameters
lead = 15 / (2*pi) # mm/rad
n = 26 # gbox reduction
MR = lead / n # mm/rad
eff = .75*.9 # efficiency

#Hydraulic parameters
k_hyd_lin = 14.28 #bar/mm
k_hyd = k_hyd_lin * MR #bar/rad
A = (pi * 12**2) / 4 #mm2 (piston area)

#Motor characteristics
k_T = 42.9e-3 #Nm/A
l_a = 0.514e-3 #H
r_a = 2.95 #ohm

#Reflected inertia at motor
j_rotor = 21.2e-7 + 3.9e-7 + 32.6e-7 / n**2 #kg/m2
#Viscous damping at motor
b = 0 # Nm/(rad/s)

#Thermal characteristics
r_w = 3.01 #K/W
r_h = 10.2  #K/W
C_w = 23.8 / 3.01 #J/K
C_h = 620 / 10.2 #J/K

#Pressure controller
K_p_p = 15
K_i_p = K_p_p/10
K_d_p = 0

# #Current controller
# K_p_i = 5
# K_i_i = 0
# K_d_i = 0

#Limtis
U_max = 40 #V

#Other
T_ambient = 25 #deg
alpha_cu = 0.0039
```

System parameters and setup

In [3]:
```
# System parameters
from brushed_dc_motor_copy import dc_brushed_motor ,saturating_voltage_supply,
transmission, linear_load, pi_controller

motor_params = {
    "kT": 42.9e-3,
    "l_a": 0.514e-3,
    "j_rotor": 21.2e-7,
    "r_a": 2.95,
    "b": 0,

}
supply_params = {
    "max": U_max,
    "min": -U_max,
}

gbox_params = {
    "n": 26,
    "j": 3.9e-7,
    "eff": 0.75,
}
gbox_op = {
    'speed': 'omega_out_gbox',
    'torque': 'torque_out_gbox',
}

bs_params = {
    "n": 2*pi / 15e-3,
    "j": 32.6e-7,
    "eff": 0.9,
}
bs_op = {
    'speed': 'speed_out_ballscrew',
    'torque': 'force_out_ballscrew',
}

load_params = {
    "m": 0.2,
    "c": 0,
    "k": 1e3 * 14.28*.1 * A
}

ct_params = {
    "kp": 15,
    "ki": 15/10,
}

motor = dc_brushed_motor(motor_params, additional_outputs=['i'])
supply = saturating_voltage_supply(supply_params)
gbox = transmission(gbox_params, motor, gbox_op)
```

```python
ballscrew = transmission(bs_params, gbox, bs_op)
load = linear_load(load_params, ballscrew)
controller = pi_controller(ct_params, 'pressure_set', 'pressure', 'u' )

pressure = ct.tf(
    10,
    A,
    inputs = 'force_out_ballscrew',
    outputs = 'pressure',
)

oltf=ct.interconnect(
    [motor, supply, gbox, ballscrew, load, pressure],
    inputs = 'u',
    outputs = 'pressure',
    name = 'oltf'
    )
```

```
C:\Users\Mark\AppData\Local\Programs\Python\Python310\lib\site-packages\control\nlsy
s.py:1198: UserWarning: Unused output(s) in InterconnectedSystem: (0, 1) : dc_motor_
brushed.i; (4, 0) : sys[32].position
  warn(msg)
```

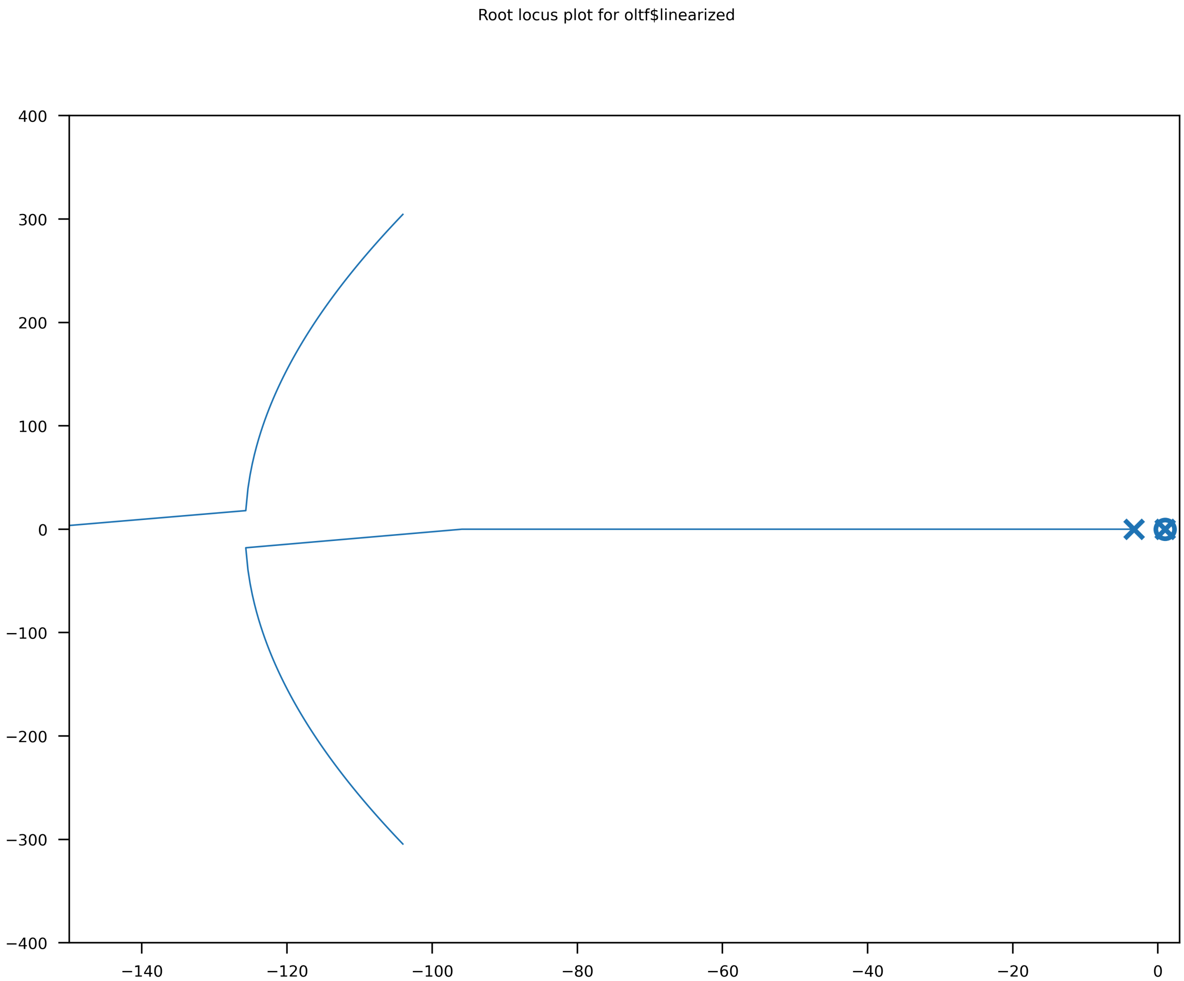
Root locus

Gives an idea of system performance under the proportional control, by visualising where the poles of the system have moved to with our proportional gain

Requires system to be linearised (not much issue in this case as only non-linear feature is voltage saturation, which should be avoided anyway). Doesn't take integral or derivative gains into account currently.

In [4]:
```python
eq = ct.find_eqpt(oltf, np.ones(oltf.nstates),20)
oltf_lin = ct.linearize(oltf,eq[0],20,copy_names=True)
plt.gca().axis('auto')
ct.root_locus(oltf_lin,xlim = (-150,3),ylim=(-400,400), gains =
np.linspace(0,ct_params["kp"],100))
```

Out[4]:
```
<control.ctrlplot.ControlPlot at 0x1711e3ea680>
```



Simulate system

Connect the system transfer functions, create input demand signals of interest, and simulate the time response of closed loop system.

In [5]:
```
output_list = ['pressure', 'i', 'u_s', 'omega_motor','omega_out_gbox',
'torque_out_gbox', 'position']
sys = ct.interconnect(
    [motor, supply, gbox, ballscrew, load, pressure, controller],
    inputs = ['pressure_set'],
    outputs = output_list,
    name = 'system'
)
```

In [6]:
```
#Input functions
def const_value(C, start,end):
    eps = 1e-4
    t = np.linspace(start, end-eps,1000)
    u = C * np.ones(len(t))
    return [t,u]

def sinusoid(A,f,phi,U,start,end):
```

```python
    eps = 1e-4
    t = np.linspace(start, end-eps,1000)
    u = A * np.sin(f*2*np.pi*(t-start) - np.radians(phi)) + U
    return [t,u]

peak_pressure = 66 #Bar
sin_amp = 5 #bar
sin_freq = 15 #Hz

on_time = 4
cooling_time = 60*5

# List of inputs, in form [t,u] where u is demand signal. Simulating a step, then
an oscillation around a mean value, then 0 input to capture cooling behaviour
inp_list = [
    const_value(peak_pressure, 0, 0.2),
    sinusoid(sin_amp, sin_freq, -90, peak_pressure - sin_amp, 0.2, on_time),
    const_value(0,on_time, on_time + 0.2), # this is its own so solver puts small
enough timestep to capture
    const_value(0 , on_time + 0.2, cooling_time),
]
```

In [7]:

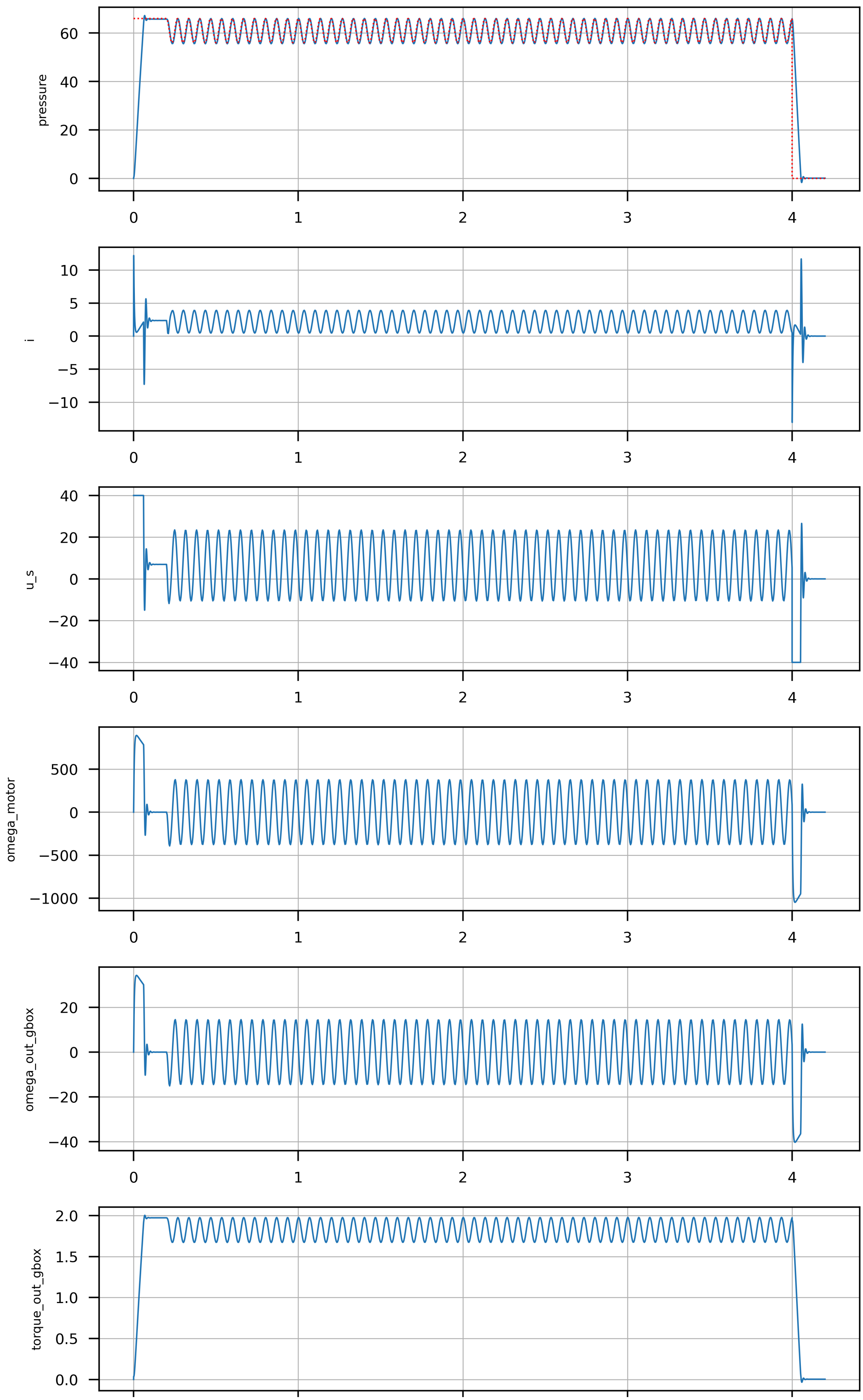
```python
states = 0

y = None
t = None
u = None

#much more efficeint to split out into multiple sims, especailly with long periods
of nothing happening
for inp in inp_list:
    r = ct.input_output_response(sys,inp[0], inp[1], solve_ivp_method = 'LSODA',
X0=states,)#solve_ivp_kwargs={'rtol': 1e-6, 'atol': 1e-9})
    t = np.concatenate((t,r.t)) if t is not None else r.t
    u = np.concatenate((u, r.u), axis = 1) if u is not None else r.u
    y = np.concatenate((y, r.y), axis = 1) if y is not None else r.y
    states = [s[-1] for s in r.x]
# print(y.shape)
# print(t.shape)
# print(u.shape)
```

Plotting

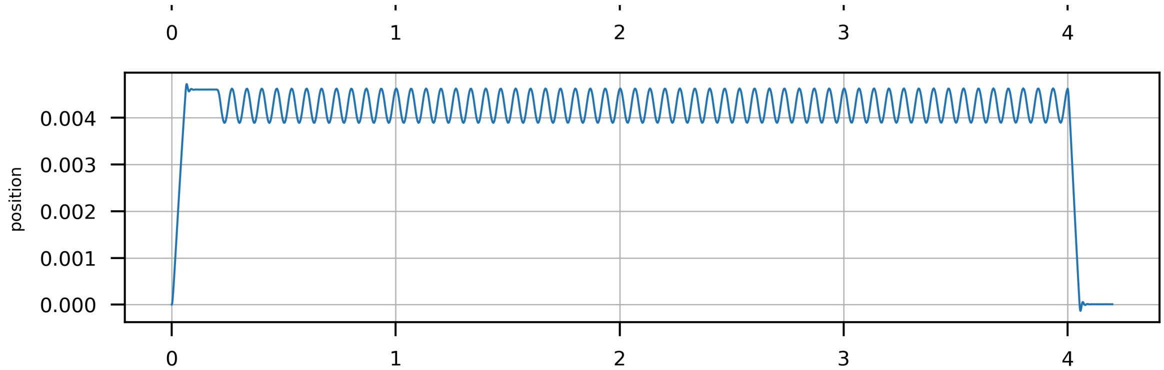
In [11]:

```python
fig, axs = plt.subplots(len(output_list), figsize = (4,8))
fig.tight_layout()
idx = np.searchsorted(t,on_time*1.1)
for i, ax in enumerate(axs):
    ax.plot(t[0:idx],y[i][0:idx], label = output_list[i])
    ax.set_ylabel(output_list[i])
    ax.grid(True)
axs[0].plot(t[0:idx],np.transpose(u)[0:idx], linestyle = 'dotted', color = 'red')
rms = np.sqrt((1/on_time)* sp.integrate.trapezoid(y[1][0:idx]**2,t[0:idx]))
print(f"RMS current is {rms:.02f}A")
```

RMS current is 2.57A

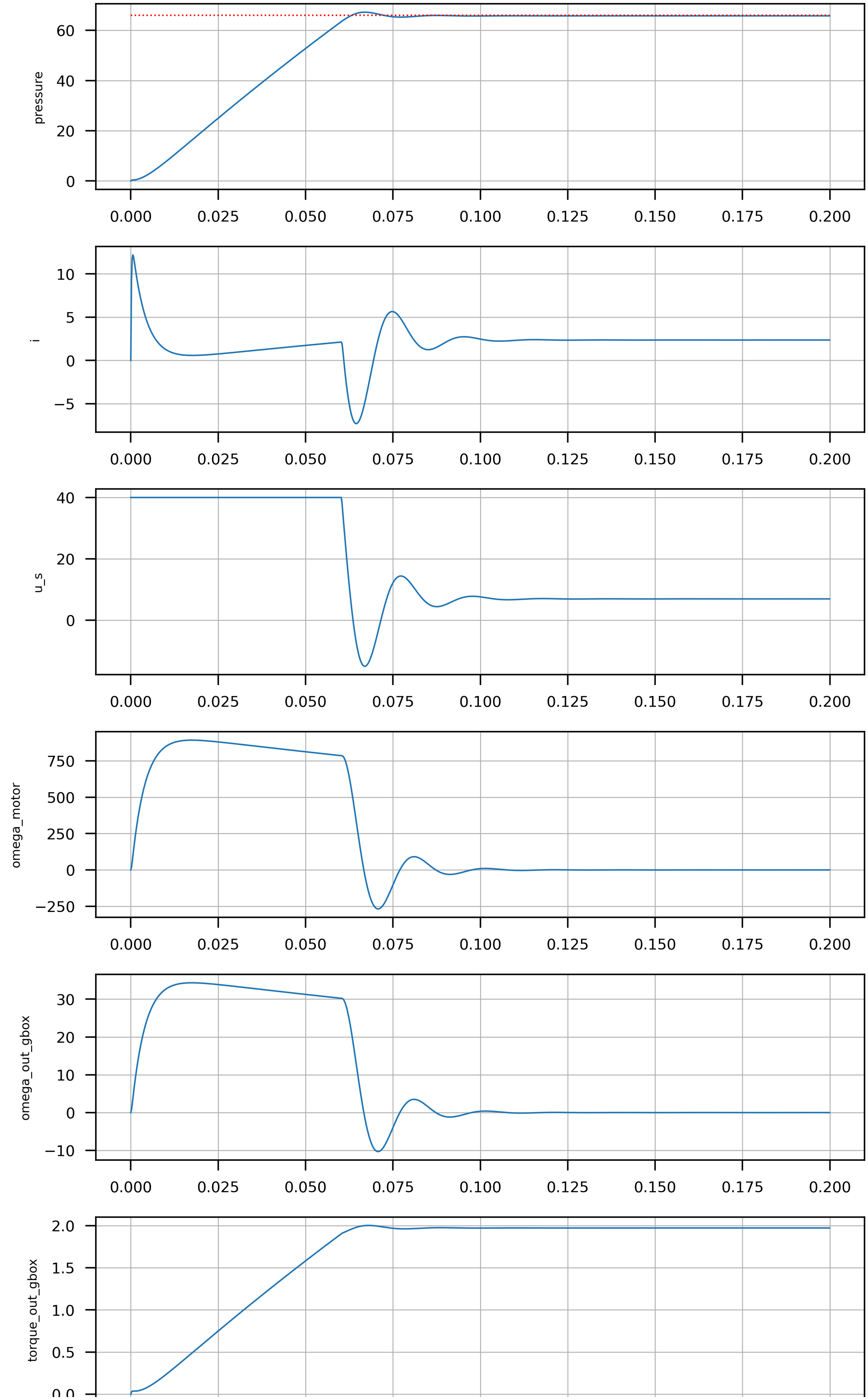


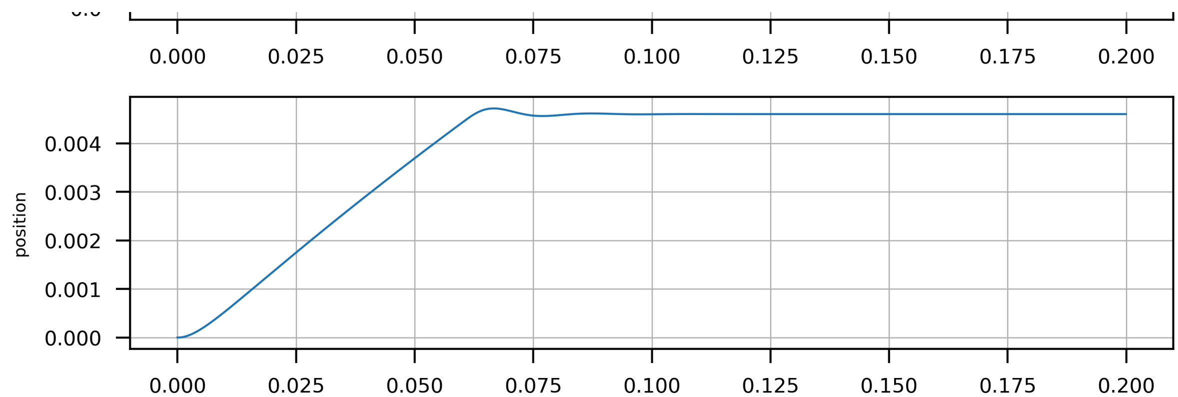
pressure
60
40
20
0
0
1
2
3
4
i
10
5
0
−5
−10
u_s
40
20
0
−20
−40
omega_motor
500
0
−500
−1000
omega_out_gbox
20
0
−20
−40
torque_out_gbox
2.0
1.5
1.0
0.5
0.0



In [10]:
```
fig, axs = plt.subplots(len(output_list), figsize = (4,8))
fig.tight_layout()
idx = np.searchsorted(t,.2)
for i, ax in enumerate(axs):
    ax.plot(t[0:idx],y[i][0:idx], label = output_list[i])
    ax.set_ylabel(output_list[i])
    ax.grid(True)
axs[0].plot(t[0:idx],np.transpose(u)[0:idx], linestyle = 'dotted', color = 'red')
rms = np.sqrt((1/on_time)* sp.integrate.trapezoid(y[1][0:idx]**2,t[0:idx]))
print(f"RMS current is {rms:.02f}A")
```

```
RMS current is 0.62A
```

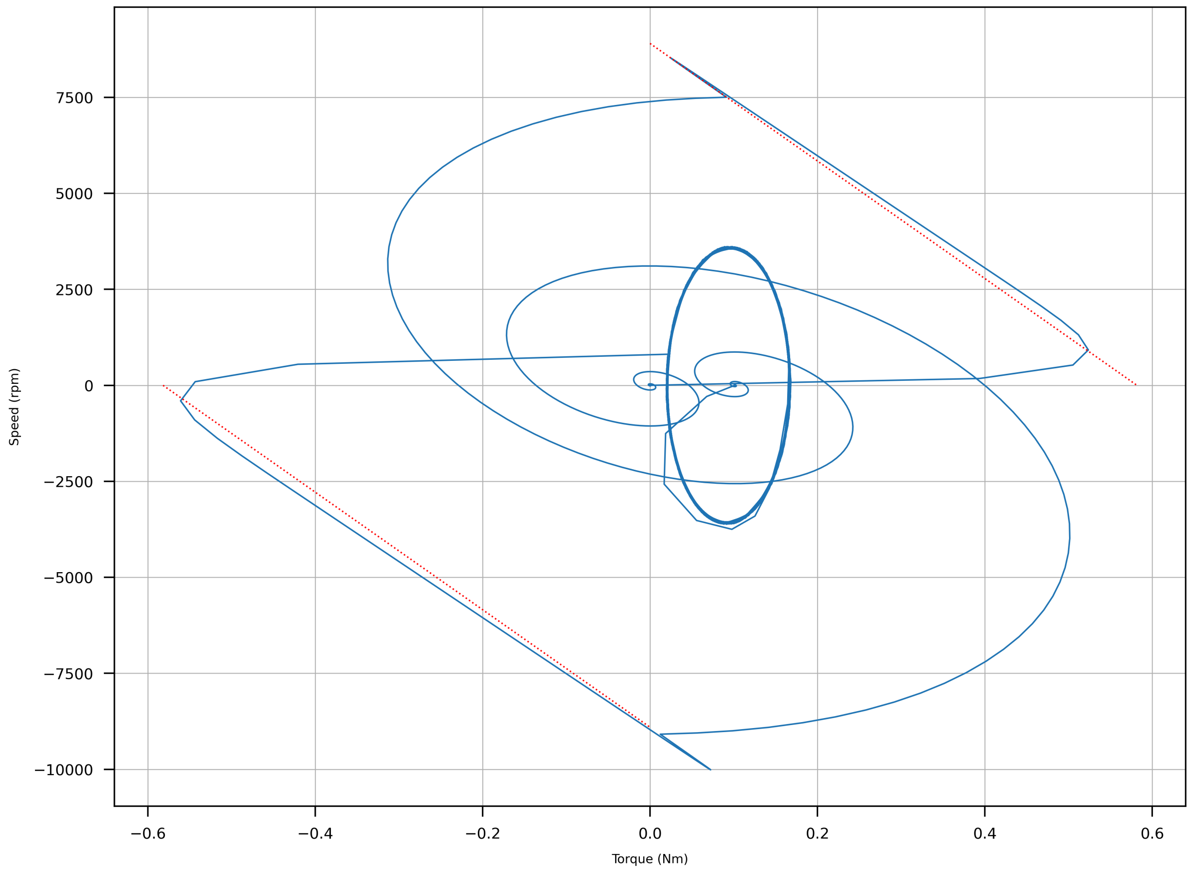

pressure
i
u_s
omega_motor
omega_out_gbox
torque_out_gbox
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200



Motor State Space

Visualisation of speed torque space of motor. Can see that motion stays (pretty much) within motor speed torque lines in +ve and -ve quadrants

In [12]:
```
fig,ax = plt.subplots()
ax.plot(y[1]*k_T,y[3]*60 / (2*pi))
x = np.linspace(0 , k_T*U_max/r_a, 100)
xx = np.linspace(-k_T*U_max/r_a, 0, 100)
ax.plot(x, ((U_max / k_T) - (x / k_T**2) * r_a) * 60/(2*pi), linestyle='dotted',
color = 'red')
ax.plot(xx, (-(U_max / k_T) - (xx / k_T**2) * r_a) * 60/(2*pi),
linestyle='dotted', color = 'red')
ax.set_ylabel('Speed (rpm)')
ax.set_xlabel('Torque (Nm)')
ax.grid()
```



Thermal Modelling

Winding heat generated is proportional to current in windings. Lumped mass model of windings and housing. Winding / housing thermal properties and heat transfer coefficient to environment taken from motor datasheets.

Effect of winding resistance is included in this analysis.

In [13]:
```
current = y[1]
current_t = t
T_ambient = 85
def f(t,y):
    I = np.interp(t, current_t, current)
    heat_gen = I**2 * r_a * (1+alpha_cu*(y[0]-25))
    return [(1/C_w)*(heat_gen - (1/r_w)*(y[0]-y[1])),
           (1/C_h)*((1/r_w)*(y[0]-y[1]) - (1/r_h)*(y[1]-T_ambient))]

sol = sp.integrate.solve_ivp(f,[0,r.t[-1]], [T_ambient,T_ambient], max_step =
r.t[-1]/ len(r.t), method = 'Radau')
print(len(sol.t))
```

```
1057
```

In [14]:
```
fig,ax = plt.subplots()
ax.plot(sol.t,sol.y[0], label = "Winding temp")
ax.plot(sol.t,sol.y[1], label = "Housing temp")
```

```python
ax.set_ylabel("Temperature (degC)")
ax.set_xlabel("Time (s)")
ax.legend()
```

Out[14]: <matplotlib.legend.Legend at 0x17129a072e0>