MIDDLE EAST TECHNICAL UNIVERSITY
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
EE568 - SELECTED TOPICS ON ELECTRICAL MACHINES
PROJECT #1 REPORT
March 2, 2020

Torque in a Variable Reluctance Machine

1 INTRODUCTION

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2 ANALYTICAL CALCULATIONS

Analytical reluctance modelling of the given electromechanical system requires several assumptions on the system. Saliency of the rotor causes a change in the reluctance as the rotor rotates. Therefore, reluctance and inductance should be modelled as a function of the rotation angle, let's say θ.

In Figure 2.1, some critical angles have been defined. As the rotor is in horizontally aligned position ($\theta = 0°$), the air-gap is 2.5 mm. As a result, the system reluctance is maximum and the inductance is at its minimum value. When the rotation angle is α, the air-gap becomes 0.5 mm and the reluctance starts to decrease as a function of surface area of the salient part of the rotor. When rot

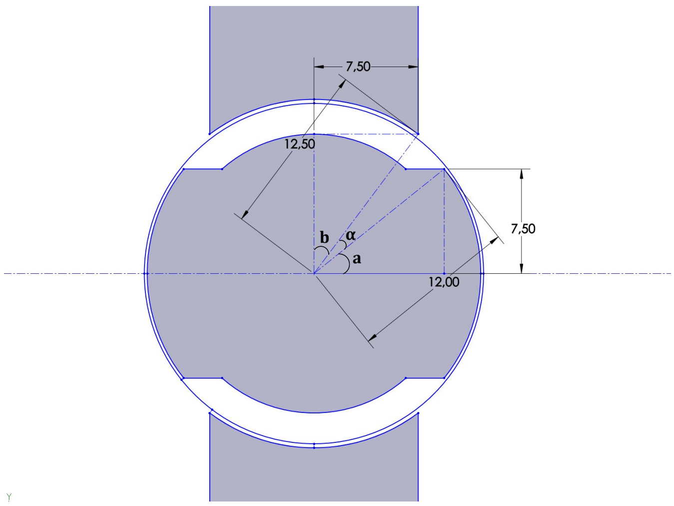

Figure 2.1: Critical angles of the geometry for accurate reluctance modeling

3 FEA Modeling (2D, Linear Material Properties)

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4 FEA Modeling (2D, Nonlinear Material Properties)

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5 FEA Modeling (3D, Nonlinear Material Properties)

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6 Control Method

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7 Conclusion

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Appendix: Matlab Code for Analytical Calculations

Analytical Calculations

Initialize

```
close all; clear all; clc;

% Variables and Constants

mu_0 = 4*pi*1e-7;
depth = 20e-3; %m
g1 = 0.5e-3; %m
r0 = 12.5e-3; %m
r1 = 12e-3; %m
g2 = 2.5e-3; %m
r2 = 10e-3; %m
L = 20e-3; %m
N = 250; %turns
I = 3; %Amps
```

Reluctance of the system varies over a period. Maximum reluctance position is where the airgap is 2x2.5 mm, i.e. the rotor is in horizontal position. To find the varying reluctance over a period, following angles are defined (see angles.png):

```
a = asin(7.5/12); %rad
b = asin(7.5/12.5); %rad

alpha = pi/2-(a+b); %rad
```

Reluctance and Inductance Definitions

Alpha is the angle where reluctance starts increasing, with respect to flux area, as a function of rotation angle. When rotor angle is alpha, corner of the salient part of the rotor is aligned with the corner of the stator. The change in the reluctance of the straight part of the rotor is ignored.

Reluctance of the system can be defined as a pwl function.

Reluctance for $\theta = 0 : \alpha$ and $\theta = 180 - \alpha : 180$

```
Rel_min = @(thet) (2*g2)/(mu_0*(2*b-thet)*r0*L);
```

Reluctance for $\theta = \alpha : 90$

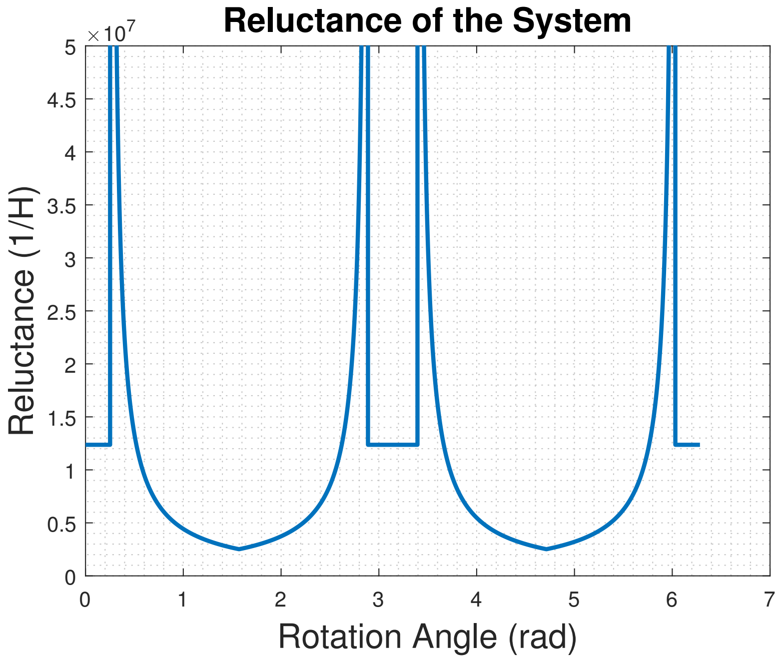
```
Rel_rise = @(thet) (2*g1)/(mu_0*r1*(thet-alpha)*L);
```

Reluctance for $\theta = 90 : 180 - \alpha$

```
Rel_fall = @(thet) (2*g1)/(mu_0*r1*(pi-alpha-thet)*L);

L_min = @(thet) N^2./Rel_min(thet);

L_rise = @(thet) N^2./(1/Rel_rise(thet)+1/Rel_min(thet-alpha))^(-1);

L_fall = @(thet) N^2./(1/Rel_fall(thet)+1/Rel_min(pi-alpha-thet))^(-1);
```

PLOT THE RELUCTANCE

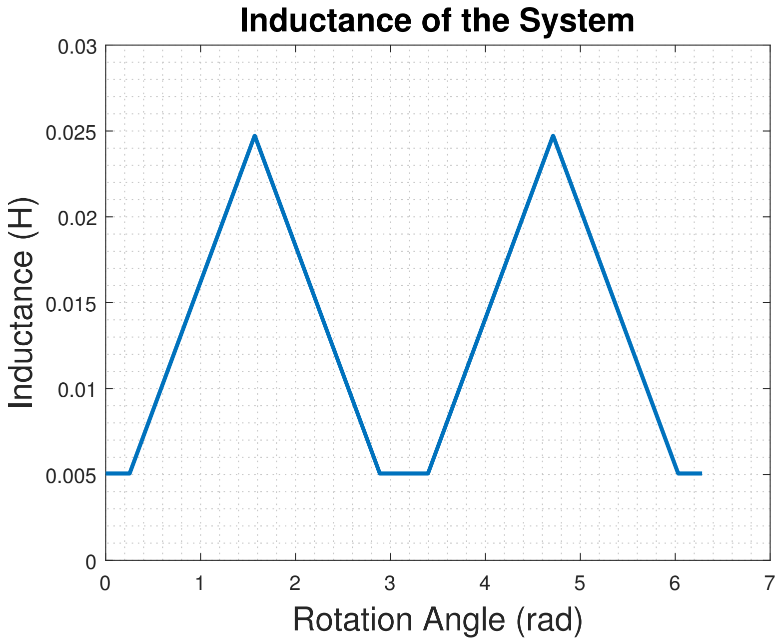
```
rot_angle = linspace(0,pi,1000);
Reluctance = zeros(1,length(rot_angle));

for i=1:length(rot_angle)
    t = rot_angle(i);
    if(t<=alpha)
        Reluctance(i) = Rel_min(0);
    end
    if(t>alpha && t<=pi/2)
        Reluctance(i) = Rel_rise(t);
    end
    if (t>pi/2 && t<=(pi-alpha))
        Reluctance(i) = Rel_fall(t);
    end
    if (t>(pi-alpha) && t<=(pi))
        Reluctance(i) = Rel_min(0);
    end

end

rot = linspace(0,2*pi,2000);
Rel_full_rot = [Reluctance,Reluctance];


figure;
plot(rot,Rel_full_rot,'LineWidth',2);
grid minor;
xlabel('Rotation Angle (rad)','FontSize',16);
ylabel('Reluctance (1/H)','FontSize',16);
ylim([0 5e7]);
title('Reluctance of the System','FontSize',16);
saveas(gcf,'Reluctance_analytical','epsc');
```



PLOT THE INDUCTANCE

```
rot_angle = linspace(0,pi,1000);
Inductance = zeros(1,length(rot_angle));

for i=1:length(rot_angle)
    t = rot_angle(i);
    if(t<=alpha)
        Inductance(i) = L_min(0);
    end
    if(t>alpha && t<=pi/2)
        Inductance(i) = L_rise(t);
    end
    if (t>pi/2 && t<=(pi-alpha))
        Inductance(i) = L_fall(t);
    end
    if (t>(pi-alpha) && t<=(pi))
        Inductance(i) = L_min(0);
    end

end

rot = linspace(0,2*pi,2000);
Ind_full_rot = [Inductance,Inductance];


figure;
plot(rot,Ind_full_rot,'LineWidth',2);
grid minor;
```

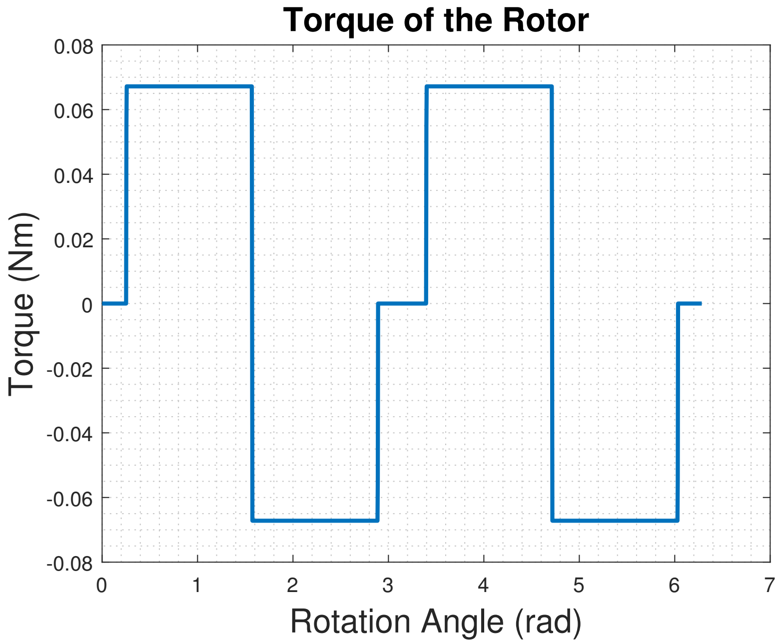
```
xlabel('Rotation Angle (rad)','FontSize',16);
ylabel('Inductance (H)','FontSize',16);
ylim([0 0.03]);
title('Inductance of the System','FontSize',16);
saveas(gcf,'inductance_analytical','epsc');
```



TORQUE CALCULATION

$T = \frac{1}{2} \cdot I^2 \cdot \frac{dL(\theta)}{d\theta}$

```
Torque_full_rot = zeros(size(Ind_full_rot));

for i = 1:length(Torque_full_rot)-1
    Torque_full_rot(i+1) = (Ind_full_rot(i+1)-Ind_full_rot(i))/(rot(i+1)-rot(i));
end

Torque_full_rot = Torque_full_rot*I^2/2;

figure;
plot(rot,Torque_full_rot,'LineWidth',2);
grid minor;
xlabel('Rotation Angle (rad)','FontSize',16);
ylabel('Torque (Nm)','FontSize',16);
% ylim([0 0.03]);
title('Torque of the Rotor','FontSize',16);
saveas(gcf,'torque_analytical','epsc');
```


Torque of the Rotor
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
Torque (Nm)
0
1
2
3
4
5
6
7
Rotation Angle (rad)