Project Report

Electrical Machines - Implementation of Modified Winding Function Theory in Synchronous Machines



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02/04/2022



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Data: Synchronous matan, Poles - P-4, Power - 475KW, 480V, 0.8 P.F. 48 Slots, 1=233.05mm, Y=422.656 mm, 9=2.54 mm, N=108 NS=3 thms/coil, Rs=0.1592 R RT=3632 R Slots Per Pole per phase = Total number of Slots = 49 = 1 Noof Poles X Phase = 41 X 3 Pole Pitch= \$\frac{4}{2}\land x \tau 180° = 60° Pole -1 4 ct cj			WII	10,6	UIII	MLI																											
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2) Fourier series of winding function (ND) Slot Pitch = 49 360 - 7.5 => 15° electrical.

Fourier Series Furmyla

The airgap flux setup by the 3 of stator winding carrying sinhusoidal currents.

The waveshape is non sinusoidal in nature-According to Fourier series analysis, any wave non-sinusoidal flux is equivalent to the number of sinusoidal flux es of fundamental and higher onder harmonics.

-) state the flux wave shafe have half wave symments, all even harmonics are absent in the Fourter series

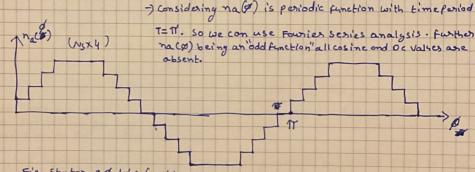


Fig- Stator ad tubs function

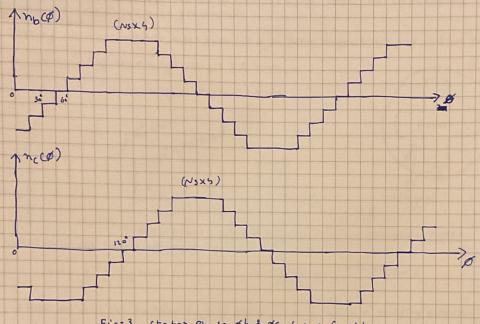
- -) so, it takes 24 slot's to complete 1 complete mechanical notation.
- -) The Fourier series for nacp) (on be written as follows considering each SEE Step as 15. ic., as by sin (T)

where $\frac{\pi}{n}$ $\int_{-\pi}^{\pi} \left(\int_{0}^{\pi} 1 \sin(2ht) dt + \int_{0}^{\pi} 2 \sin(2ht) dt + \int_{0}^{\pi} 3 \sin(2ht) dt$

-- 5 20 (-3) Sin (2nt) dt + 5 (-1) Sin (2nt) dt + 5 (-1) Sin (2nt) dt)

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> similarly, phase of and of turns function are same as of a except that they are shirted by 60° and 120° mechanical respectively.



- Fig-3 stator phase \$6 & pc turns function
- -) we can't use the Fourier series formula to generate the turn function similar to for pb and gc i.e.s nb (p) and nc (p), we must consider the Phase Shift and Provide the limits accordingly-
- -) So, we implement mathematical process using matlab to geneate plots to find the connectness of the winding function.
- -) For na (d), nb(d), nc(d) we use only sin component of Founier series

1.e., E by sin (*x(2#))

T

T

LIP(1)

T

LIP(1)

T

LIP(1)

L

where by for na(q) is = = (Sisin(2nt) dt + Sisin(2nt) dt + ---

by shifting nalp) by 60° and 120° mech 120° me

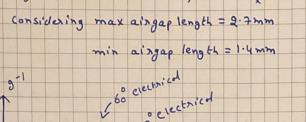
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- 3) Generate Inverse Augus function 9-1 (\$, 8m)
 - -) Airgap is the space blw the Stator and the notor. Where the RMF (Rotating magnatic field) can robe generated.
 - -) Being it's a salient pole notor, there is a uniform magnatiair gap in time period.

Staton

Roton



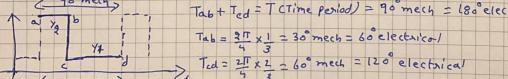
ain gaps

Dm=Do Fig:- Invesse ain gap function in case of Symmetric noton.

calculation for Inverse airgap $g^{-1} = \frac{1}{1.4} \times 1000 = 714.2$, min $g^{-1} = \frac{1}{2.7} \times 1000 = 370.3$

- -) here we consider am rotor position angle as a Bo initial or starting notor position
- -) Using the Fourier series we can generate the airgap function. since it is not an even add function the add harmonics are absent it., to sincterm is zero. So we consider only fundmental component as and obsine component an'.

- -) In the air gap function the squore wave represent's the Hair gap length bluthe stator and the rotor. P.
- -7 The complete time period for one pole out to take 90 mechanical is 180 electrical



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an =
$$\frac{9}{7}$$
 $\int_{0}^{t_{0}+7} f(t) \cdot \cos\left(\frac{2\pi nt}{r}\right) dt$ where $n = 0, 1, 2, 3 - \cdots$

$$= \frac{9}{7} \int_{0}^{\pi/L} \gamma_{L} \cos\left(2n\frac{L}{r}\right) dt + \int_{\pi/L}^{\pi/3} \gamma_{L} \cos\left(2n\frac{L}{r}\right) dt + \int_{\pi/L}^{\pi/2} \gamma_{L} \cos\left(2n\frac{L}{r}\right) dt + \int_{\pi/L}^{\pi/3} \gamma_{L} \cos\left(2n\frac{L}{r}\right) dt + \int_{\pi/L}^{\pi/2} \gamma_{L} \sin\left(2n\frac{L}{r}\right) dt + \int_{\pi/L}^{\pi/2} \gamma_{L} \sin\left(2n\frac{L}{r}\right) dt + \int_{\pi/L}^{\pi/2} \gamma_{L} \sin\left(2n\frac{L$$

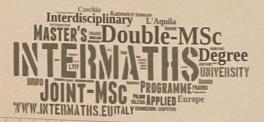
$$= \frac{1}{n\pi} \left(\gamma_{1} \left(\sin \frac{2n\pi}{5} - 0 \right) + \left(\sin \frac{4n\pi}{3} - \sin \frac{2n\pi}{3} \right) + \left(\sin \frac{2n\pi}{3} - \sin \frac{5n\pi}{3} \right) \right)$$

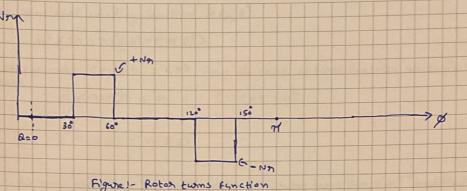
$$+ \gamma_{2} \left[\left(\sin \frac{2n\pi}{3} \pi - \sin \frac{n\pi}{3} \right) + \left(\sin \frac{5n\pi}{3} - \sin \frac{4n\pi}{3} \right) \right]$$

-) The plots for the gilld is generated by using the matlab. The values of as & an are used for the math-

4) Roton Turns Function (NA)

- -) The noton turns function can be found similar to that of Statons turn function
- -) Rotor turns function in is a periodic function with time periodit
- -) So, we can use the Fourier series analysis. Further N's being an "odd fraction" all the "cas" and the "De" values are ignored.





-) so, The Fourier series used for the " At" can be written as follows

$$f(\phi) = \sum_{n=1}^{\infty} b_n \sin\left(\frac{2\pi n}{\tau}\right)$$

$$b_n = \sum_{t=1}^{\infty} \int_{t_0}^{t_0+T} f(\phi) \cdot \sin\left(\frac{2\pi n}{\tau}\right) dt \quad \text{where } n = 1,2,3,----$$

$$\vdots \quad b_n = \sum_{t=1}^{\infty} \int_{\pi/\delta}^{\pi/\delta} (N_n) \sin\left(\frac{2\pi n}{\delta}\right) + \int_{0}^{\infty} (-N_n) \sin\left(\frac{2\pi n}{\delta}\right)$$

$$= \sum_{t=1}^{\infty} \int_{\pi/\delta}^{\pi/\delta} (N_n) \sin\left(\frac{2\pi n}{\delta}\right) + \cos\left(\frac{2\pi n}{\delta}\right) + \cos\left(\frac{5\pi n}{\delta}\right) - \cos\left(\frac{5\pi n}{\delta}\right)$$

$$= \sum_{t=1}^{\infty} \int_{\pi/\delta}^{\pi/\delta} (N_n) \sin\left(\frac{2\pi n}{\delta}\right) + \cos\left(\frac{5\pi n}{\delta}\right) - \cos\left(\frac{5\pi n}{\delta}\right) - \cos\left(\frac{5\pi n}{\delta}\right) = \cos\left(\frac{5\pi n}{\delta}\right)$$

calculations of self-inductance and mutual inductance

- In order to get the self-inductance and mutual be require the information of Stator turns function, inverse airgap function and modified winding function.
- -) We already have the stator turns function and air gap function from the above information. We now need to get the modified winding function.
- -) In the paper it is been mentioned that for the air gap with only "even harmonics", the modified winding function can be represented as

where can is the de value of the tunns function.

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-) so modified winding function M(\$,0)

m(\$0) = n(\$0) - 2m(0) >

to In our case < mco> = < m> i.e., de value of turns function which is equal

: < mc@>> = 0 (: < n> = 0)

-) M(\$0) = n(\$0)

-) so, as now we have the information of "stator turns function", "modified winding function" & "inverse airgap function". We can get the

self inductance by using

LAA = HOYL Sma(\$,0) MA(\$,0) g'(\$,0) d\$

mutual inductore by using

LBA = ABA = hort 5 no (x 0) Ma(x 0) o (x 0) dx

Similarly we can get the info of LBB Lee & LEA, LBC.

Matlab Plots

Figure 1- Stator Turns Function for Phase A, Phase B and Phase C The Highest Harmonic Order N = 5.

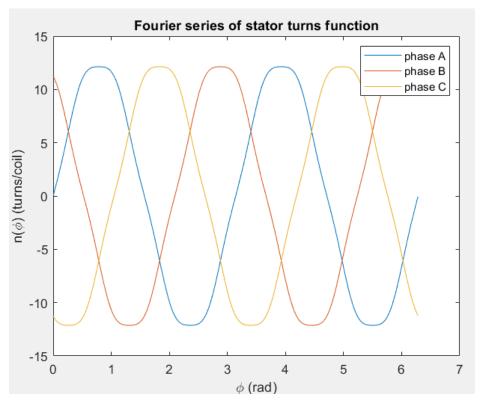


Figure 2- Inverse Air Gap Function The Highest Harmonic Order N = 2.

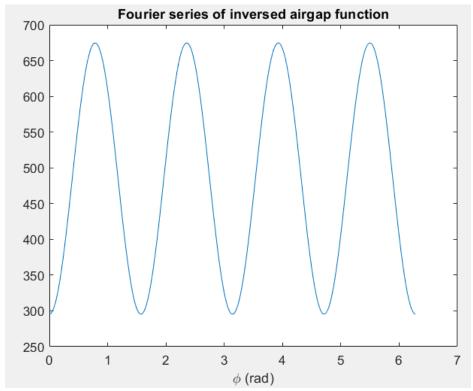


Figure 3- Rotor Turns Function
The Highest Harmonic Order N = 4.

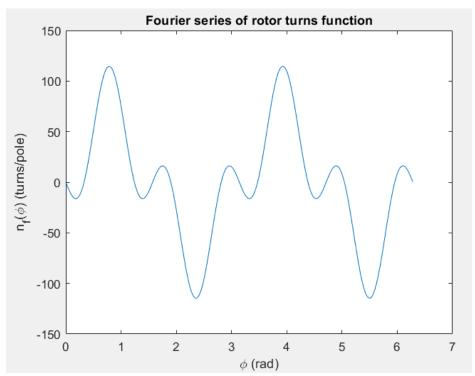


Figure 4- Self -Inductance

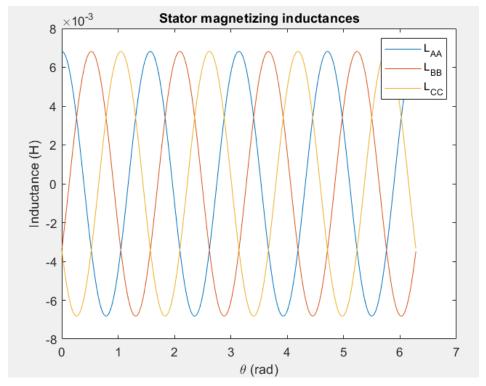
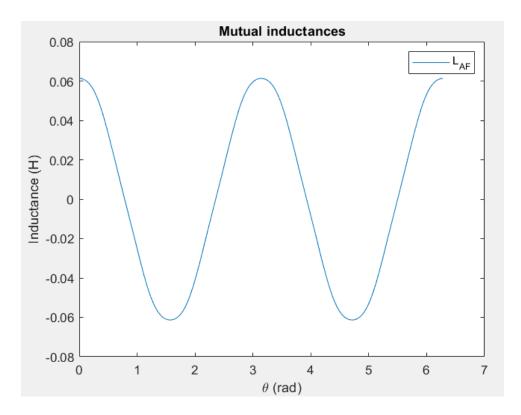


Figure 4- Mutual -Inductance LAF



Appendix - Matlab Scripts

Code - Stator Turns Function

```
% Fourier series of Stator turns function % S_slots = 48; intv = 2*pi/S_slots; % mechanical angle of each slot

Ns = 3; % unit: turns per coil
T = pi; % here we consider the time period of n_A is pi.
N = 5; % the highest harmonic order

for i=1:N
% coefficient b_n of sin components %
bi = intg_sin2nfa(0,intv,i)+ 2*intg_sin2nfa(intv,2*intv,i)+ 3*intg_sin2nfa(2*intv,3*intv,i)+...
4*intg_sin2nfa(3*intv,8*intv,i)+...
3*intg_sin2nfa(8*intv,9*intv,i)+ 2*intg_sin2nfa(9*intv,10*intv,i)+ intg_sin2nfa(10*intv,11*intv,i)+...
(-1)*intg_sin2nfa(12*intv,13*intv,i)+ (-2)*intg_sin2nfa(13*intv,14*intv,i)+
(-3)*intg_sin2nfa(14*intv,15*intv,i)+...
(-4)*intg_sin2nfa(20*intv,21*intv,i)+ (-2)*intg_sin2nfa(21*intv,22*intv,i)+
```

```
(-1)*intg_sin2nfa(22*intv,23*intv,i);
  nA_b(i) = Ns*2*bi/T;
  % elimination of calculation error %
    if (abs(nA_b(i))-1e-10 < 0)
%
       nA_b(i) = 0;
%
     end
end
fa=0:0.01:2*pi; % mechanical angle in stationary frame (stator)
fs_na = zeros(size(fa)); % request memory
fs_nb = zeros(size(fa));
fs_nc = zeros(size(fa));
syms phi;
F_fsna = 0;
F_fsnb = 0;
F_fsnc = 0;
for i=1:N
  fs_na = fs_na + nA_b(i)*sin(2*pi*i*fa/T); % phase A
  fs_nb = fs_nb + nA_b(i)*sin(2*pi*i*(fa-2*pi/3)/T); % phase B
  fs_nc = fs_nc + nA_b(i)*sin(2*pi*i*(fa+2*pi/3)/T); % phase C
  F_fsna = F_fsna+nA_b(i)*sin(2*pi*i*phi/T); % symbolic function of this Fourier series
  F_{fsnb} = F_{fsnb} + nA_{b(i)} * sin(2*pi*i*(phi-2*pi/3)/T);
  F_fsnc = F_fsnc + nA_b(i)*sin(2*pi*i*(phi+2*pi/3)/T);
end
figure()
plot(fa,fs_na,fa,fs_nb,fa,fs_nc)
xlabel('\phi (rad)')
ylabel('n(\phi) (turns/coil)')
title('Fourier series of stator turns function')
legend('phase A', 'phase B', 'phase C')
```

Code - Inverse Air Gap Function

```
% Fourier series of inversed air gap function g^-1 y1 = 1000/2.7; % minimum value y2 = 1000/1.4; % maximum value alpha0 = 1/2*(4/3*y1+2/3*y2); % DC value in Fourier series

N = 2; % the highest harmonic order

for i=1:N
% coefficient a_n of cos components %
ivg_a(i) = 1/i/pi*(y1*(sin(2*i*pi/6)+sin(4*i*pi/3)-sin(2*i*pi/3)-sin(5*i*pi/3))...
+y2*(sin(2*i*pi/3)-sin(i*pi/3)+sin(5*i*pi/3)-sin(4*i*pi/3)));
end

fa = 0:0.01:2*pi; % mechanical angle in stationary frame (stator)
fs_ivg = alpha0*ones(size(fa)); % request memory and initialization

F_fsivg = 0;
syms theta; % rotor position
```

```
for i=1:N
    fs_ivg = fs_ivg + ivg_a(i)*cos(2*i*fa);
    F_fsivg = F_fsivg + ivg_a(i)*cos(2*i*(phi-theta));
end

figure()
plot(fa,fs_ivg)
xlabel("\phi (rad)")
title("Fourier series of inverse air gap function")
)
```

Code - Rotor Turns Function

```
% Calculate the Fourier series of Turns function n f
Nr = 108; % unit: turns/pole
N = 4; % the highest harmonic order
for i=1:N
  % coefficient b_n of sin components %
  nf_b(i) = Nr/\rho i/i*(cos(i*\rho i/3)-cos(2*i*\rho i/3)+cos(5*i*\rho i/3)-cos(4*i*\rho i/3));
end
fa = 0:0.01:2*pi; % mechanical angle in stationary frame (stator)
fs_nf = zeros(size(fa)); % request memory
F_fsnf = 0;
syms theta; % rotor position
for i=1:N
  fs_nf = fs_nf + nf_b(i)*sin(2*i*fa);
  F_f snf = F_f snf + nf_b(i) sin(2*i*(phi-theta));
end
figure()
plot(fa,fs_nf)
xlabel('\phi (rad)')
ylabel('n_f(\phi) (turns/pole)')
title('Fourier series of rotor turns function')
```

Code - Self and Mutual Inductances

```
mu0 = 4*pi*(1e-7); % permeability of vacuum
r = 422.656*(1e-3);
L = 273.05*(1e-3);
fcna = F_fsna*F_fsna*F_fsivg; % n_A*M_A*g^-1
fcnb = F_fsnb*F_fsnb*F_fsivg;
fcnc = F_fsnc*F_fsnc*F_fsivg;
```

```
fcnaf = F_fsnf*F_fsna*F_fsiva; % n_f*M_A*a^-1
fcnbf = F_fsnf*F_fsnb*F_fsivg;
fcncf = F_fsnf*F_fsnc*F_fsivg;
syms LAA(theta) LBB(theta) LCC(theta)
syms LAF(theta) LBF(theta) LCF(theta)
LAA(theta) = mu0*r*L*(int(fcna,phi,[0 2*pi])); % [lower bound, upper bound]
LBB(theta) = mu0*r*L*(int(fcnb,phi,[0 2*pi]));
LCC(theta) = mu0*r*L*(int(fcnc,phi,[0 2*pi]));
LAF(theta) = mu0*r*L*(int(fcnaf,phi,[0 2*pi]));
LBF(theta) = mu0*r*L*(int(fcnbf,phi,[0 2*pi]));
LCF(theta) = mu0*r*L*(int(fcncf,phi,[0 2*pi]));
% numerically approximate the integral by using vpa
LAA(theta) = vpa(LAA(theta));
LBB(theta) = vpa(LBB(theta));
LCC(theta) = vpa(LCC(theta));
LAF(theta) = vpa(LAF(theta));
LBF(theta) = vpa(LBF(theta));
LCF(theta) = vpa(LCF(theta));
figure()
plot(fa,LAA(fa),fa,LBB(fa),fa,LCC(fa))
xlabel("\theta (rad)")
ylabel('Inductance'(H)')
title('Stator magnetizing inductances')
legend('L_A_A','L_B_B','L_C_C')
figure()
plot(fa,LAF(fa),fa,LBF(fa),fa,LCF(fa))
xlabel("\theta (rad)")
ylabel('Inductance (H)')
title('Mutual inductances')
legend('L_A_F','L_B_F','L_C_F')
```