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EE362 HW#1

NAME: *SOLUTION*

STUDENT NUMBER: 123456

Q.1)

```
% PART A
```

a) Pole number is 2 (see figure).

```
pole = 2;
```

b) There are a total of 30 slots in one layer.

```
slot_number = 30;
```

c) Electrical angle of one slot is: $slot - angle = 2\pi/slot - number = \pi/15$

```
slot_angle = 2*pi/slot_number;
```

d) Phase belt angle is the electrical angle for one pole of one phase $Phase - belt = 2\pi/2pole/3phase = pi/3$

```
phase = 3;
phase_belt = 2*pi/(pole*phase);
```

e) Number of slots per phase per pole is: $q = slot - number/pole/phase = 5$

```
q = slot_number/(phase*pole);
```

f) Coil span is the angle spanning one coil: $\lambda = 12\pi/15 = 4\pi/5$

```
coil_span = pi*4/5;
```

g) Total number of series turns per phase: $N_{ph} = turn - in - one - coilxlayerxslot - number$

$$N_{ph} = 8x2x5 = 80$$

```
conductor = 8;
layer = 2;
Nph = q*conductor*layer*(pole/2);
```

h) Distribution factor: $k_d = 0.9567$

```
kd = sin(q*slot_angle/2)/(q*sin(slot_angle/2));
```

i) Pitch factor: $k_c = 0.9511$

```
kc = sin(coil_span/2);
```

j) Winding factor: $k_w = 0.91$

```
kw = kd*kc;
```

k) Mechanical speed of the air gap MMF: Nr = 3000 rpm

```
frequency = 50;
Nr = 120*frequency/pole;
```

PART B

Parts a, b, c, d)

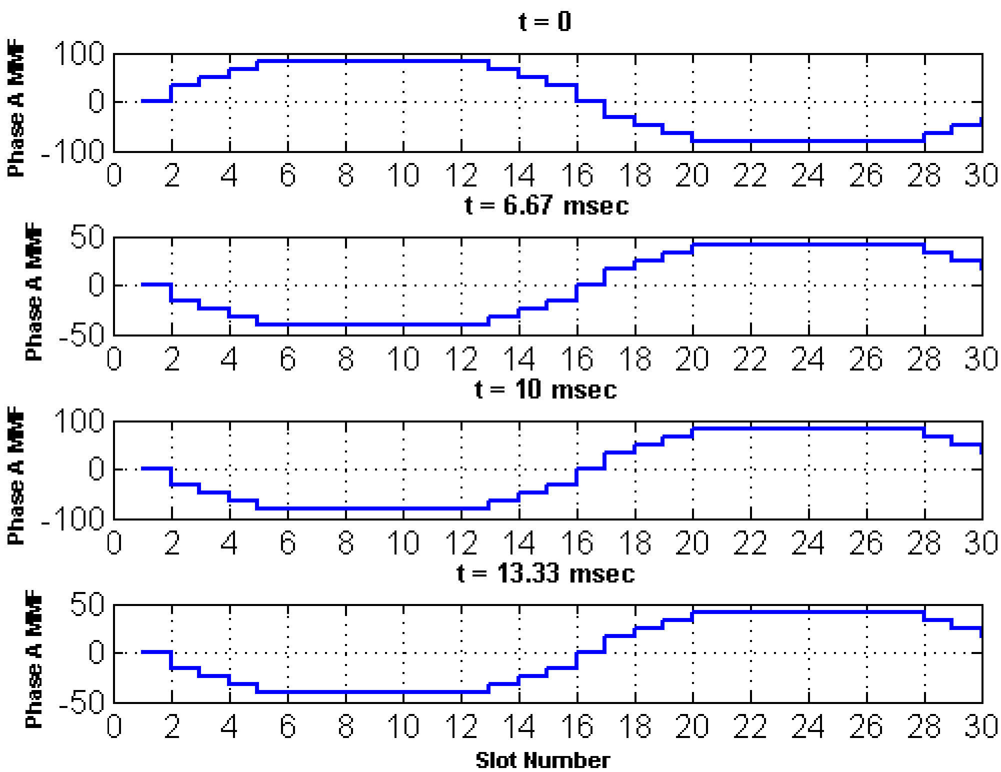
```
peak_current = 2; % Amps

parts = 4;

% Define MMF components
mmfa = zeros(parts,slot_number);
mmfb = zeros(parts,slot_number);
mmfc = zeros(parts,slot_number);
mmftotal = zeros(parts,slot_number);

% Time array is the time instants at which MMF will be calculated
time_array = [0,6.67e-3,10e-3,13.33e-3];

for l = 1:parts

    % Define the time according the index l
    time = time_array(l);

    % Calculate the phase currents at that time instant
    Ia = peak_current*cos(2*pi*frequency*time);
    Ib = peak_current*cos(2*pi*50*time-2*pi/3);
    Ic = peak_current*cos(2*pi*50*time-4*pi/3);

    MMFa_layer1 = conductor*[Ia,Ia,Ia,Ia,Ia,0,0,0,0,0,0,0,0,0,0,-Ia,-Ia,...
        -Ia,-Ia,-Ia,0,0,0,0,0,0,0,0,0,0];
    MMFa_layer2 = conductor*[Ia,Ia,0,0,0,0,0,0,0,0,0,0,-Ia,-Ia,-Ia,-Ia,...
        -Ia,0,0,0,0,0,0,0,0,0,0,Ia,Ia,Ia];

    MMFb_layer1 = conductor*[0,0,0,0,0,0,0,0,0,0,Ib,Ib,Ib,Ib,Ib,0,0,0,0,0,...
        0,0,0,0,0,-Ib,-Ib,-Ib,-Ib,-Ib];
    MMFb_layer2 = conductor*[0,0,0,0,0,0,0,Ib,Ib,Ib,Ib,Ib,0,0,0,0,0,0,0,0,...
        0,0,-Ib,-Ib,-Ib,-Ib,-Ib,0,0,0];

    MMFc_layer1 = conductor*[0,0,0,0,0,-Ic,-Ic,-Ic,-Ic,-Ic,0,0,0,0,0,0,0,0,...
        0,0,0,Ic,Ic,Ic,Ic,Ic,0,0,0,0,0];
```

```
    MMFc_layer2 = conductor*[0,0,-Ic,-Ic,-Ic,-Ic,-Ic,0,0,0,0,0,0,0,0,0,0,...
        Ic,Ic,Ic,Ic,Ic,0,0,0,0,0,0,0,0];

    for k = 1:slot_number
        mmfa(l,k) = sum(MMFa_layer1(1:k))+sum(MMFa_layer2(1:k));
        mmfb(l,k) = sum(MMFb_layer1(1:k))+sum(MMFb_layer2(1:k));
        mmfc(l,k) = sum(MMFc_layer1(1:k))+sum(MMFc_layer2(1:k));
    end

    % To get rid of the offset on the MMF waveforms, use the following
    % routine for each phase MMF
    average = sum(mmfa(l,:))/slot_number;
    mmfa(l,:) = mmfa(l,:)-average;
    average = sum(mmfb(l,:))/slot_number;
    mmfb(l,:) = mmfb(l,:)-average;
    average = sum(mmfc(l,:))/slot_number;
    mmfc(l,:) = mmfc(l,:)-average;

    mmftotal(l,:) = mmfa(l,:)+mmfb(l,:)+mmfc(l,:);

end
```

Part e)

```
subplot(4,1,1)
stairs(mmfa(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')

subplot(4,1,2)
stairs(mmfa(2,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 6.67 msec','FontSize',10,'FontWeight','Bold')

subplot(4,1,3)
stairs(mmfa(3,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 10 msec','FontSize',10,'FontWeight','Bold')

subplot(4,1,4)
stairs(mmfa(4,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
xlabel('Slot Number','FontSize',8,'FontWeight','Bold');
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
```

```
set(gca,'xtick',[0:2:30]);
title('t = 13.33 msec','FontSize',10,'FontWeight','Bold')
```

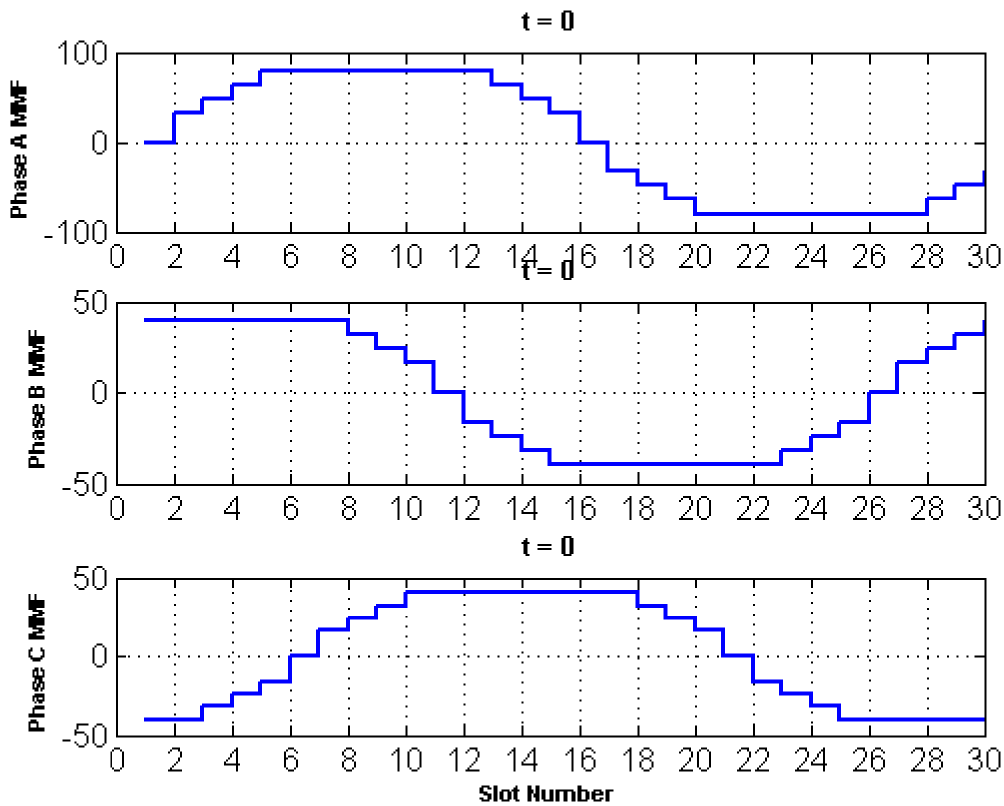


Since the MMF is due to phase-A (1 phase), it is pulsating over time. We can observe that the maximum peak-to-peak is obtained at "t=0" which is the instant where phase-A current is maximum. We can also observe that at "t = 10msec" which is the half period for a 50 Hz voltage, the waveform is completely reversed.

Parf f)

```
subplot(3,1,1)
stairs(mmfa(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')


subplot(3,1,2)
stairs(mmfb(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase B MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')
```

```
subplot(3,1,3)
stairs(mmfc(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase C MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')
xlabel('Slot Number','FontSize',8,'FontWeight','Bold');
```

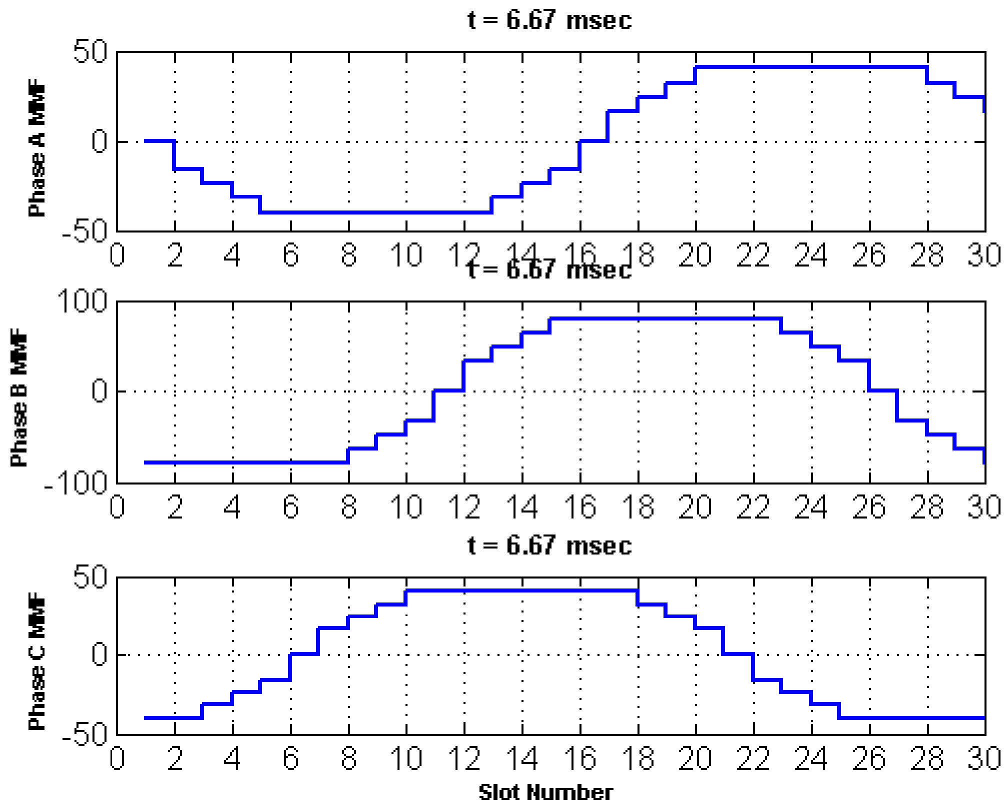


At "t=0", phase A current is maximum which can also be observed on the MMF waveforms of each phase. Phase-B and Phase-C MMF's are at their negative half-cycles with half of the peak-to-peak value compared to Phase-A MMF.

Parf g)

```
subplot(3,1,1)
stairs(mmfa(2,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 6.67 msec','FontSize',10,'FontWeight','Bold')

subplot(3,1,2)
stairs(mmfb(2,:),'b- ','Linewidth',1.5)
grid on;
```

```
set(gca,'FontSize',12);
ylabel('Phase B MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 6.67 msec','FontSize',10,'FontWeight','Bold')

subplot(3,1,3)
stairs(mmfc(2,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase C MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 6.67 msec','FontSize',10,'FontWeight','Bold')
xlabel('Slot Number','FontSize',8,'FontWeight','Bold');
```

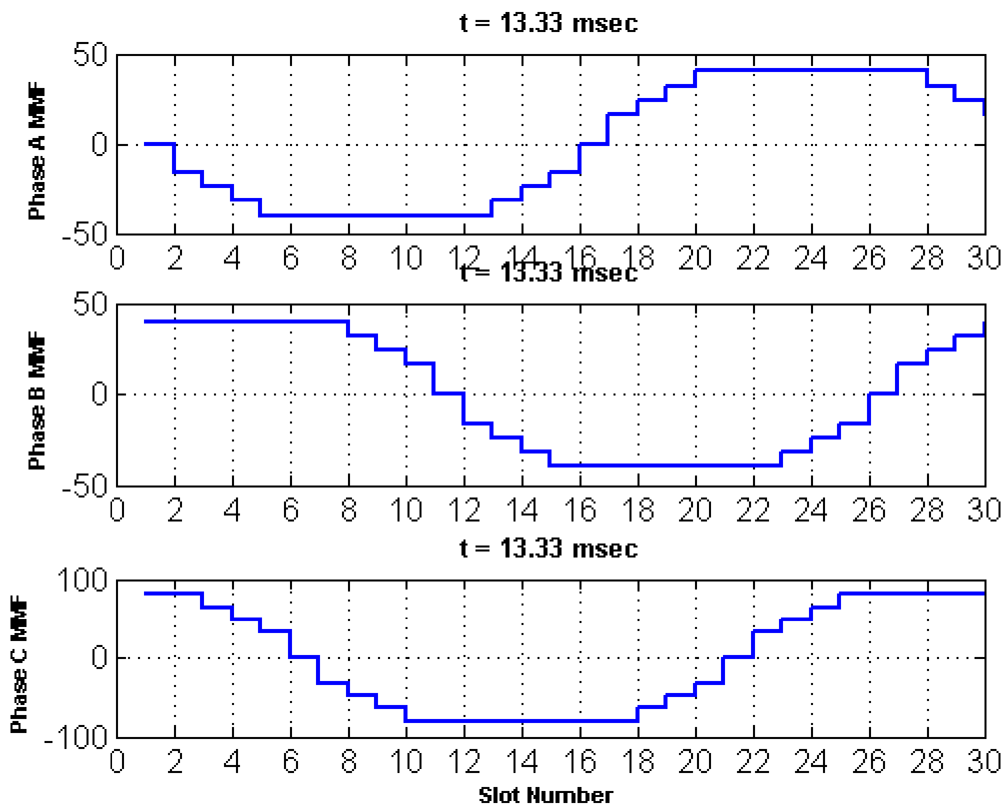


At "t=6.67msec", phase B current is maximum and its MMF waveform has its maximum peak-to-peak value. Phase-A and Phase-C MMF's are at their negative half-cycles this time, with half of the peak-to-peak value compared to Phase-B MMF.

Parf h)

```
subplot(3,1,1)
stairs(mmfa(4,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 13.33 msec','FontSize',10,'FontWeight','Bold')
```

```
subplot(3,1,2)
stairs(mmfb(4,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase B MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 13.33 msec','FontSize',10,'FontWeight','Bold')

subplot(3,1,3)
stairs(mmfc(4,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase C MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 13.33 msec','FontSize',10,'FontWeight','Bold')
xlabel('Slot Number','FontSize',8,'FontWeight','Bold');
```

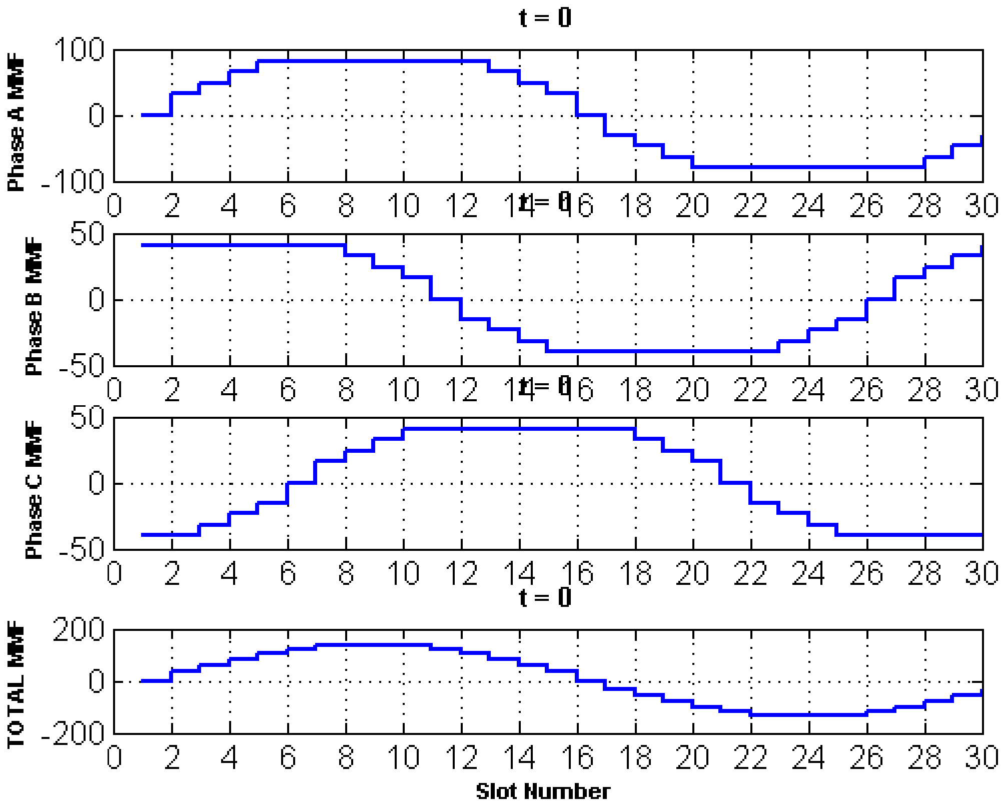


The situation is very similar to the previous cases, only Phase-C MMF is at its maximum at "t=13.33 msec" as expected.

Parf i)

```
subplot(4,1,1)
stairs(mmfa(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
```

```
ylabel('Phase A MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')

subplot(4,1,2)
stairs(mmfb(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase B MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')

subplot(4,1,3)
stairs(mmfc(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('Phase C MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')

subplot(4,1,4)
stairs(mmftotal(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('TOTAL MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold')
xlabel('Slot Number','FontSize',8,'FontWeight','Bold');
```

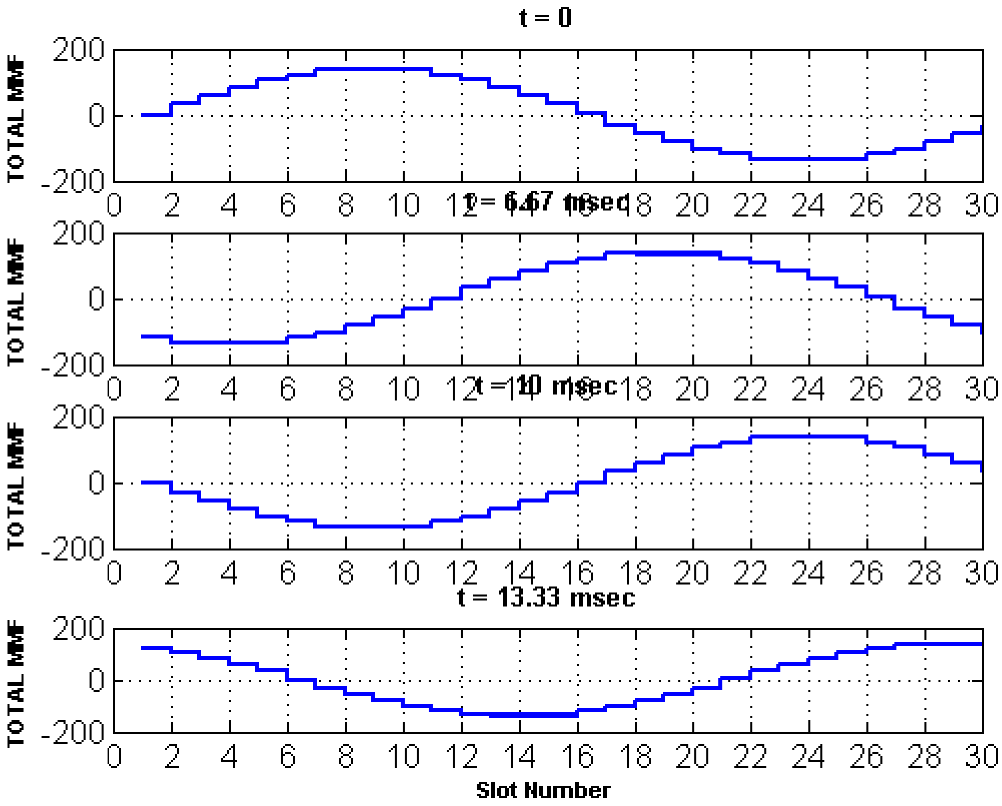


Here, it is observed that at each instant (say "t=0"), sum of the three MMF waveforms of individual phases (the resultant or the total MMF) is a near-sinusoidal waveform with a better shape and peak-value 3/2 times the peak value of phase-A.

Parf j)

```
subplot(4,1,1)
stairs(mmftotal(1,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('TOTAL MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 0','FontSize',10,'FontWeight','Bold');

subplot(4,1,2)
stairs(mmftotal(2,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('TOTAL MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 6.67 msec','FontSize',10,'FontWeight','Bold');

subplot(4,1,3)
stairs(mmftotal(3,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('TOTAL MMF','FontSize',8,'FontWeight','Bold');
```

```
set(gca,'xtick',[0:2:30]);
title('t = 10 msec','FontSize',10,'FontWeight','Bold');

subplot(4,1,4)
stairs(mmftotal(4,:),'b- ','Linewidth',1.5)
grid on;
set(gca,'FontSize',12);
ylabel('TOTAL MMF','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[0:2:30]);
title('t = 13.33 msec','FontSize',10,'FontWeight','Bold');
xlabel('Slot Number','FontSize',8,'FontWeight','Bold');
```



It can be observed that the resultant MMF is a rotating MMF (its phase is shifted at each time instant). The peak value does not change, which is 3/2 times the maximum peak value of the pulsating MMF waveforms. The frequency of the total MMF can also be observed as 50 Hz as the difference between positive half cycle and negative half cycle is 10 msec. This was also expected since the machine has 2 poles.

Parf k)

Phase sequence should be A-C-B

Q.2)

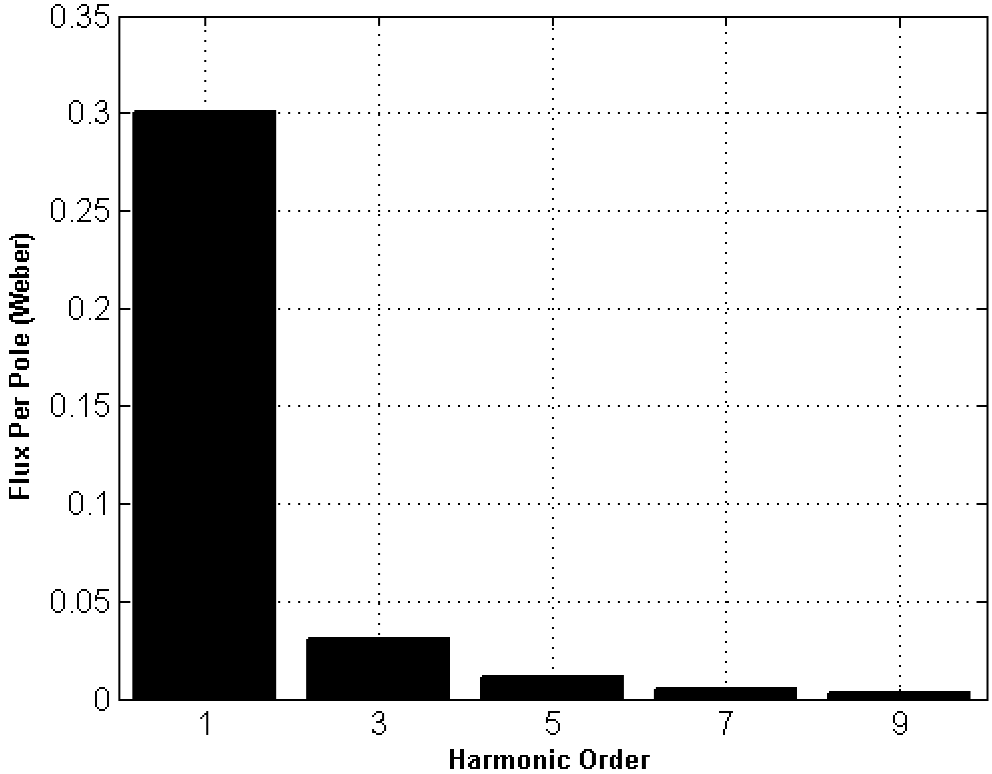
All parts)

```
% Define parameters
length = 0.5;
```

```
radius = 0.3;

flux_density = [1,0.3,0.18,0.11,0.09];

% Define harmonic order variable
harmonic = 1:2:9;

% Define variables
kd = zeros(1,numel(harmonic));
kc = zeros(1,numel(harmonic));
kw = zeros(1,numel(harmonic));
flux = zeros(1,numel(harmonic));
induced_voltage = zeros(1,numel(harmonic));

for k = 1:numel(harmonic)
    flux(k) = 4*flux_density(k)*radius*length/(pole*harmonic(k));
    frequency = 50;
    slot_angle_rad = slot_angle;
    kd(k) = sin(harmonic(k)*q*slot_angle_rad/2)/...
        (q*sin(harmonic(k)*slot_angle_rad/2));
    kc(k) = sin(harmonic(k)*coil_span/2);
    kw(k) = kc(k)*kd(k);
    induced_voltage(k) = 4.44*Nph*flux(k)*frequency*harmonic(k)*kw(k);
end
```

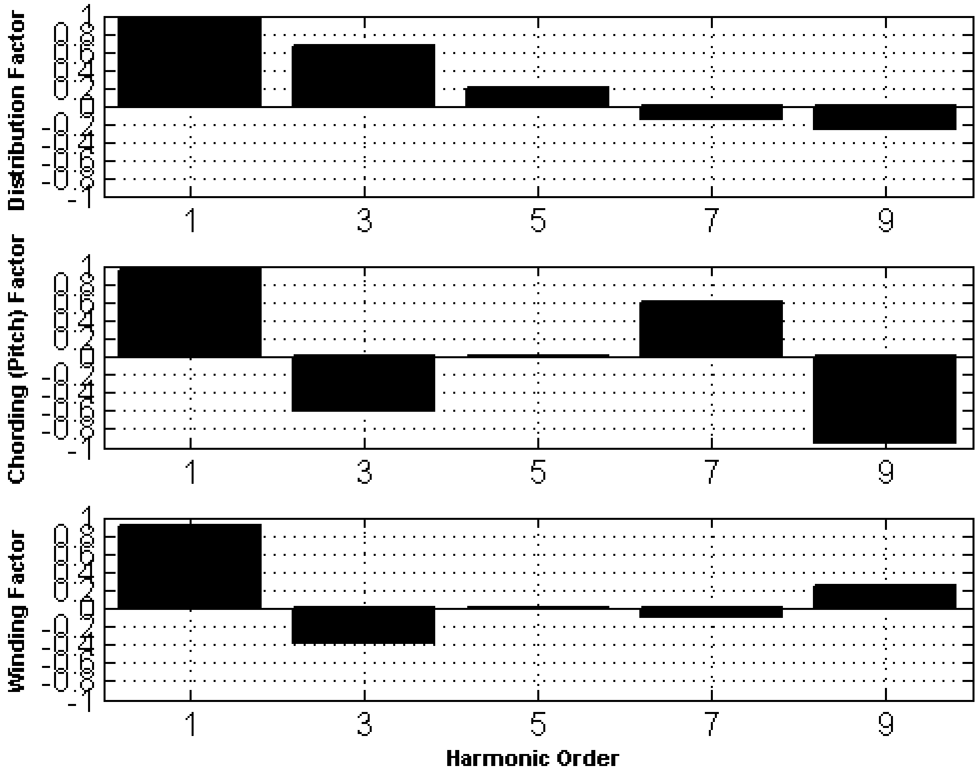
Pard a)

```
figure;
bar(harmonic,flux,'k','Linewidth',1.5);
grid on;
set(gca,'FontSize',12);
ylabel('Flux Per Pole (Weber)','FontSize',10,'FontWeight','Bold');
set(gca,'xtick',[1:2:9]);
xlabel('Harmonic Order','FontSize',10,'FontWeight','Bold');
```



Pard b)

```
figure;
subplot(3,1,1);
bar(harmonic,kd,'k','Linewidth',1.5);
grid on;
set(gca,'FontSize',12);
ylabel('Distribution Factor','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[1:2:9]);
set(gca,'ytick',[-1:0.2:1]);

subplot(3,1,2);
bar(harmonic,kc,'k','Linewidth',1.5);
grid on;
set(gca,'FontSize',12);
ylabel('Chording (Pitch) Factor','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[1:2:9]);
set(gca,'ytick',[-1:0.2:1]);

subplot(3,1,3);
bar(harmonic,kw,'k','Linewidth',1.5);
grid on;
set(gca,'FontSize',12);
ylabel('Winding Factor','FontSize',8,'FontWeight','Bold');
set(gca,'xtick',[1:2:9]);
xlabel('Harmonic Order','FontSize',8,'FontWeight','Bold');
set(gca,'ytick',[-1:0.2:1]);
```



The distribution factor decreases as the harmonic order increase, which is desired to reduce the harmonic components on the induced voltages. On the other hand, due to the utilization of distributed windings, the distribution factor for the fundamental also decreases which will result in a reduction on the fundamental voltages.

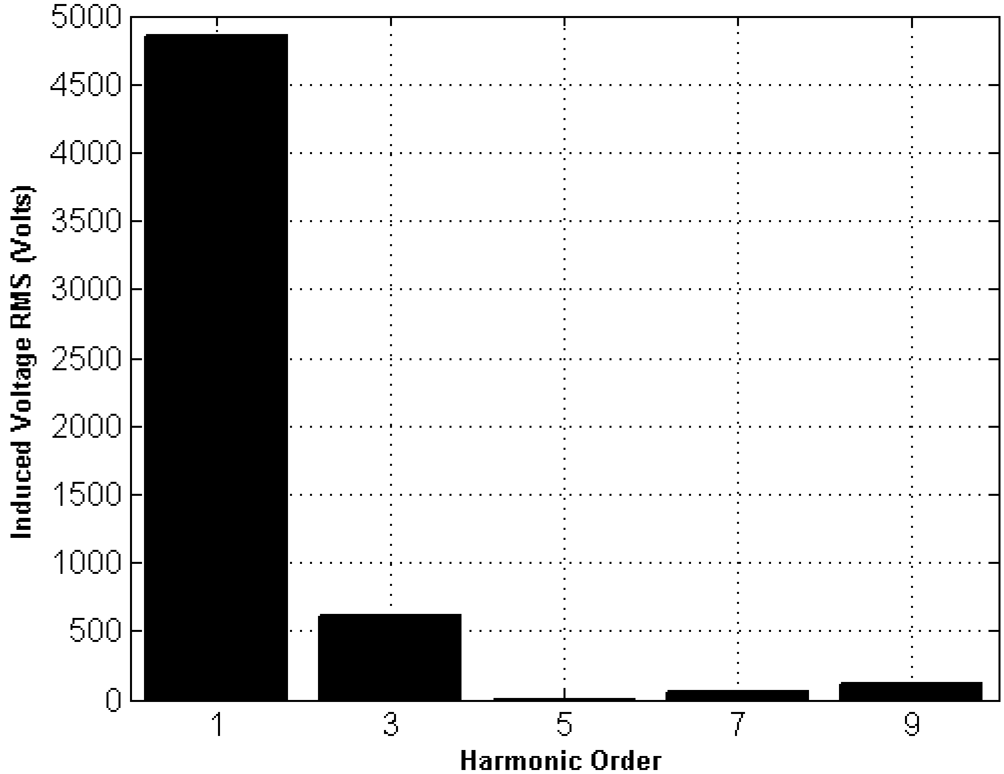
The pitch (or chording) factor is zero for the 5th harmonic as expected. It is below 1 for the fundamental component which will also contribute to the reduction on the fundamental voltages.

From the winding factor plot, it can be observed that, the 5th harmonic can completely be eliminated. Although chording factor is high for 7th and 9th harmonics, they are reduced by their distribution factor significantly. The 3rd harmonic winding factor still seems to be an issue. The fundamental component reduction on the fundamental voltages is at acceptable levels.

The negative winding factor components are expected to result in out of phase waveforms for those particular harmonics.

Pard c)

```
figure;
bar(harmonic,abs(induced_voltage),'k','Linewidth',1.5);
grid on;
set(gca,'FontSize',12);
ylabel('Induced Voltage RMS (Volts)','FontSize',10,'FontWeight','Bold');
set(gca,'xtick',[1:2:9]);
xlabel('Harmonic Order','FontSize',10,'FontWeight','Bold');
```

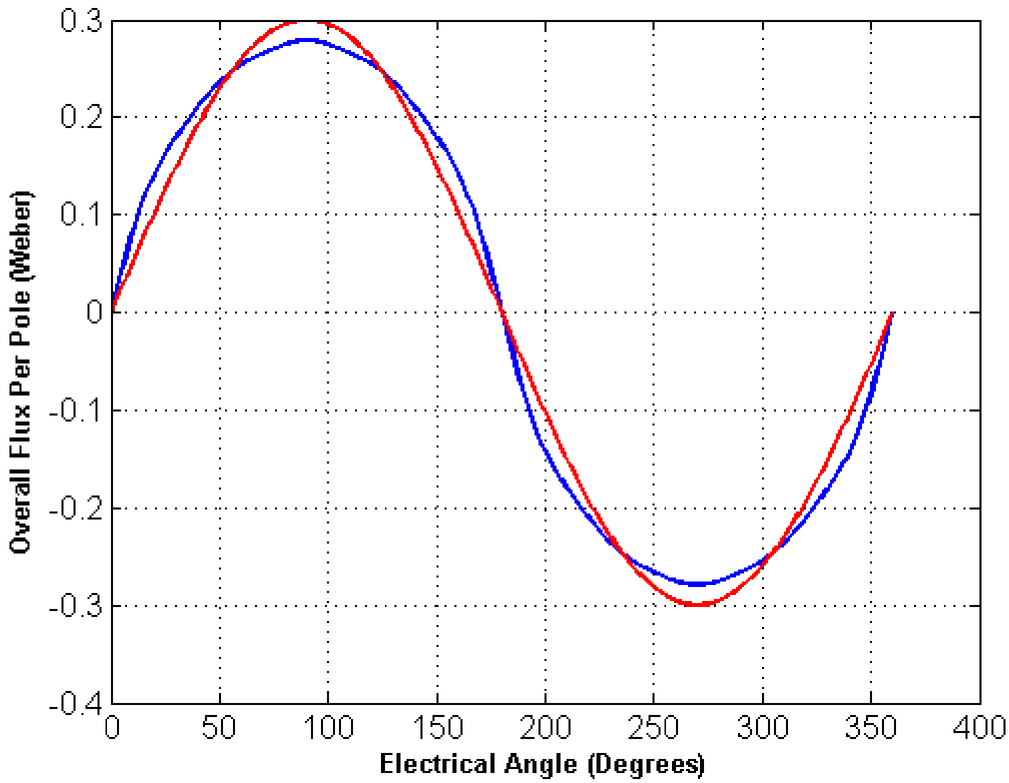


On the line-to-neutral voltages, 5th, 7th and 9th harmonic components are reduced significantly, on the other hand, 3rd harmonic component (around 13 % of the fundamental component) is still an issue to be dealt with.

Part d)

```
% Define angle array
theta = 0:pi/180:2*pi;

% Define flux for each harmonic
flux_harmonic = zeros(numel(harmonic),numel(theta));
flux_actual = zeros(1,numel(theta));

for m = 1:numel(harmonic)
    flux_function(m,:) = flux(m)*sin(harmonic(m)*theta);
end

flux_actual(1,:) = sum(flux_function(:,:));

figure;
plot(theta*180/pi,flux_actual,'b- ','Linewidth',1.5);
hold on;
plot(theta*180/pi,flux_function(1,:),'r- ','Linewidth',1.5);
hold off;
grid on;
set(gca,'FontSize',12);
ylabel('Overall Flux Per Pole (Weber)','FontSize',10,'FontWeight','Bold');
```

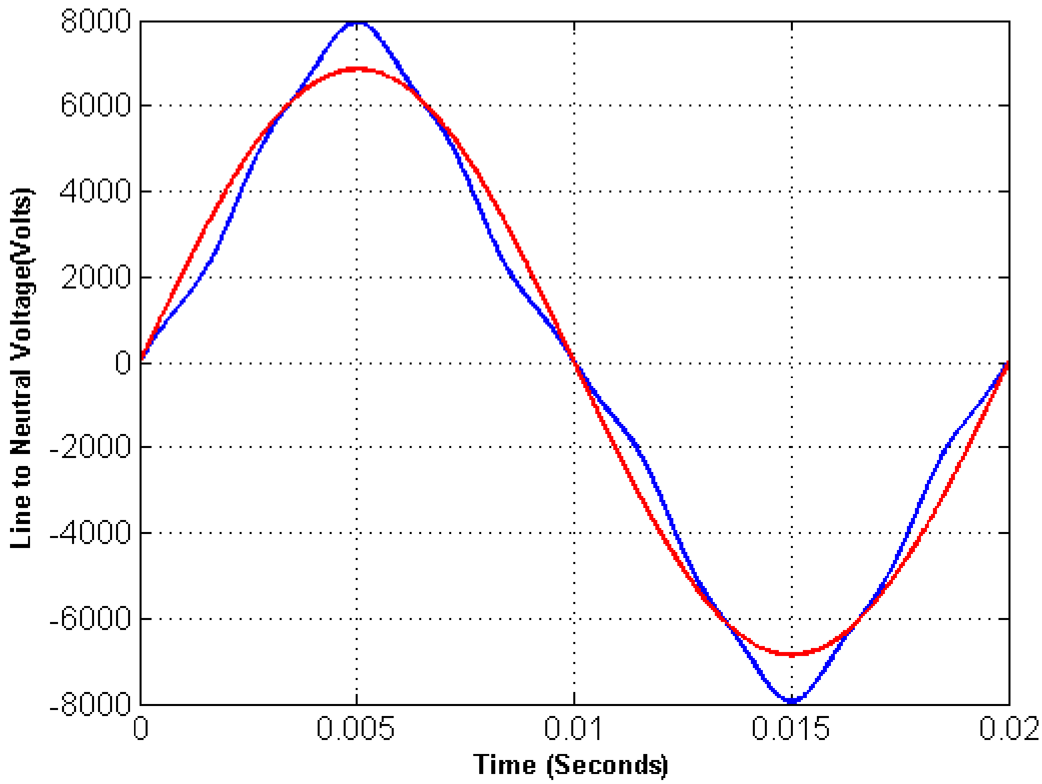
```
xlabel('Electrical Angle (Degrees)','FontSize',10,'FontWeight','Bold');
```

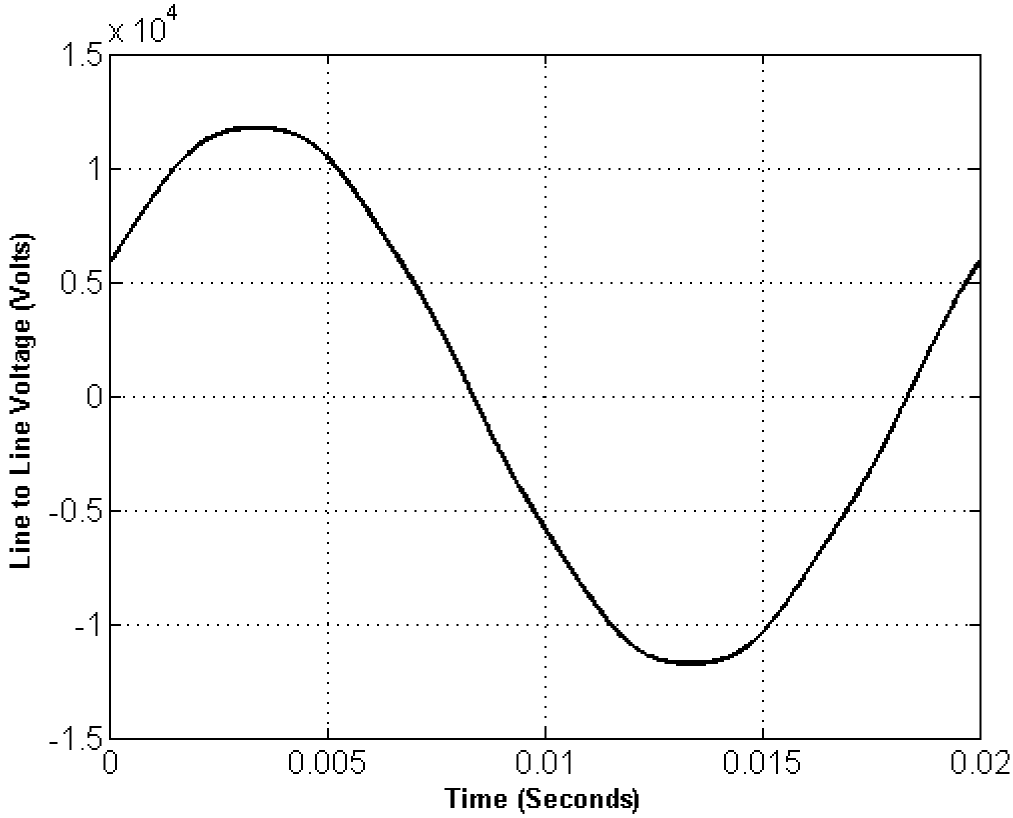


Part e, f)

```
% Define time array
t = 0:1e-5:20e-3;

voltage_harmonic_a = zeros(numel(harmonic),numel(t));
voltage_harmonic_b = zeros(numel(harmonic),numel(t));
voltage_actual_a = zeros(1,numel(t));
voltage_actual_b = zeros(1,numel(t));

for m = 1:numel(harmonic)
    voltage_function_a(m,:) = induced_voltage(m)*sqrt(2)*...
        sin(2*pi*harmonic(m)*50*t);
    voltage_function_b(m,:) = induced_voltage(m)*sqrt(2)*...
        sin(harmonic(m)*(2*pi*50*t-2*pi/3));
end

voltage_actual_a(1,:) = sum(voltage_function_a(:,:));
voltage_actual_b(1,:) = sum(voltage_function_b(:,:));

linetoline = voltage_actual_a-voltage_actual_b;


figure;
plot(t,voltage_actual_a(1,:),'b- ','Linewidth',1.5);
```

```
hold on;
plot(t,voltage_function_a(1,:),'r- ','Linewidth',1.5);
hold off;
grid on;
set(gca,'FontSize',12);
ylabel('Line to Neutral Voltage(Volts)','FontSize',10,'FontWeight','Bold');
xlabel('Time (Seconds)','FontSize',10,'FontWeight','Bold');

figure;
plot(t,linetoline(1,:),'k- ','Linewidth',1.5);
grid on;
set(gca,'FontSize',12);
ylabel('Line to Line Voltage (Volts)','FontSize',10,'FontWeight','Bold');
xlabel('Time (Seconds)','FontSize',10,'FontWeight','Bold');
```





Part g)

The actual line-to-neutral waveform seems highly distorted due to mostly 3rd harmonic and some 9th harmonic. One adverse effect of the harmonic content is the increase of the peak value as the peak difference between the actual and fundamental is around 1 kV.

It can be observed from the line-to-line voltage waveform that, the triplen harmonics (3rd and 9th) are eliminated and the resultant waveform is lowly distorted. This is one of the advantages of using Y connected machines.

All in all, the four harmonic components on the air gap flux density have been eliminated by different methods.

Q.3)

Part a)

Since the rotor rotation dirction and the MMF waveform direction produced by the stator windings are the same, the induced voltage frequency can be calculated by the relative speed (their difference) as following:

$$f = f_{stator} - f_{rotor}$$

$$f = 50 - Nr * p/120$$

Nr = 1400, p = 4

$$f = 50 - 1400 * 4/120$$

f = 3.33 Hz

Part b)

Using the same procedure in (a):

f = 13.33 Hz

Part c)

When the rotor direction is reversed, the relative speed will be the sum of two frequencies which can be calcuulated as follows:

$f = f_{stator} + f_{rotor}$

$f = 50 + Nr * p/120$

Nr = 1400, p = 4

$f = 50 + 1400 * 4/120$

f = 96.67 Hz

Part d)

Using the same procedure in (c):

f = 86.67 Hz

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