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Unbalanced Load Compensation

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ABSTRACT

Practical systems rarely have perfectly balanced loads, currents, voltages or impedances in all three phases. The analysis of unbalanced cases is greatly simplified by the use of the techniques of symmetrical components. An unbalanced system is analyzed as the superposition of three balanced systems, each with the positive, negative or zero sequence of balanced voltages. In case of unbalance in three phase systems it gives rise to sequence currents i.e positive, negative and zero sequence currents.

Introduction:

Practical systems rarely have perfectly balanced loads, currents, voltages or impedances in all three phases. The analysis of unbalanced cases is greatly simplified by the use of the techniques of symmetrical components. An unbalanced system is analyzed as the superposition of three balanced systems, each with the positive, negative or zero sequence of balanced voltages. In case of unbalance in three phase systems it gives rise to sequence currents i.e positive, negative and zero sequence currents. Zero sequence and negative sequence currents give rise to following problems:

1. Heating of motors and transformers connected in the power system.
2. Less utilization of capacity of machine.
3. Increase in line losses.
4. More KVA demand.
5. Reduction in power factor.

So the zero and negative sequence currents are undesirable in the power system. If there is a delta connection or grounded star connection present in the power system then effect of zero sequence current can be eliminated but the negative sequence current is directly fed back to source.

For effective utilization of machines associated in power system we need compensation of unbalanced load so as to balance the source current and reduce the effect of negative and zero sequence currents and source due to unbalanced load and for improvement of power factor. The present work explains the principle of load balancing using different load conditions and recommends suitable susceptance to be connected in parallel with delta in deltaconnection.In actual system the SVC design takes into consideration the economics of compensation so that after balancing the system meets the requirement of standard.

Load Equalization Technique:

The analysis of the compensation requirements of a general unbalanced load is done in terms of symmetrical component method which gives a proper mathematical basis. The compensating currents are transformed to symmetrical components to find out the required balancing susceptance. Then with the inverse transform the actual line currents and voltages are retrieved for practical implementation. The general unbalanced three-phase (ungrounded) load can be represented by a delta-connected network in which the load admittances Y_{RYl},Y_{YBl} and Y_{BRl} are complex in value and unequal. If the magnitude of the supply phase voltage is represented as V and h is the customary complex operator (equal to **h = e^(j2∏/3)=-1/2+j√3/2)** then the susceptance of compensating network would be by simple mathematical transformations.

$$\mathbf{B_{RYY} = -1/3V[Im\ I_{Rl} + Im\ hI_{Yl} - Im\ h^2 I_{Bl}]}$$
$$\mathbf{B_{YBY} = -1/3V[-ImI_{Rl} + ImhI_{Yl} + Imh^2 I_{Bl}]}$$
$$\mathbf{B_{BRY} = -1/3V[ImI_{Rl} - ImhI_{Yl} + Imh^2 I_{Bl}]}$$

The above equations represent the desired compensating susceptance in terms of the phasor line currents I_{Rl} ,I_{Yl} and $I_{Bl}$of the load circuit.Here,the admittance in general vary with time. For fulfilling the basic compensation requirements, the three phase load may be viewed as represented by three steady state impedances' at a particular time instant. A series of 'steady state' impedances, representing the load at discrete time instants appropriately close to one another, can reconstruct a time varying load. In this analysis it is assumed that the changes in the load are sufficiently slow or 'quasi-stationary', so that the phasor analysis can be carried out. The load equalization technique makes not only the line currents to be balanced but also programs them to operate in phase with their respective phase voltages so that each phase of a wye-connected supply system can supply one-third of the total power and no reactive power. Although the currents in the three branches of the delta are unbalanced, there is a reactive power equilibrium within the delta which assumes no absorption from the source. With non-linear circuit like thyristorized load it cannot be assumed that the line currents are not carrying reactive power but they can be minimized for better power factor.

Fundamentals of Load Compensation: One of the applications of the SVCs is to balance single phase loads such as traction loads, so that the negative sequence voltage at the point of common coupling(PCC) is within the limits set by the respective national standards.Gyugi et al have discussed steinmetz's earlier work, which shows that in a supply system with phase sequence ABC, a resistive load of P watts connected between phases A and B can be made to appear in the three phase ac supply system as a balanced resistive load by connecting a capacitive source of $+jP/\sqrt{3}$ vars between phases B and C and an inductive source of $-jP/\sqrt{3}$ vars between phases C and A. We will try to establish in the following text. Consider the R,C and L elements connected across the phases AB,BC and CA,respectively, in a delta configuration .From the phasor diagram and considering V_{AN} as a reference phasor, the following equations can be written:

$$V_{AB}=V_L\angle 30$$

$$V_{BC}=V_L\angle -90=-jV_L$$

$$V_{CA}=V_L\angle 150=(-\sqrt{3}/2)V_L+jV_L/2$$

$$I_R=V_{AB}/R=V_L/R(\sqrt{3}/2+j/2)$$

$$I_{CAP}=jV_{BC}\omega C=j(-jV_L)\omega C=V_L\omega C$$

$$I_L=V_{CA}/j\omega L=[V_L/j\omega L][1/2+j\sqrt{3}/2]$$

$$I_A=I_R-I_L=[[\sqrt{3}/(2R)-1/(2\omega L)]+j[1/(2R)-\sqrt{3}/(2\omega L)]]\,V_L$$

$$I_B=I_{CAP}-I_R=V_L[[\omega C-\sqrt{3}/(2R)]-j1/(2R)]$$

$$I_C=I_L-I_{CAP}=V_L[[1/(2\omega L)-\omega C]+j\sqrt{3}/(2\omega L)]$$

If I_A, I_B, I_C are to be balanced three phase currents drawn by resistive loads(i.e. unity power factor loads) , then their magnitudes must be equal with 120 degree phase angle difference between them. Further the phase angle of I_A must be zero because it is in phase with V_{AN} and hence the imaginary component of the current I_A must be zero. Therefore

$$1/(2R)=\sqrt{3}/(2\omega L)$$

$$\omega L=\sqrt{3}R$$

Imposing the condition that the phase angle of I_B must be -120 degree , we can show that

$$1/\omega C=\sqrt{3}R$$

$$I_B=V_L/(\sqrt{3}R)\angle -120$$

BY substituting the values of L and C from above equations we can show that

$$I_C=V_L/(\sqrt{3}R)\angle 120$$

Hence we have established that a single phase resistive load connected across the phases A and B can be balanced by connecting pure reactive elements C and L across BC and CA, respectively, with the values given by the above equations. If the power consumed by the resister R is P watts, the reactive power generated by C and L are $+jP/\sqrt{3}$ and $-jP/\sqrt{3}$ vars, respectively. If there are two single phase lagging loads P_1+jQ_1 and P_2+jQ_2 connected across phases AB and BC, respectively, they can be made to appear in the supply system as a pure resistive load by connecting purely reactive loads of the values shown in the table.

Capacities of Reactive Elements(Positive sign indicates Capacitive source)			
	Q_{AB}	Q_{BC}	Q_{CA}
To compensate a lagging load P_1+jQ_1 between phases A and B	$+jQ_1$	$+jP_1/\sqrt{3}$	$-jP_1/\sqrt{3}$
To compensate a lagging load P_2+jQ_2 between phases A and B	$-jP_2/\sqrt{3}$	$+jQ_2$	$+jP_2/\sqrt{3}$
Total	$jQ_1-jP_2/\sqrt{3}$	$jP_1/\sqrt{3}+jQ_2$	$jP_2/\sqrt{3}-jP_1/\sqrt{3}$

Case Study:

Case: 1

Three Phase Balanced Load:

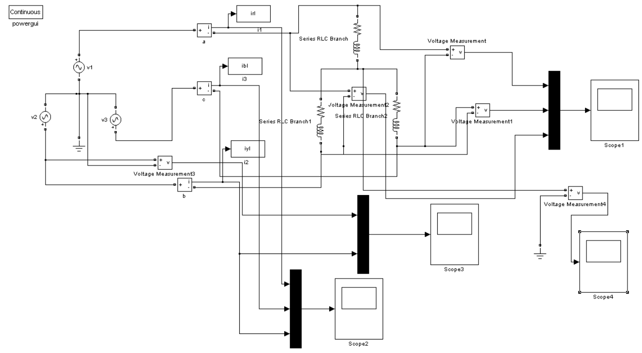


Fig: 1.1 Circuit diagram for MATLAB simulation of 3-phase balanced load (star connected)

Circuit parameters:-

1. R-L Load 50+j30 (each)
2. Three-phase supply V_L=400 v

Calculation of current in each phase:

MATLAB Program:

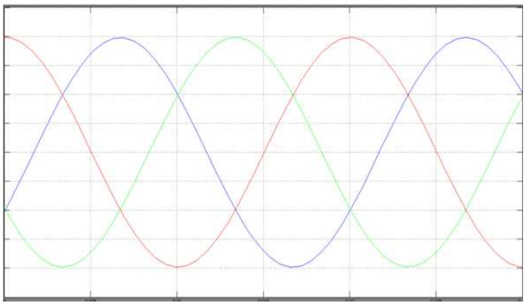
```
%Calculation of Zero,Negative and Positive sequence Current Of Balance Load
h=-0.5+0.866i
va=400/sqrt(3)
vb=va*h*h
vc=va*h
Za=(50+30i);
Ia=(va)/(Za);
Ib=(vb)/(Za);
Ic=(vc)/(Za);
Io=(Ia+Ib+Ic)/3
abs(Io)
I1=(Ia+(h*Ib)+((h^2)*Ic))/3
abs(I1)
I2=(Ia+((h^2)*Ib)+(h*Ic))/3
```

abs(I2)

Output:

h = -0.5000 + 0.8660i
va = 230.9401
vb =-1.1546e+002 -1.9999e+002i
vc = -1.1547e+002 +1.9999e+002i
Io = 4.9811e-005 -2.9886e-005i
ABS (I0)=5.8089e-005
I1 =3.3961 - 2.0375i
ABS (I1) =3.9604
I2 = -1.9504e-006 -1.1616e-004i
ABS (I2)=1.1618e-004

Current Waveform:



$I_{a=3.9645}$ $I_{b=3.9615}$ $I_{c=3.9595}$

Fig: 1.2

Case: 2

Three Phase Unbalanced Load:

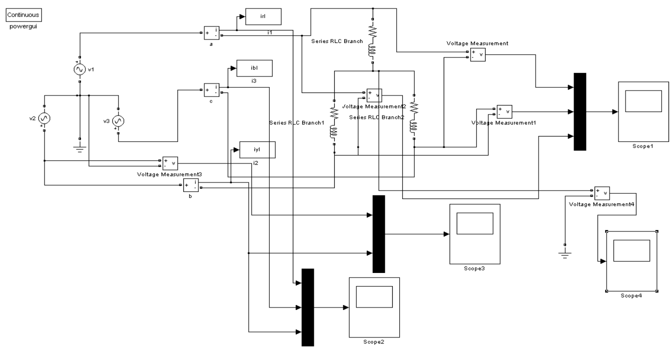


Fig: 2.1 Circuit diagram for MATLAB simulation of 3-phase unbalanced load (star connected)

Circuit Parameter:

Z_a=50+j30
Z_b=80+j50
Z_c=60+j40
3-phase supply v_L=400v

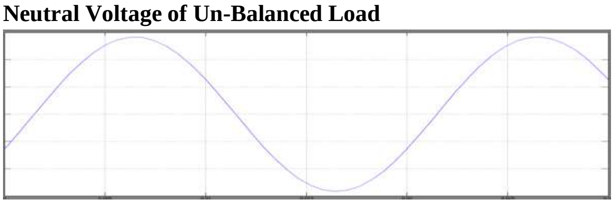
MATLAB Program:

```
h=-0.5+0.866i
va=400/sqrt(3)
vb=va*h*h
vc=va*h
x=((va/(50+30i))+(vb/(60+40i))+(vc/(80+50i)))
y=((1/(50+30i))+(1/(60+40i))+(1/(80+50i)))
vs=x/y
ia=(va-vs)/(50+30i)
ib=(vb-vs)/(60+40i)
ic=(vc-vs)/(80+50i)
Io=(Ia+Ib+Ic)/3
abs(Io)
I1=(Ia+(h*Ib)+((h^2)*Ic))/3
abs(Ib)
I2=(Ia+((h^2)*Ib)+(h*Ic))/3
abs(Ic)
```

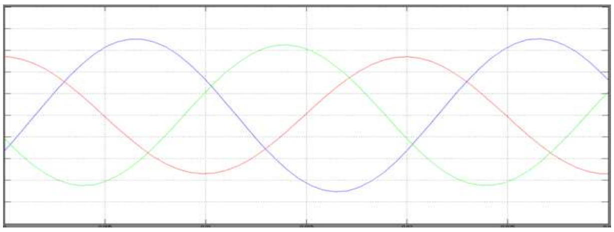
Output:

h = -0.5000 + 0.8660i
va = 230.9401
vb =-1.1546e+002 -1.9999e+002i
vc = -1.1547e+002 +1.9999e+002i
x = 0.6112 - 1.0108i
y = 0.0352 - 0.0221i
vs = 25.3601 -12.7566i
Ia = 3.1358 - 1.6263i
Ib = -3.0651 - 1.0772i
Ic = -0.0707 + 2.7035i
Io = -7.8641e-017 -1.4803e-016i
Abs(I0) =1.6762e-016
I1 =2.6593 - 1.6775i
Abs(I1) = 3.2489
I2 = 0.4765 + 0.0512i
Abs(I2) =2.7045

Neutral Voltage of Un-Balanced Load



Unbalanced current wave form



$I_{a=3.5307}$ $I_{b=3.2474}$ $I_{c=2.7036}$

Fig: 2.3

Voltage and current wave form showing phase difference:

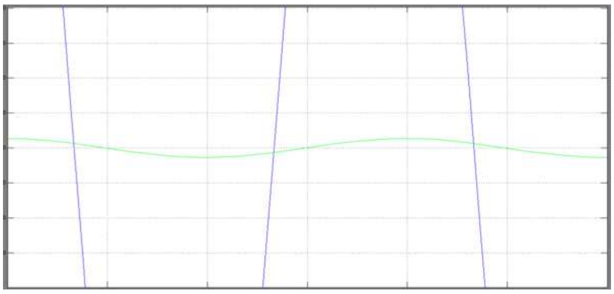


Fig: 2.4

MATLAB Code for Compensator:

```
Babl=(-1/(3*va))*[imag(Ia)+imag(h*Ib)-      imag(h*h*Ic)]
Bbcl=(-1/(3*va))*[-imag(Ia)+imag(h*Ib)+imag(h*h*Ic)]
Bcal=(-1/(3*va))*[imag(Ia)-imag(h*Ib)+imag(h*h*Ic)]
%capacitance
Cabl=Babl/(2*pi*50)
```

Cbcl=Bbcl/(2*pi*50)
Ccal=Bcal/(2*pi*50)
%inductor
labl=Babl*(2*pi*50)
lbcl=Bbcl*(2*pi*50)
lcal=Bcal*(2*pi*50)

Output:

Babl = 0.0035
Bbcl = 0.0026
Bcal = 0.0012
Cabl =1.1264e-005
Cbcl = 8.1777e-006
Ccal = 3.6801e-006
labl = 1.1117
lbcl = 0.8071
lcal = 0.3632

Circuit Using Compensator:

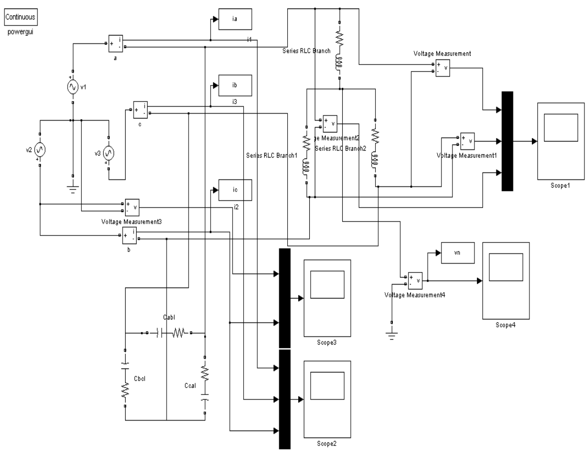
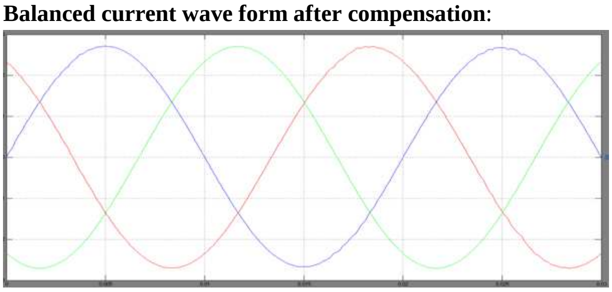


Fig: 2.5 Circuit diagram for MATLAB simulation of 3-phase unbalanced load with compensator (star connected)

Balanced current wave form after compensation:



I_a= 2.7155 I_b= 2.7057 I_c= 2.7089

Comment:-Balanced line current

Fig: 2.6

Voltage and Current Wave Form Showing Phase Difference=0, =>Unity Pf:-

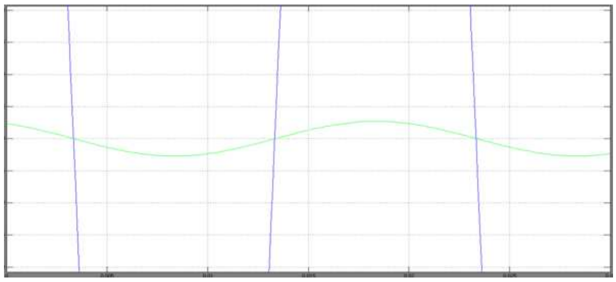


Fig: 2.7

Case -3

Single phasing in 3-phase circuit:

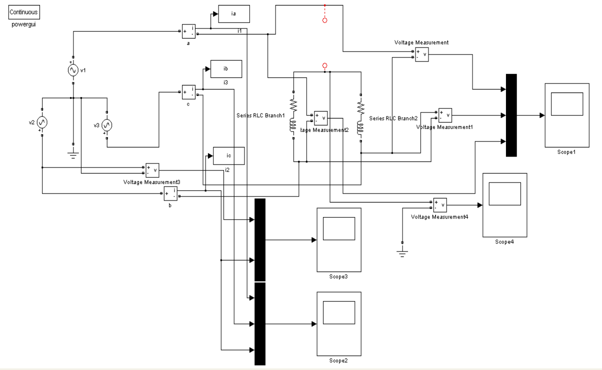


Fig: 3.1 Circuit diagram for matlab simulation of 3-phase unbalanced load (single- phasing)

Calculation of Current in Each Phase:

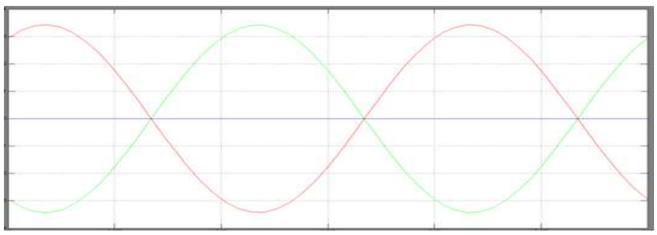
MATLAB Program:

clc
h=-0.5+0.866i
va=400/sqrt(3)
vb=va*h*h
vc=va*h
ia=0
ib=(vb-vc)/(100+60i)
ic=(vc-vb)/(100+60i)

Output:

h =-0.5000 + 0.8660i
va =230.9401
vb =-1.1546e+002 -1.9999e+002i
vc =-1.1547e+002 +1.9999e+002i
ia =0
ib =-1.7646 - 2.9411i
ic =1.7646 + 2.9411i

Current Wave Form:



I_a= 0 I_b= 3.4167 I_c= 3.4289

Comment: Un Balanced line current

Fig: 3.2

Voltage and Current Wave Form Showing Phase Difference:

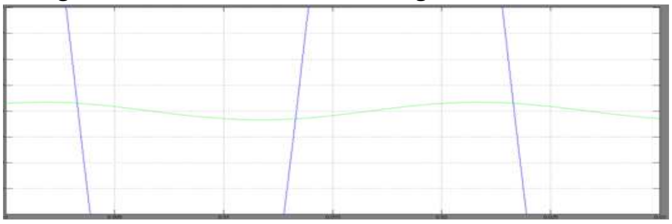


Fig: 3.3

Calculation for Compensator:

Babl=(-1/(3*va))*[imag(ia)+imag(h*ib)-imag(h*h*ic)]
Bbcl=(-1/(3*va))*[-imag(ia)+imag(h*ib)+imag(h*h*ic)]
Bcal=(-1/(3*va))*[imag(ia)-imag(h*ib)+imag(h*h*ic)]

%capacitance

Cabl=Babl/(2*pi*50)
Cbcl=Bbcl/(2*pi*50)
Ccal=Bcal/(2*pi*50)

%inductor

labl=abs(Babl)*(2*pi*50)
lbcl=abs(Bbcl)*(2*pi*50)
lcal=abs(Bcal)*(2*pi*50)

Output:

Babl =-0.0042
Bbcl =0.0044
Bcal =0.0042
Cabl =-1.3512e-005
Cbcl =1.4041e-005
Ccal =1.3512e-005
labl =1.3336
lbcl =1.3858
lcal =1.3336

Circuit using compensator:

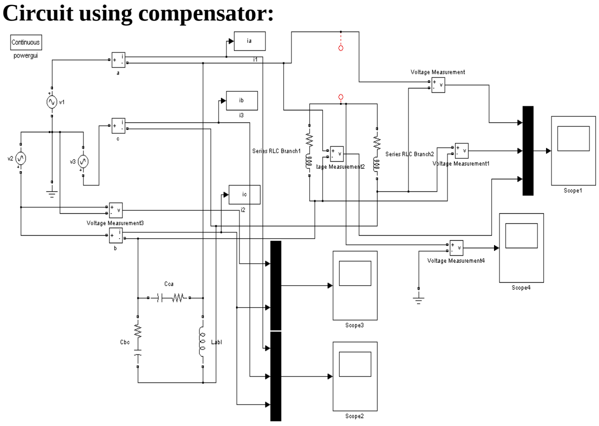
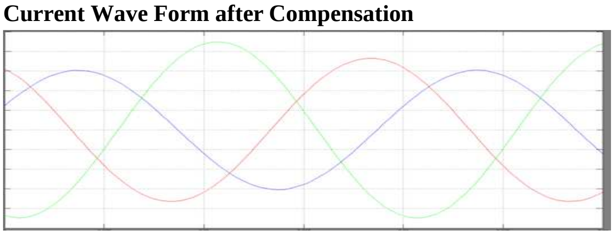


Fig: 3.4 Circuit diagram for MATLAB simulation of 3-phase unbalanced load with compensator (star connected)

Current Wave Form after Compensation

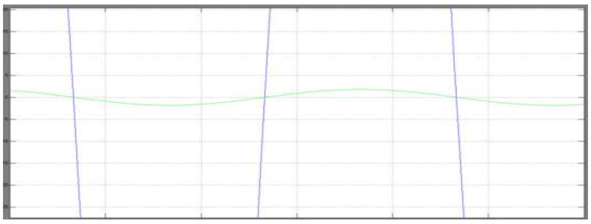


I_a= 1.5223 I_b= 2.2346 I_c= 1.8187

Comment: compensated line current

Fig: 3.5

Voltage and Current Wave Form Showing Phase Difference=0, =>Unity Pf:



Case: 4

Unbalance in Traction:

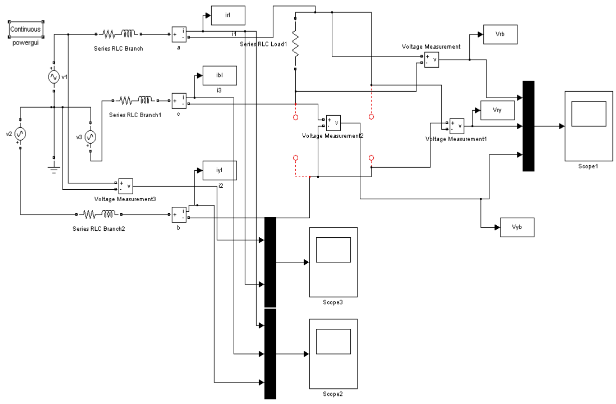
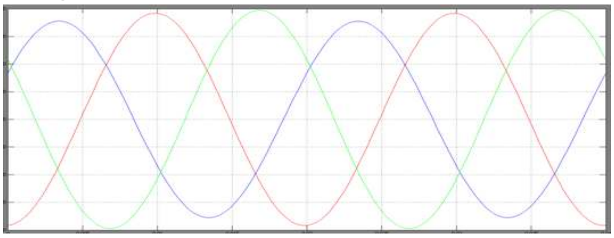


Fig: 4.1 Circuit diagram for matlab simulation having one resistive load between phase AB

Circuit parameters:

R_l=10000 watt R_s=1 ohm L_s=1e-3 henry

Voltage wave form of unbalanced load

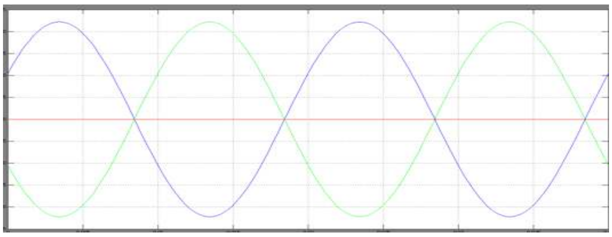


Vry=394.7313 Vyb =383.7033 Vrb =355.2069

Comment: Line voltages are unbalance

Fig: 4.2

Current wave form of unbalanced load



I_a=22.2004 I_b=22.1949 I_c=0

Comment: Unbalanced line current

Fig: 4.3

Current and voltage waveform showing phase difference

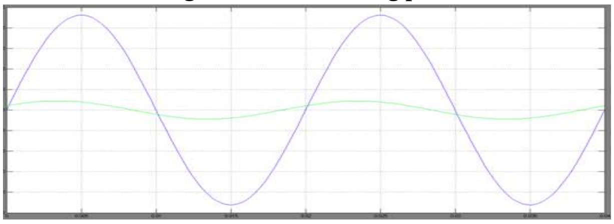


Fig: 4.4

Circuit after using compensator:

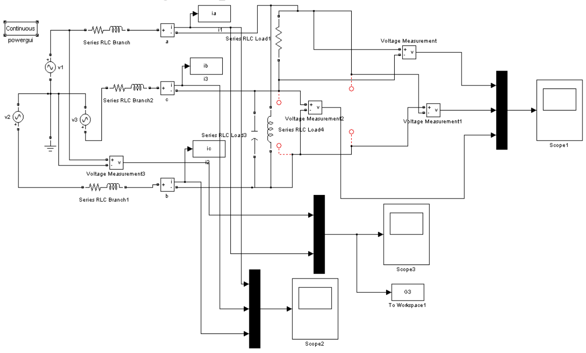


Fig: 4.5 Circuit diagram for MATLAB simulation of 3-phase unbalanced load using compensator delta connected)

Compensator Calculation:

Q_{bc}=+jP/√3 and Q_{ca}=-jp/√3

Line currents after compensation:

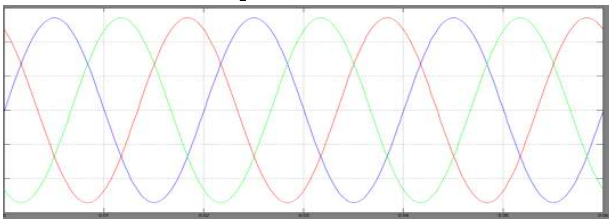


Fig: 4.6

I_a=13.5668 I_b=13.5797 I_c =13.5759

Comment: Line currents are balanced

Line voltage waveform after compensation

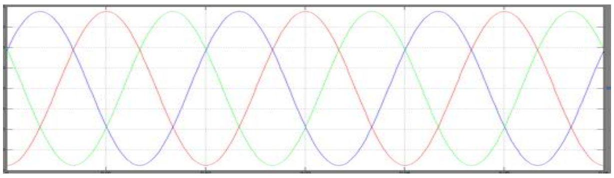


Fig: 4.7

Vry = 376.0005 Vrb=376.1327 Vyb=376.1086

Comment: Line voltage become balance

Voltage and Current Wave Form Showing Phase Difference=0, =>Unity Pf:

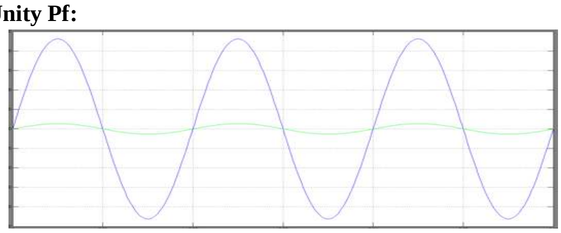


Fig: 4.8

Case: 5

Load on two phase unbalance condition

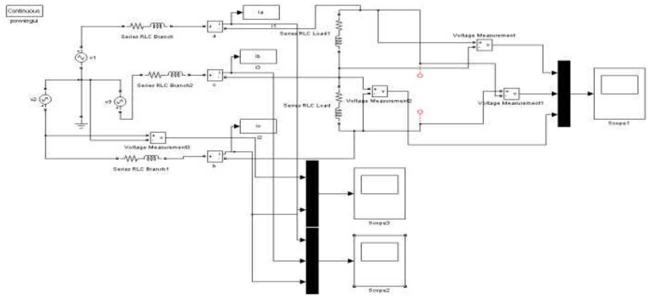
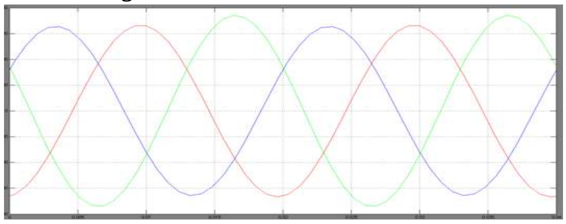


Fig: 5.1 Circuit diagram for MATLAB simulation of 3-phase unbalanced delta connected load

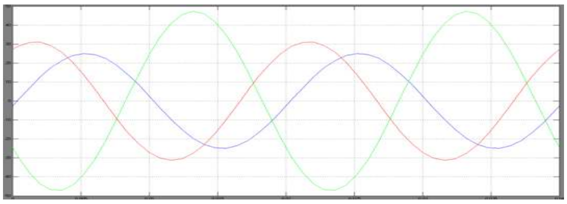
Unbalance voltage waveform



Vry=370.3906 Vrb=327.4744 Vyb=330.7690

Fig: 5.2

Unbalance current wave form:



I_a=25.0216 I_b=47.2546 I_c=31.0585

Fig: 5.3

Voltage and current wave form showing phase difference:

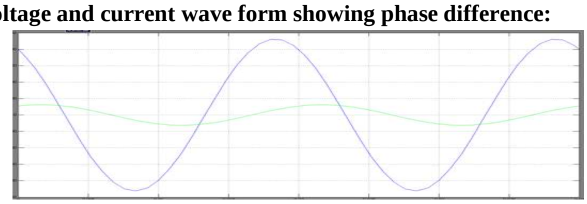


Fig: 5.4

Circuit diagram using compensator:

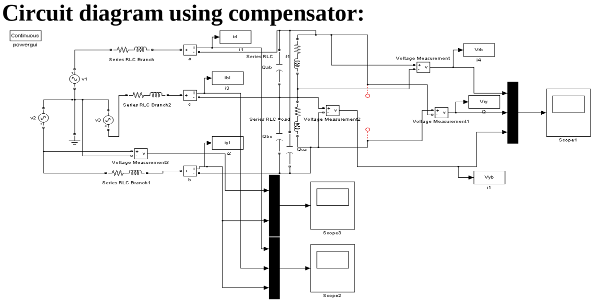
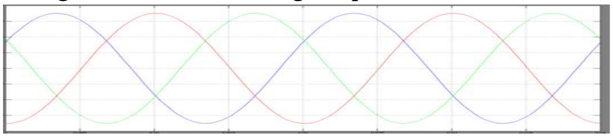


Fig: 5.5 Circuit diagram for MATLAB simulation of 3-phase unbalanced load using compensator delta connected

Voltage wave form after using compensator:

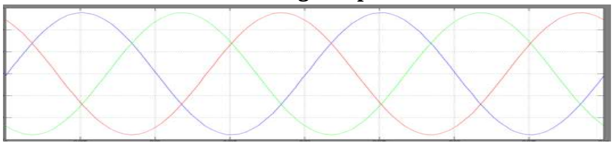


Vrb=351.2543 Vry=351.1348 Vyb=351.2635

Comment: voltage become balance

Fig: 5.6

Current wave form after using compensator:-

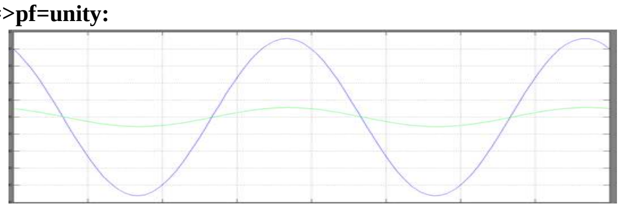


I_a=27.9442 I_b=27.9243 I_c=27.8668

Comment: line current become balance

Fig: 5.7

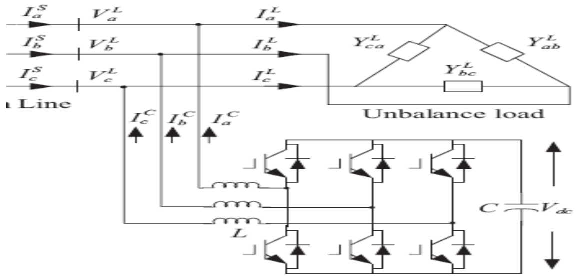
Voltage and current wave form showing phase difference=0, =>pf=unity:



Comment: power factor become unity

Fig: 5.8

Conclusion:-The elements of the compensator here calculated may be capacitor or inductor depending upon the degree of unbalance in the load. But in real practice the capacitor corresponds to the maximum reactive power demand by the load is connected permanently and a thyristor controlled reactor connected across it combinely performs the action of compensator depending upon the requirement of load as shown in figure.



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