


**Power Quality**  
**Prof. Bhim Singh**  
**Department of Electrical Engineering**  
**Indian Institute of Technology, Delhi**

**Lecture - 44**  
**Power Quality Improvement in Diesel Generator Set Based Power Supply System**  
**(Contd.)**

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**PMSG BASED DG SETS**


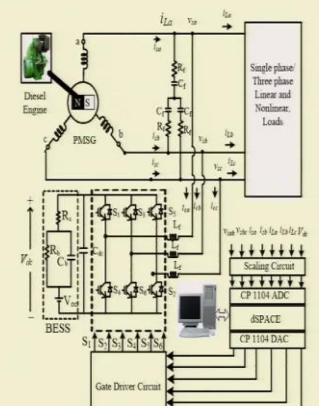
- A DSTATCOM is used for voltage control and power quality improvement.
- A diesel engine run at constant speed is used as prime mover.



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**PMSG based DG sets for 1P2W and 3P3W Loads**




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Welcome to the course on Power Quality. We are discussing Power Quality Improvement in Permanent Magnet Synchronous Generator Based Diesel Generator Sets.

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### Control algorithms for PMSG based DG sets

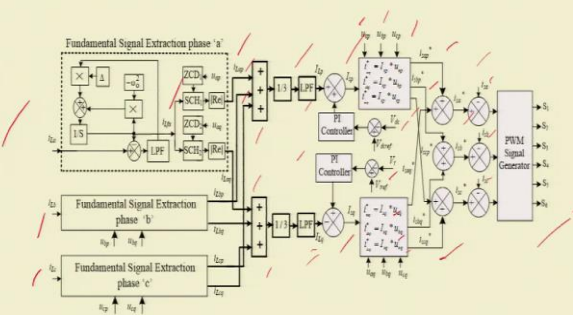

- ILST Control Algorithm for 1P2W Loads
- ADALINE Based Control Algorithm for 3P3W Loads
- Hyperbolic Tangent Function based LMS Algorithm for 3P3W Loads with BESS



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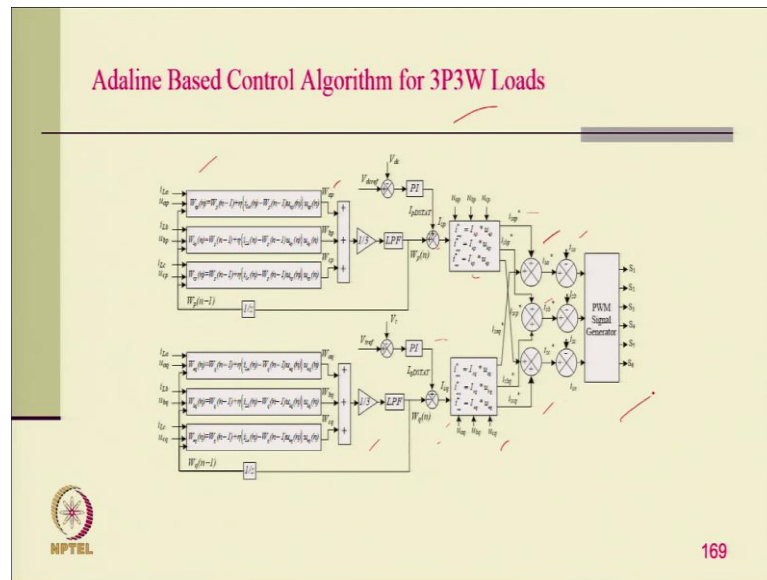
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### ILST based Control Algorithm for 1P2W Loads

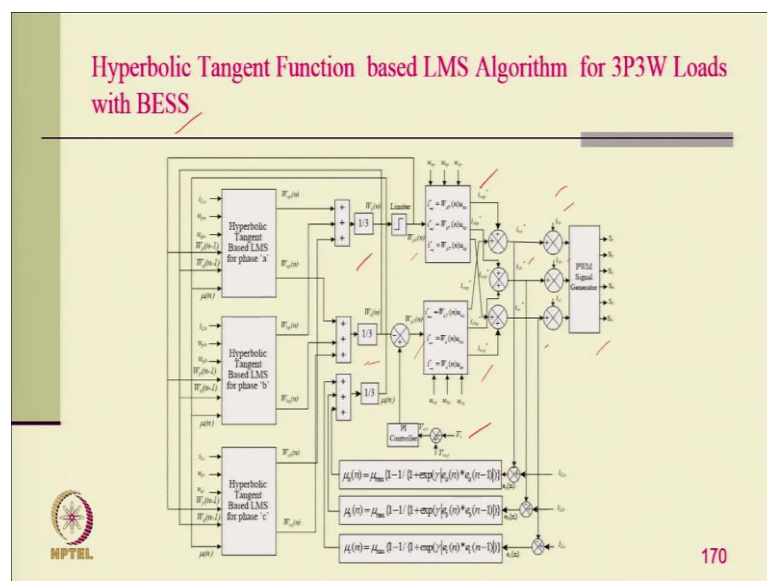



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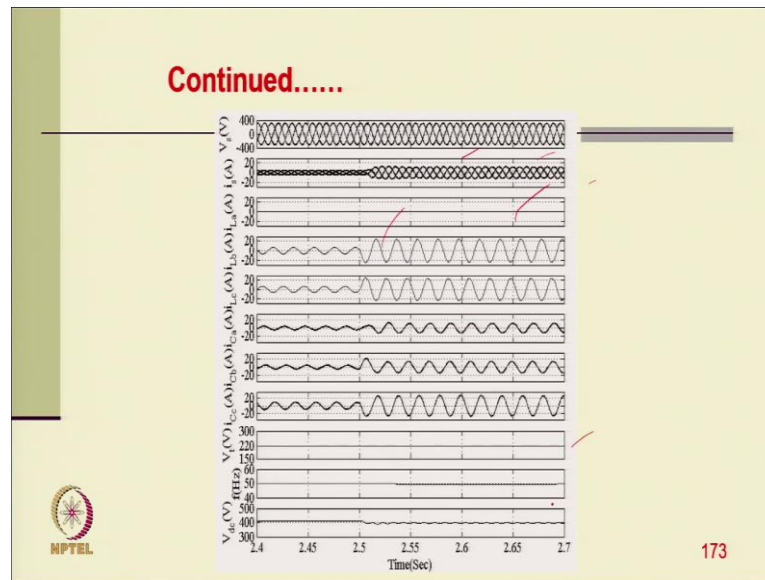
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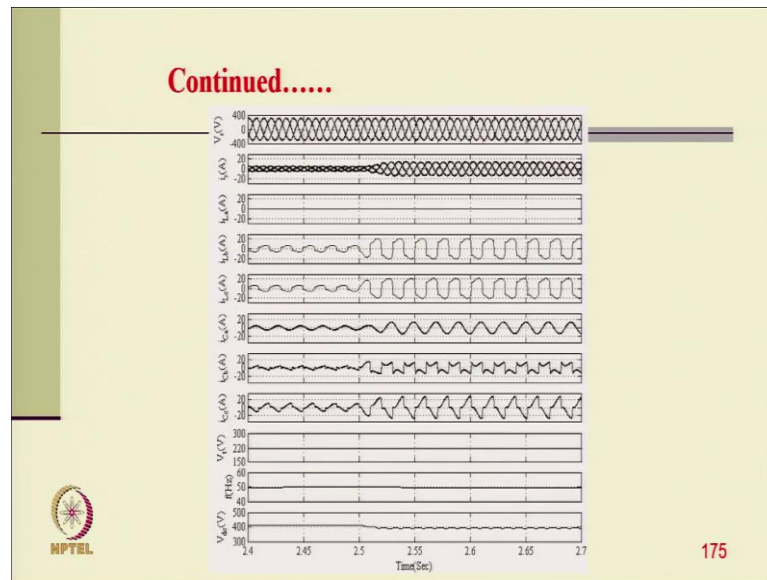
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**Simulated Performance of PMSG based DG set under 1P2W Nonlinear Loads**

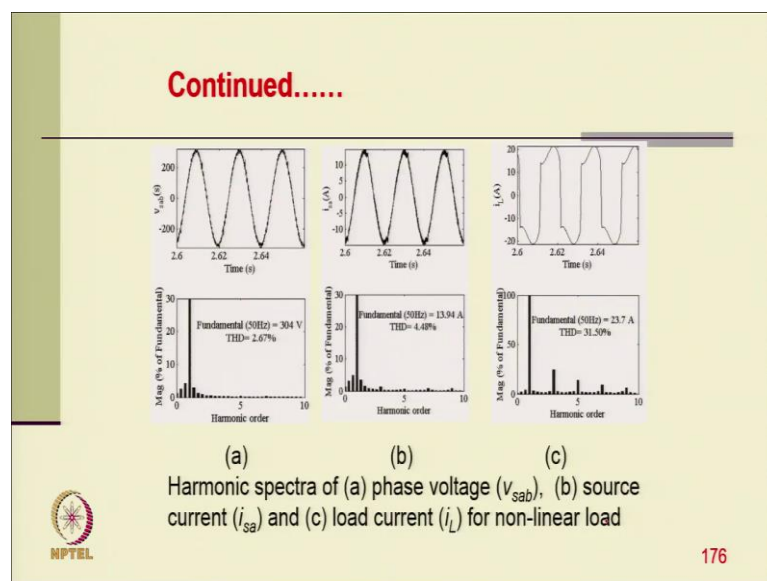
- The system is loaded with a single phase rectifier load connected between phases 'b' and 'c'.
- Initially system is subjected to a load of 1 kW and then it is subjected to load of 3.6 kW at  $t = 2.6$  s.

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And this is the typically harmonic spectrum of the load current the total harmonic distortion of load current is 31.5 percent, where the generator voltage THD is 2.67 percent and the generator current THD is 4.48 percent like.

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### Simulated Performance of PMSG based DG set under 3P3W Linear Loads

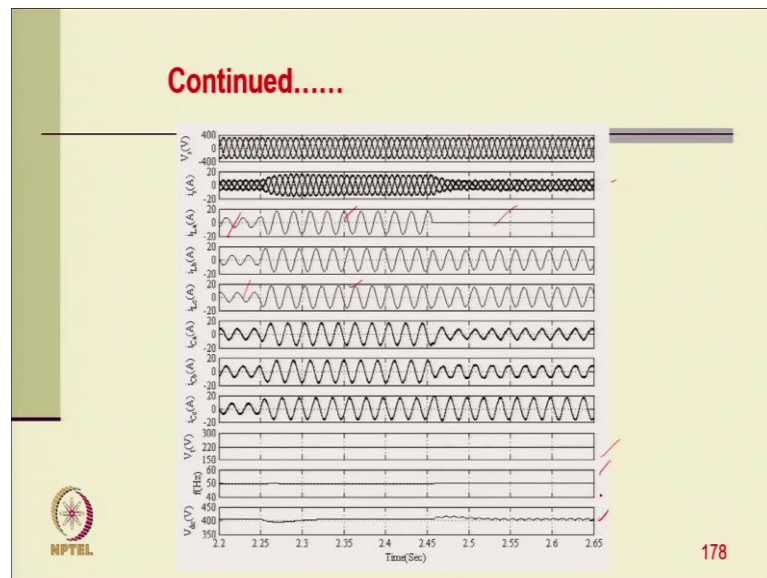
- Initially system is subjected to a inductive load of 1.6 kW with lagging power factor of 0.8.
- At  $t = 2.25$  s the set is subjected to load of 3.6 kW with lagging power factor 0.8.
- At  $t = 2.45$  s the system is subjected to unbalanced load by removing load from phase 'a'.



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Now, coming to the performance of PMSG DG set with the 3 phase 3 wire lagging power factor load.


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### Simulated Performance of PMSG based DG set under 3P3W Non-linear Loads

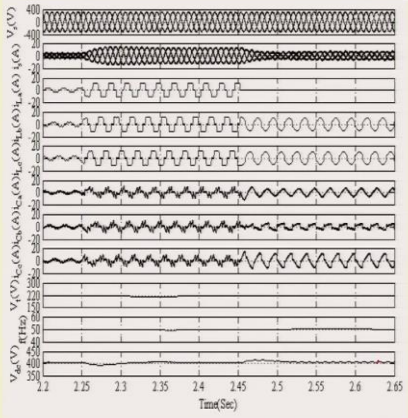
- Initially system is subjected to a non-linear load of 1 kW and then it is subjected to non-linear load of 3.7 kW at  $t = 2.25$  s.



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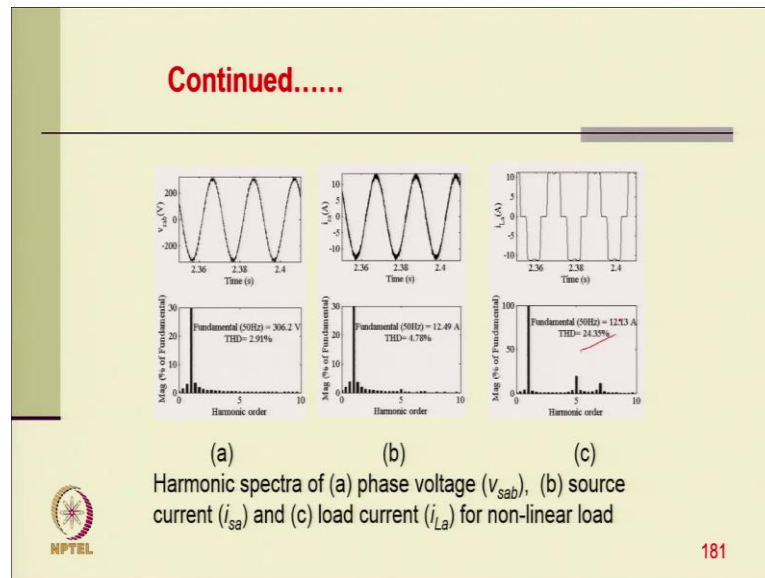
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And the THD of load current is 24.33 % and the generator current THD is 4.78% whereas the voltage THD is 2.91 %.

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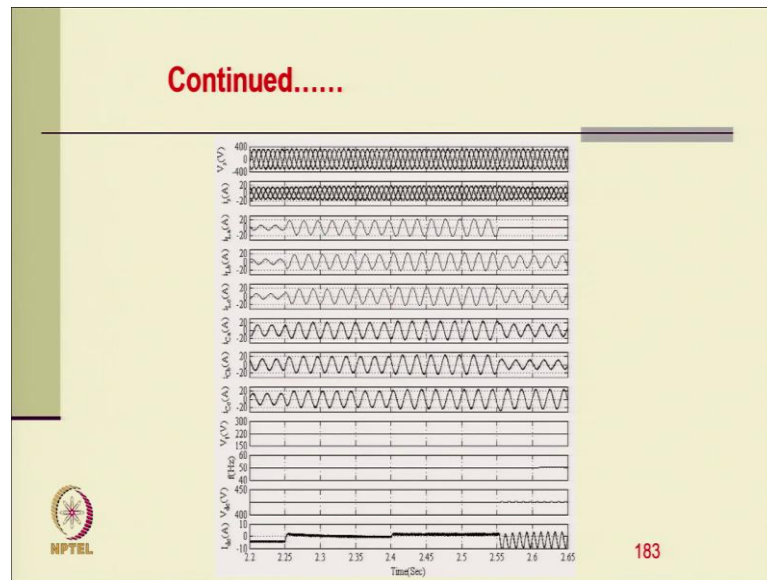
**Simulated Performance of PMSG based DG set with BESS under 3P3W Linear Loads**

- Initially system is subjected to a load of 1.2 kW at 0.8 lagging power factor which is less than 80 % of generator rating so battery is taking a charging current.
- At  $t = 2.25$  s a load of 3.6 kW is connected to the system. This load is almost equal to the rating of generator so whole of the load power is drawn from the source and the battery current is almost zero.
- At  $t = 2.4$  s a load of 4.44 kW is connected to the system. This load is more than rating of the generator so battery is supplying the current to meet the excess load demand.
- At  $t = 2.55$  s system is subjected to unbalanced load by removing the load from phase 'a'.

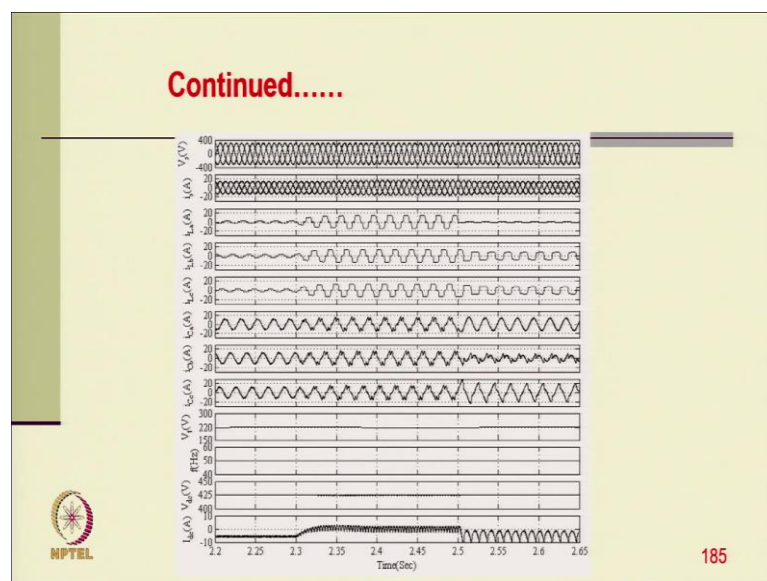
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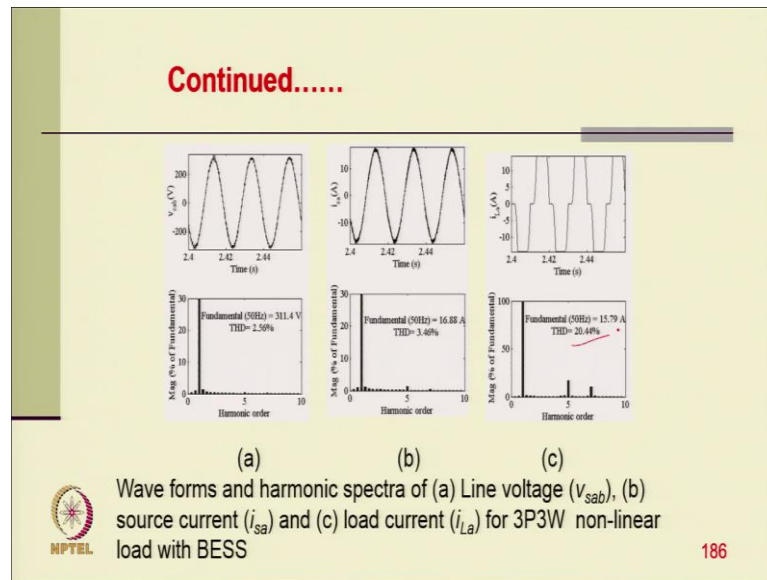
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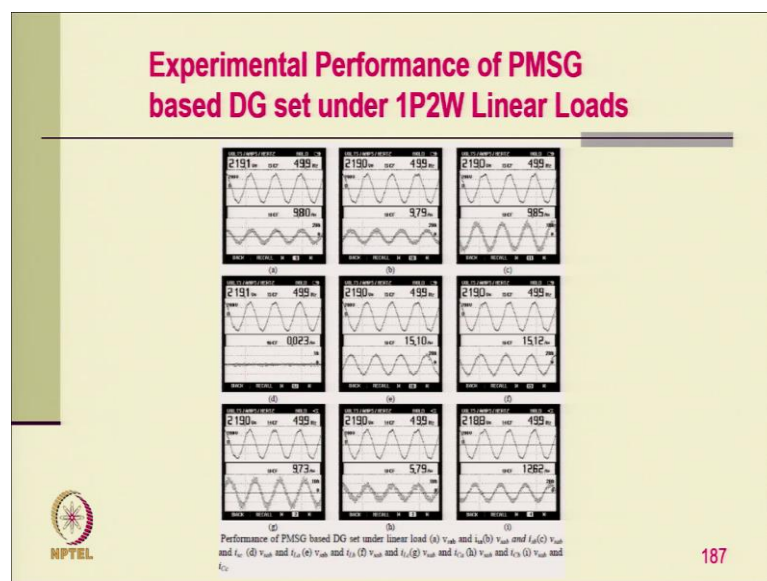
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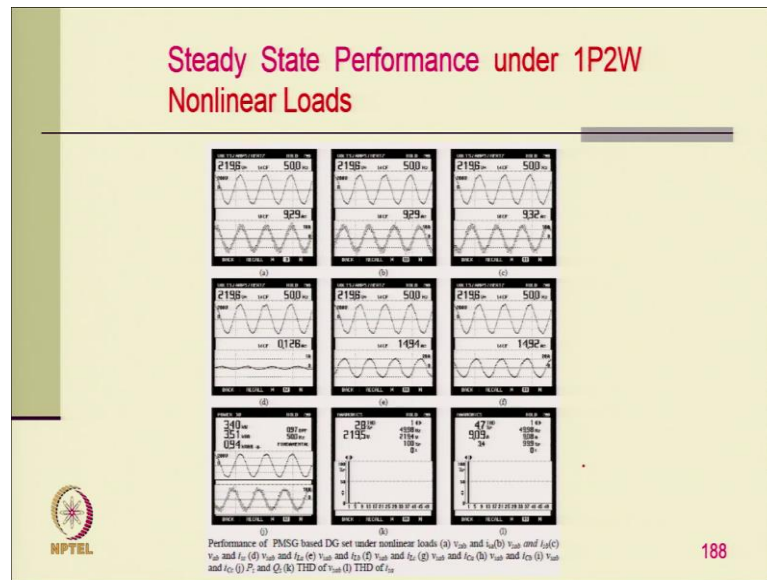


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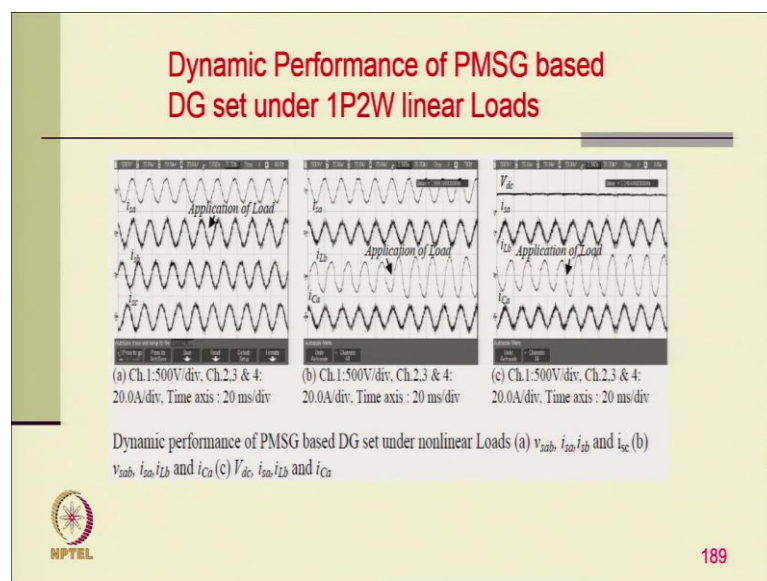


These are the typical experimental results, you can clearly see, that the load generator currents are balanced sinusoidal where the load is unbalanced.

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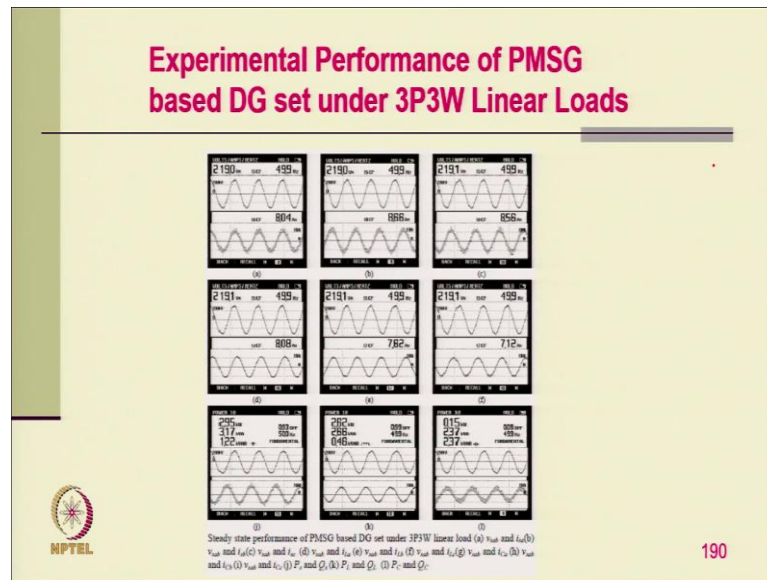


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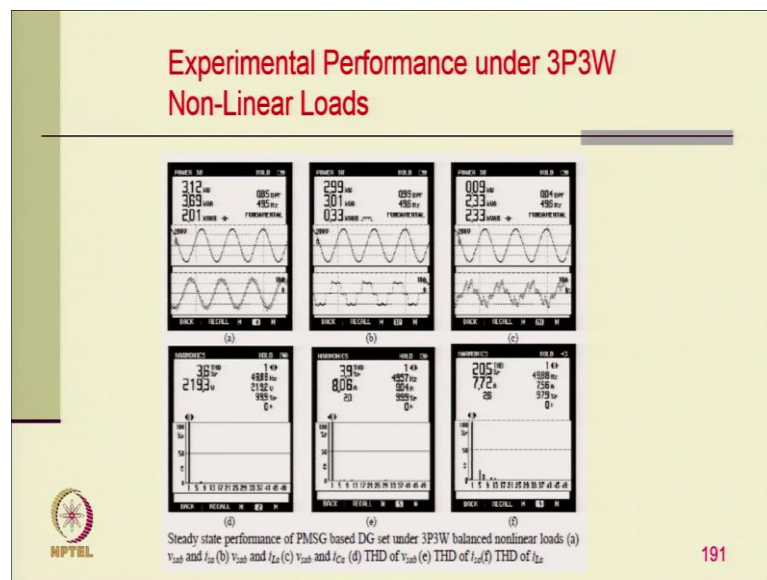
And then during the dynamics, if non-linear load is increased, still you will find the generator currents are not getting disturbed, they remain constant and DC link voltage is also regulated.

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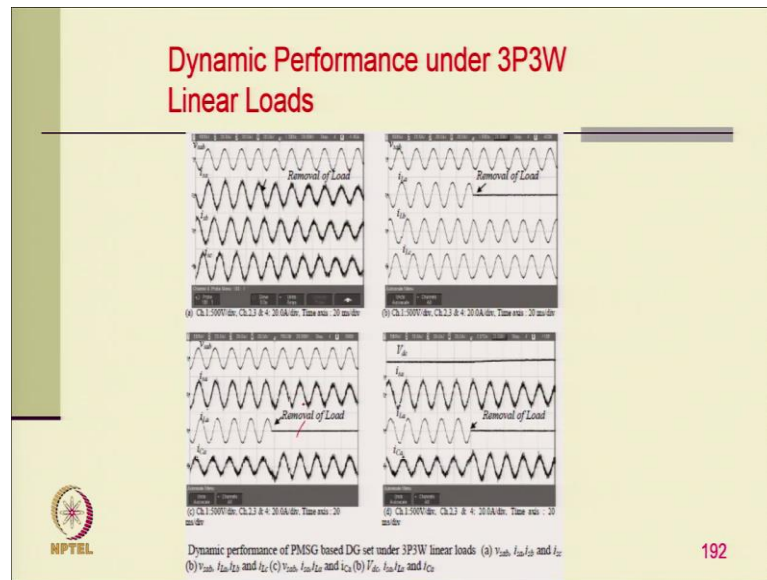
And then with the lagging power factor load, it works very well for correction of typically the power factor of the load and providing compensation.

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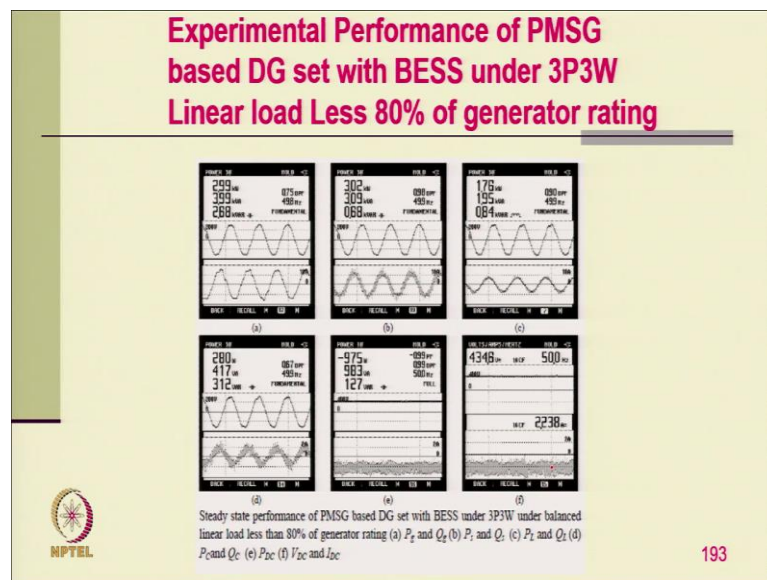
This with the non-linear load, but generator current is balanced and sinusoidal. The voltage THD is 3.6 % where the generator current THD 3.9 % where the load THD is 20.5 %

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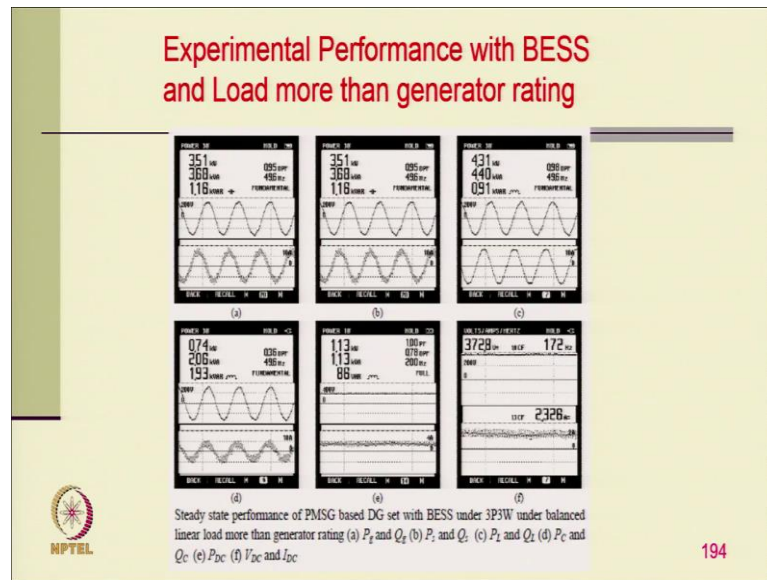


And during dynamics when load is unbalanced, the generator currents are not disturbed as they remain sinusoidal and balanced.

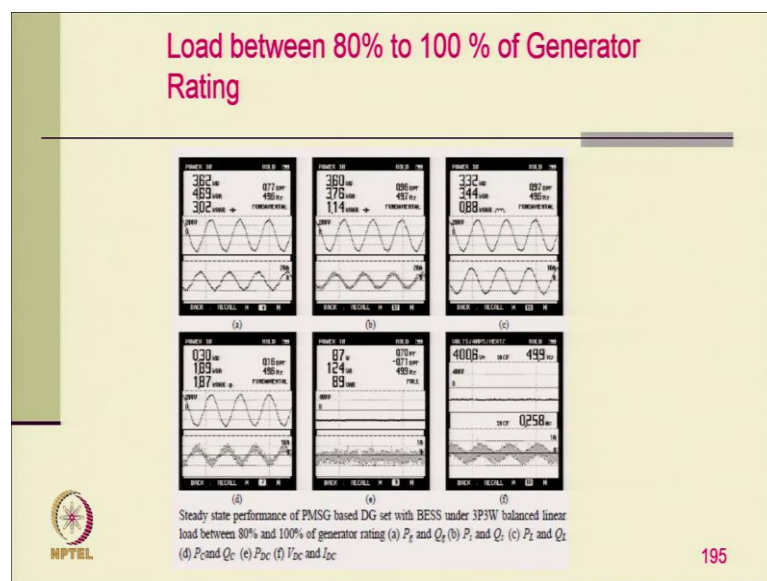
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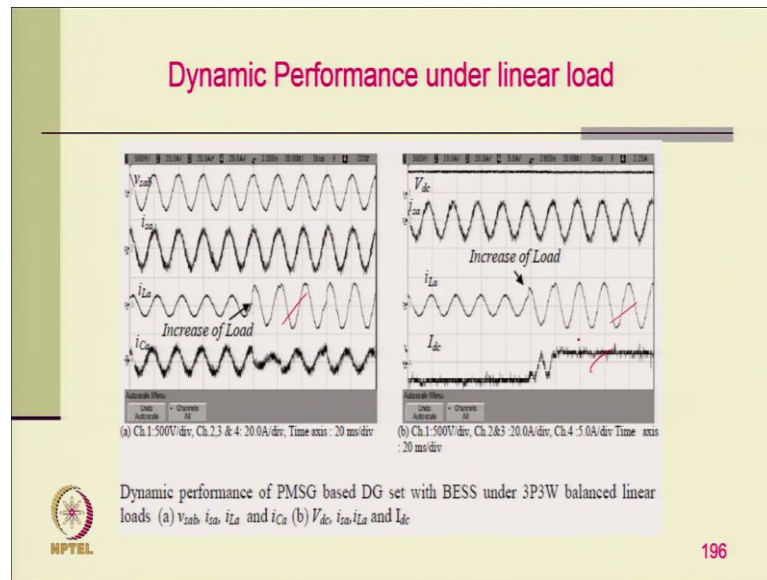
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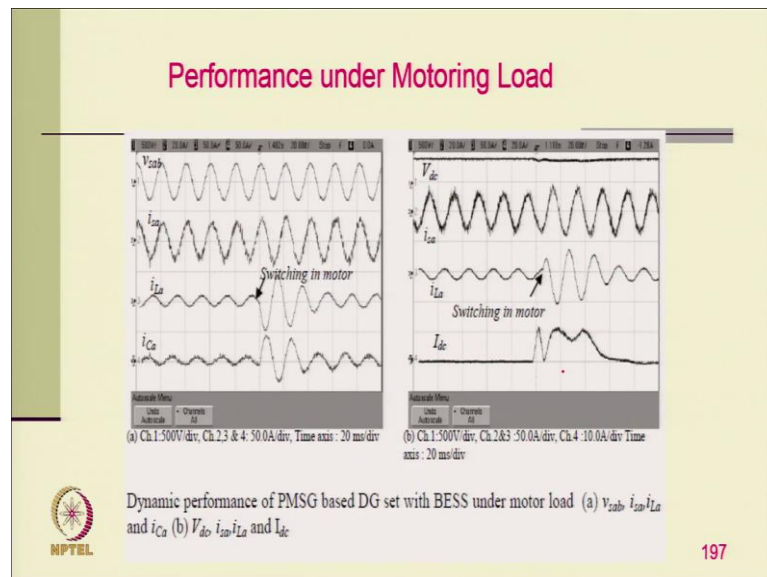


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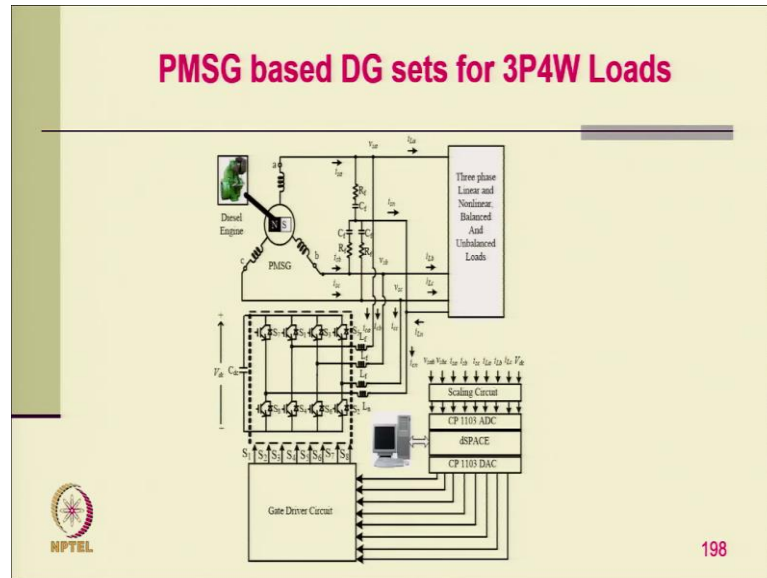


And this is you can say, when load is increased you will not find any change in the generator current. And when the load is off again generator current are not affected. Because the charging and discharging of the battery take place as you can see the battery current here.

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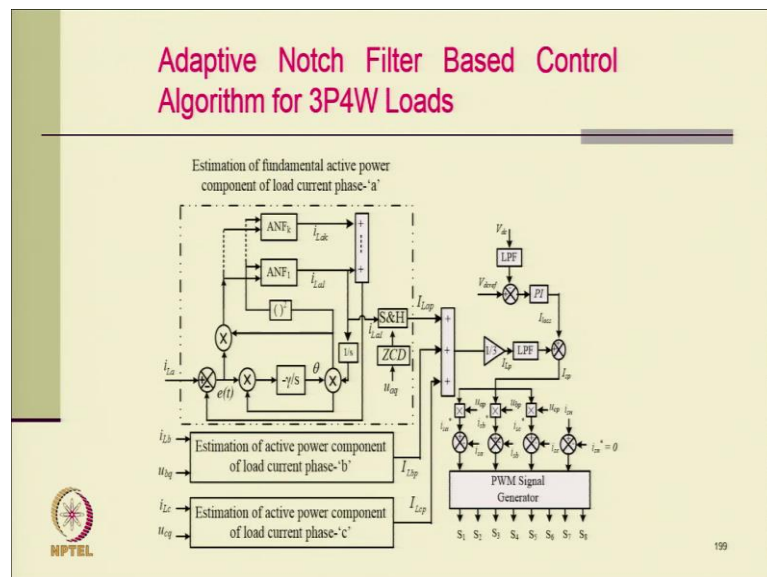


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And now we are coming for 3 phase 4 wire system by providing fourth leg. So, that neutral current is also compensated either with the unbalanced load or with your non-linear load neutral current is always there in 3 phase 4 wire system.

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And this is the typical control we are using here notch adapting notch filter.



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### Simulated Performance of PMSG based DG set under 3P4W Linear loads


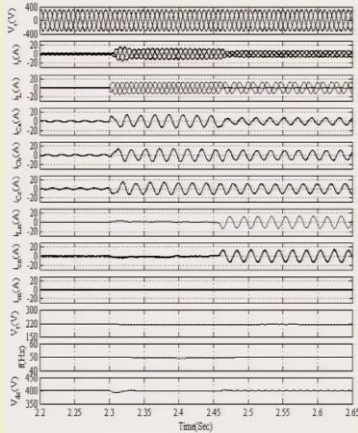
- Initially system is at no load and it is subjected to a RL load of 3 kW at 0.8 lagging power factor at  $t = 2.3$  s.
- The system is subjected to unbalanced load by removing load from phase 'a' at  $t = 2.45$  s.



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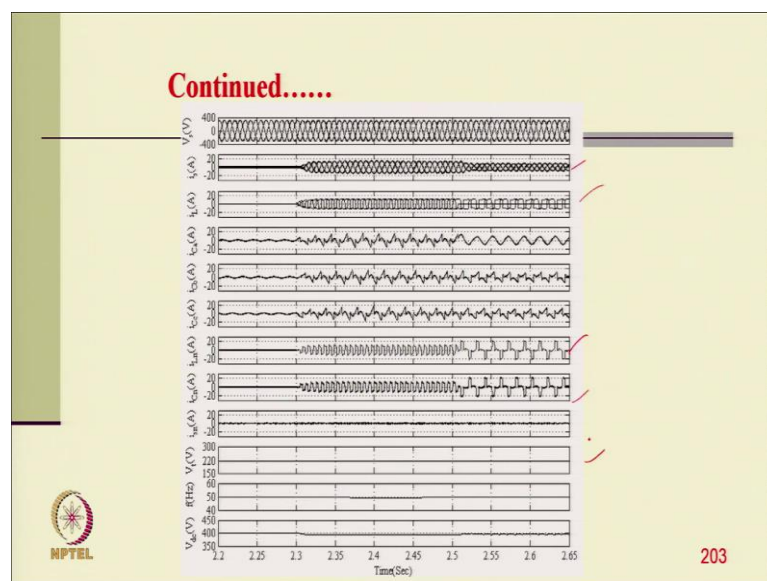
### Simulated Performance of PMSG based DG set under 3P4W Nonlinear loads

- Initially system is at no load and it is subjected to a non-linear load of 3.7 kW at  $t = 2.3$  s.
- The system is subjected to unbalanced load by removing load from phase 'a' at  $t = 2.5$  s.

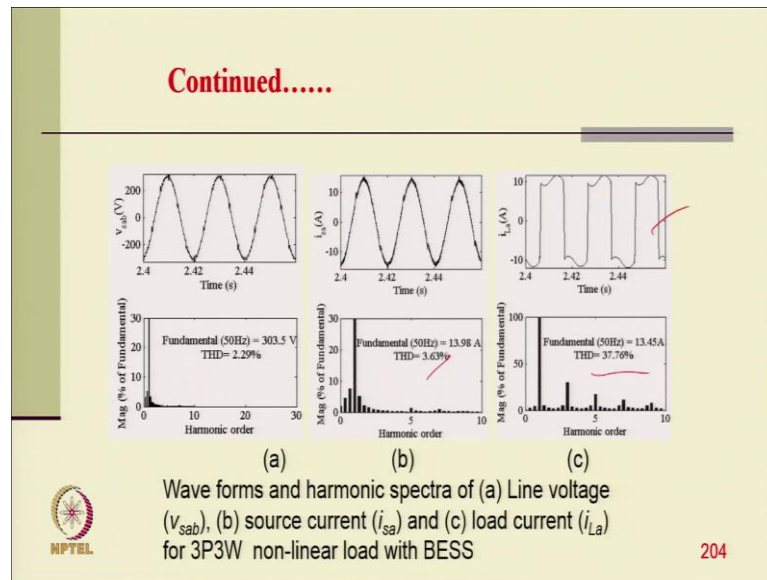


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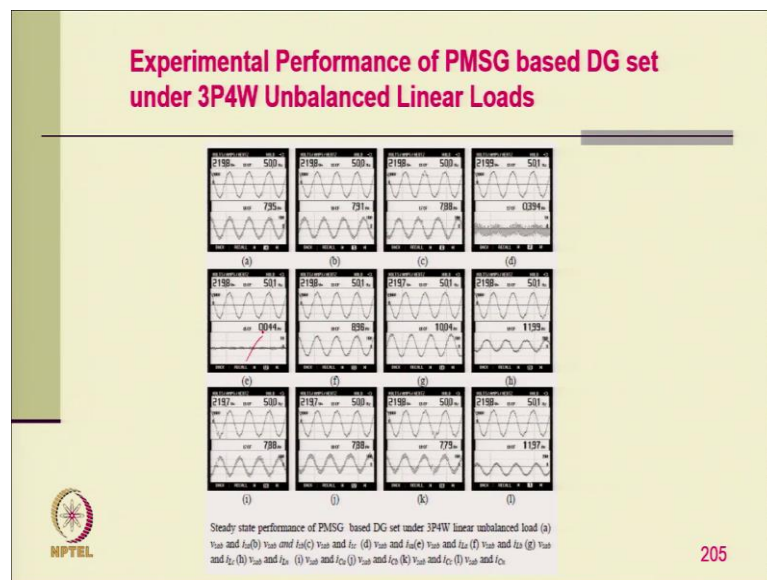


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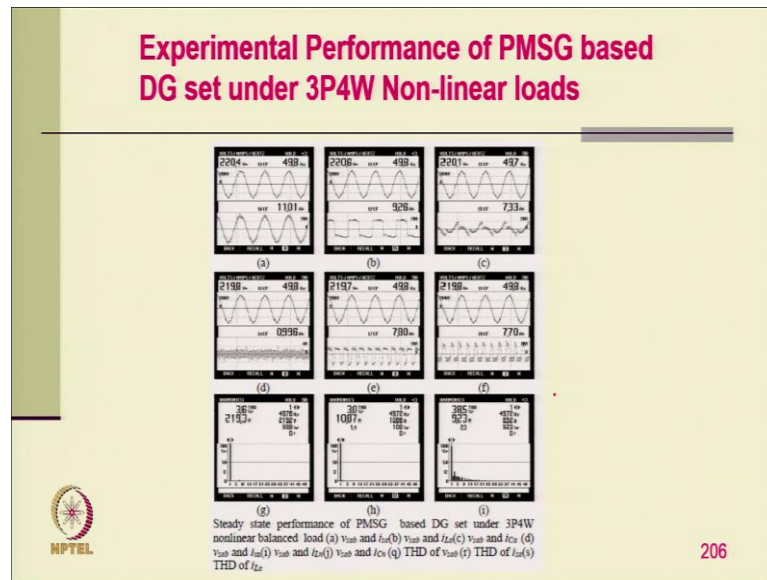
And you have a total harmonic distortion of the load current around 37.76 %, but the generator current THD is 3.63 % and the terminal voltage THD is 2.129 %.

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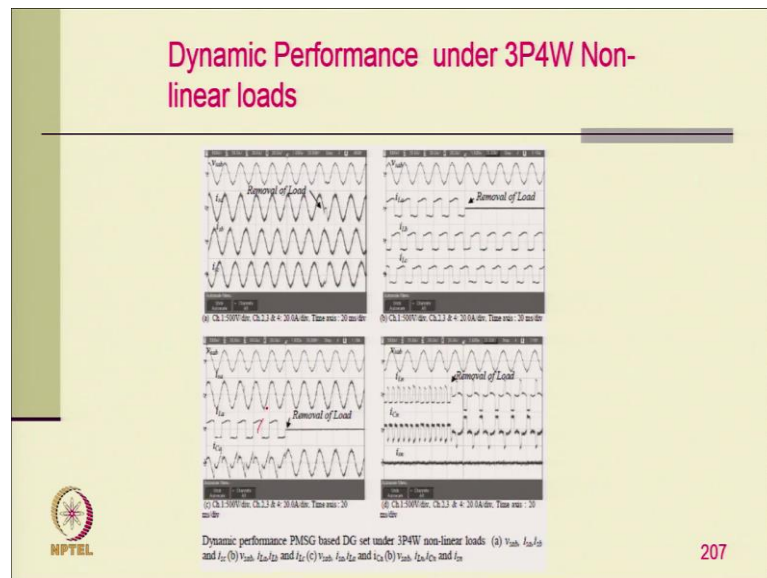
And you can see the here under unbalanced load, you are able to have a balance generator current with the node current almost negligible.

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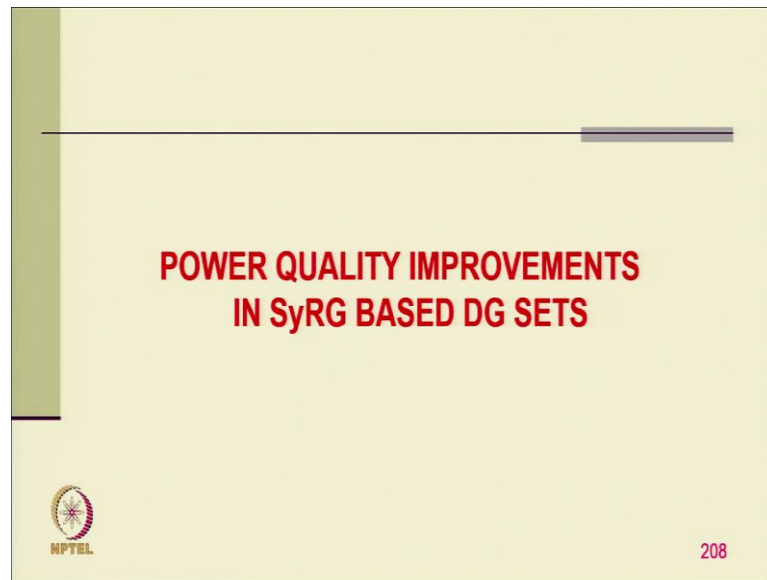


The voltage THD is 3.6 percent and where the generator current THD 3 percent where the load current THD 38.5 percent like.

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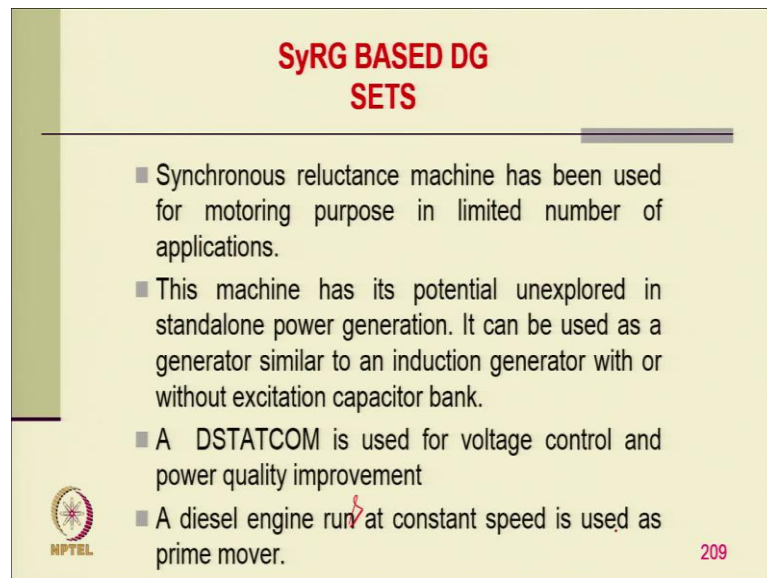


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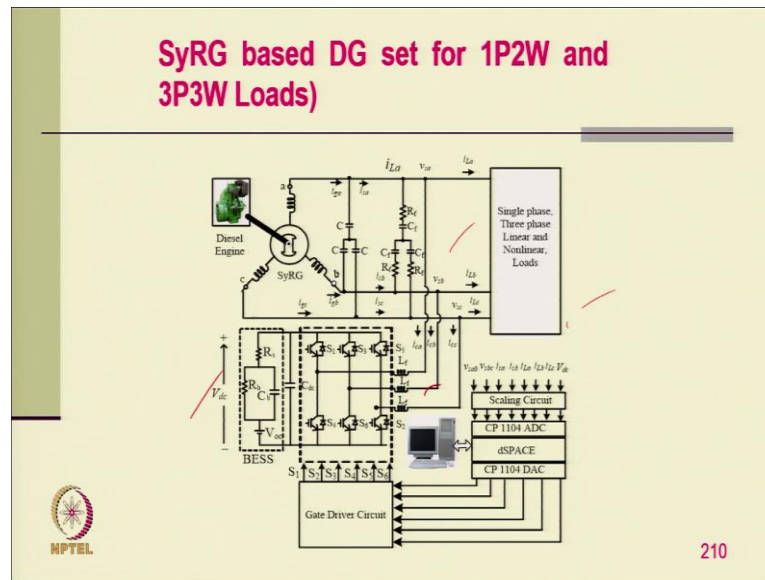


Now, coming to the power quality improvement in synchronous reluctance based DG set.

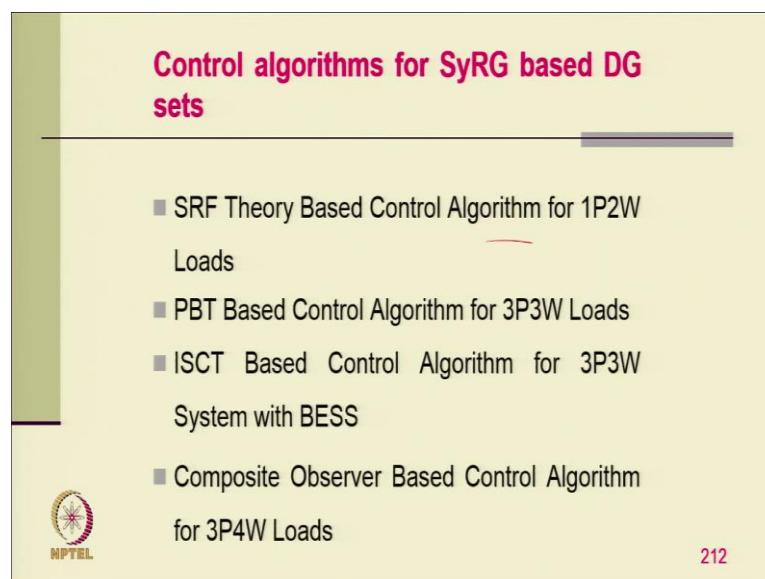
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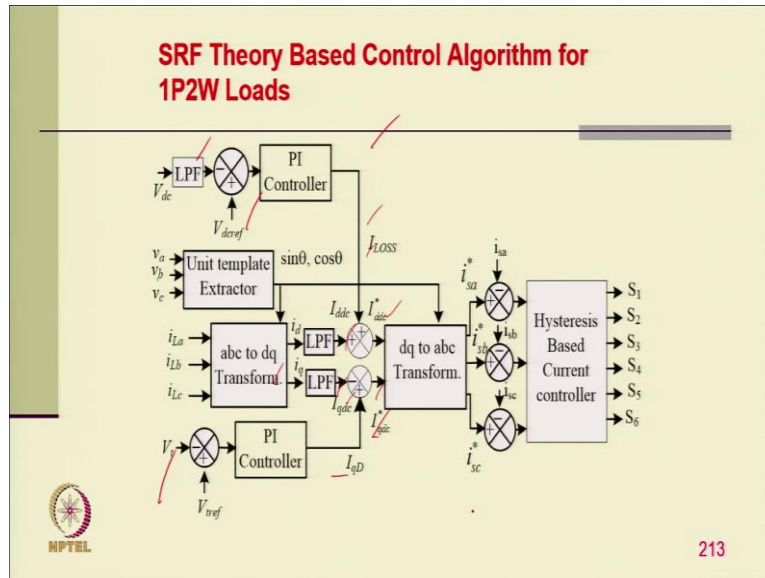


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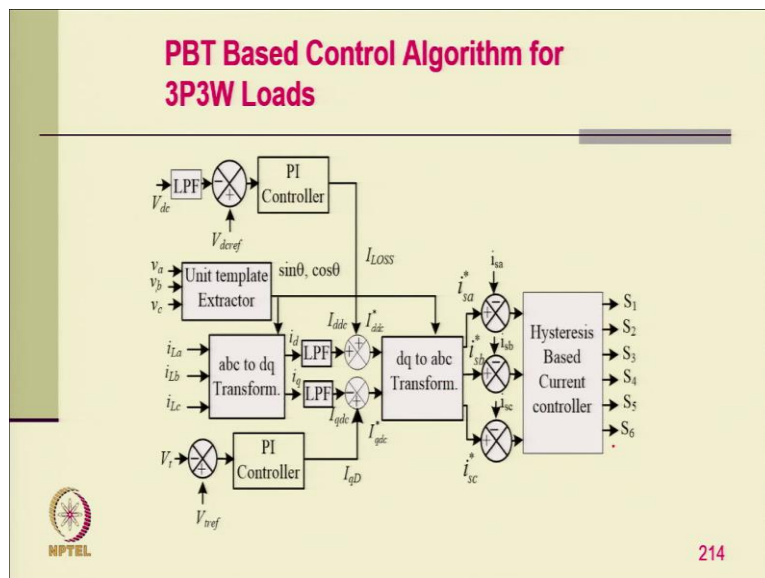
We have used here the synchronous reference frame theory for typical case of single phase load and power balance theory for 3 phase 3 wire load.

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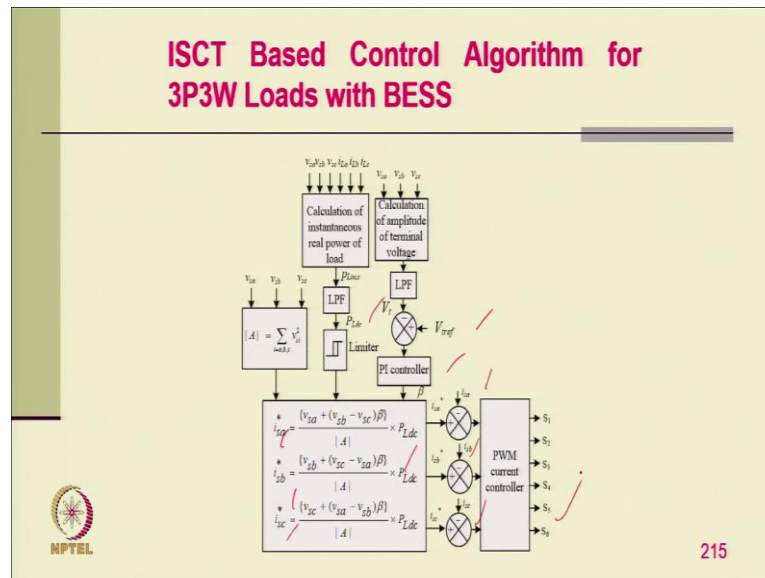
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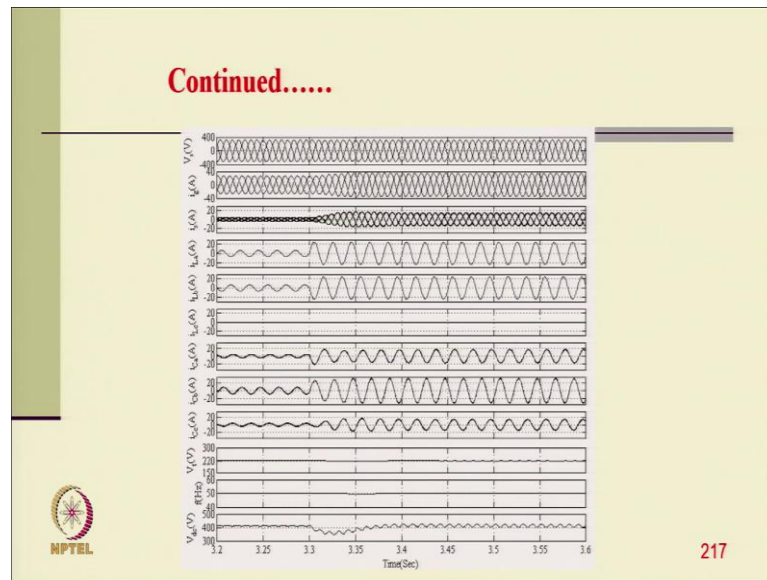
### Simulated Performance of SyRG based DG set under 1P2W Linear Loads

- The DG set is initially loaded with a single phase load of 1 kW at lagging power factor of 0.8 connected between phases 'a' and 'b'.
- Then it subjected to a load of 3.4 kW at  $t = 2.5$  s.

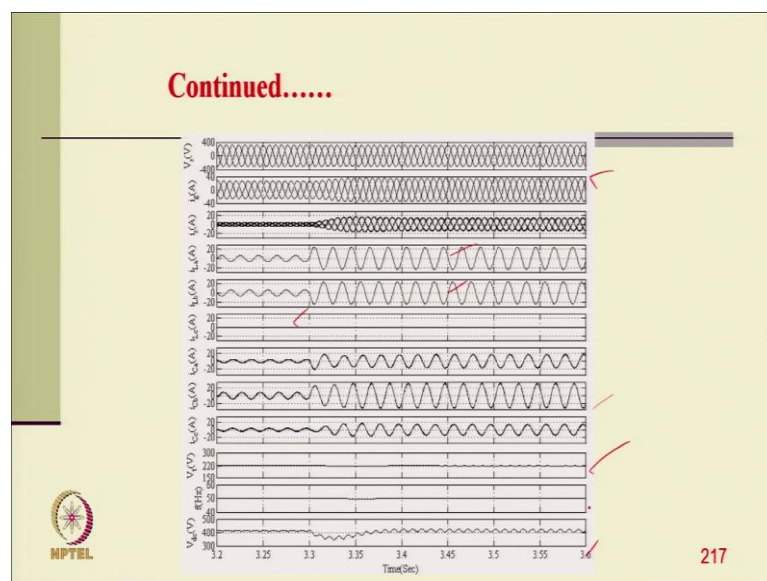
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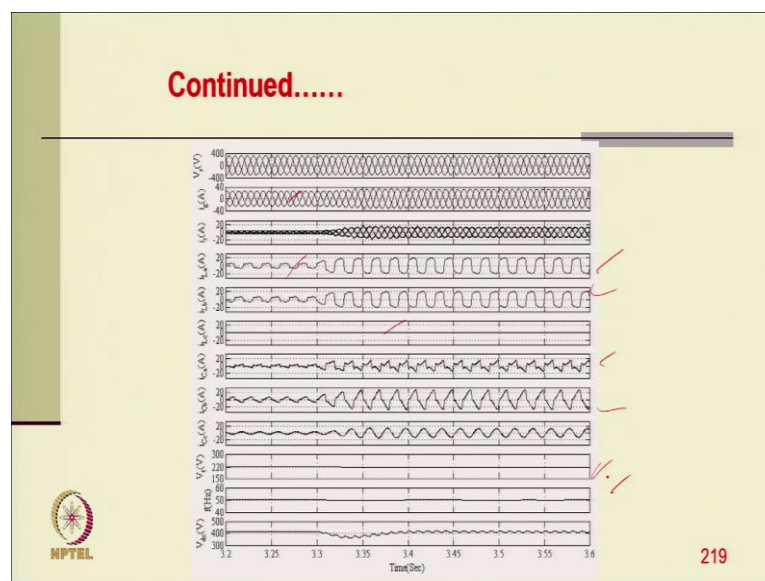
### Simulated Performance of SyRG based DG set under 1P2W Nonlinear Loads

- The system is loaded with a single phase rectifier load connected between phases 'a' and 'b'.
- Initially system is subjected to a load of 1 kW and then it is subjected to load of 3.6 kW at  $t = 2.6$  s.



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### Simulated Performance of SyRG based DG set under 3P3W Linear Loads


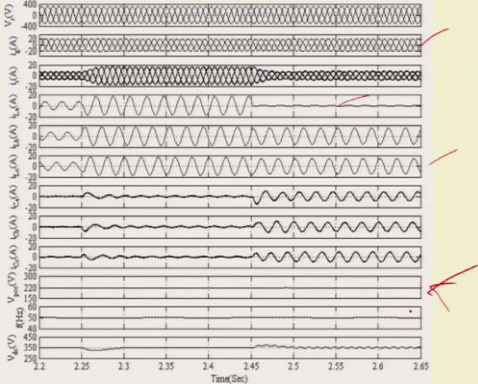
- Initially system is subjected to a inductive load of 1.6 kW with lagging power factor of 0.8.
- At  $t = 2.25$  s the set is subjected to load of 3.6 kW with lagging power factor 0.8.
- At  $t = 2.45$  s the system is subjected to unbalanced load by removing load from phase 'a'.



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### Simulated Performance of SyRG based DG set under 3P3W Nonlinear Loads


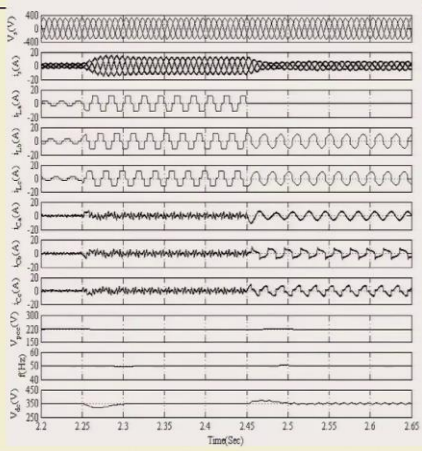
- Initially system is subjected to a non-linear load of 1 kW and then it is subjected to non-linear load of 3.7 kW at  $t=2.25$  s.



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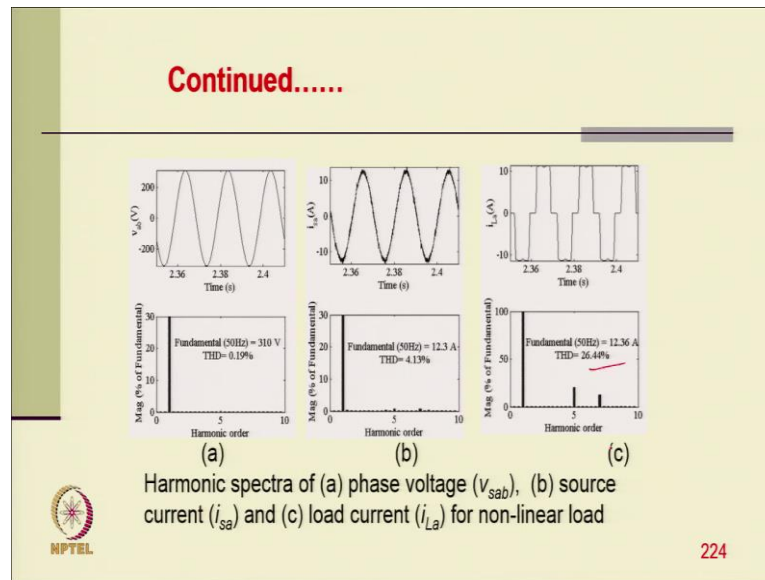
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And this is the typically harmonic spectrum of load current is 24.44 percent, total harmonic distortion where generator current is 4.13 percent and the terminal voltage THD is only 0.19 percent.

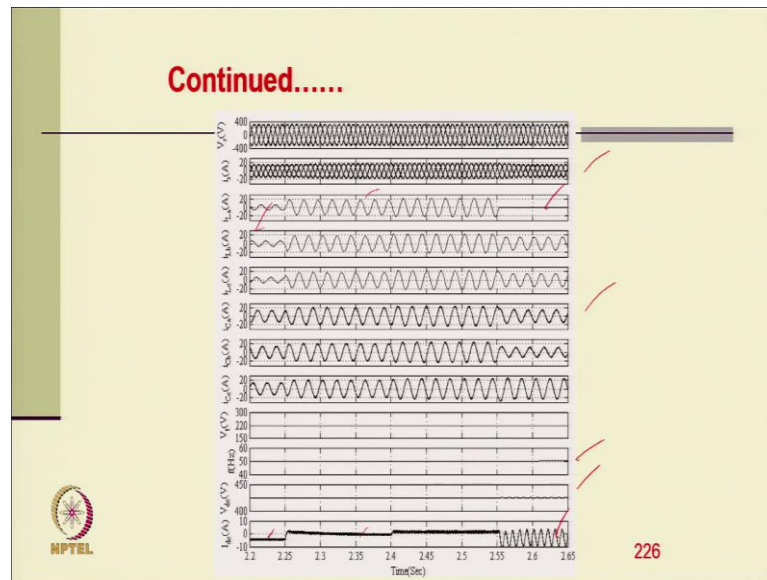
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**Simulated Performance of SyRG based DG set with BESS under 3P3W Linear Loads**

- Initially system is subjected to a load of 1.2 kW at 0.8 lagging power factor which is less than 80 % of generator rating so battery is taking a charging current.
- At  $t = 2.25$  s a load of 3.6 kW is connected to the system.
- This load is almost equal to the rating of generator so whole of the load power is drawn from the source and the battery current is almost zero.

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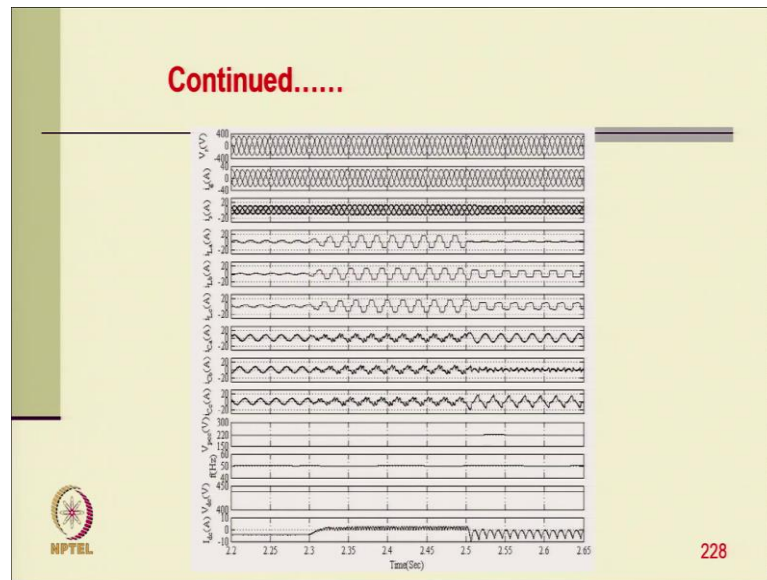
**Simulated Performance of SyRG based DG set with BESS under 3P3W Nonlinear loads**

- Initially system is subjected to a non-linear load of 840 W then it is subjected to non-linear load of 4.4 kW at  $t=2.3$  s.
- From  $t=2.5$  s to 2.65, the system is subjected to unbalanced load by removing load from phase 'a'.

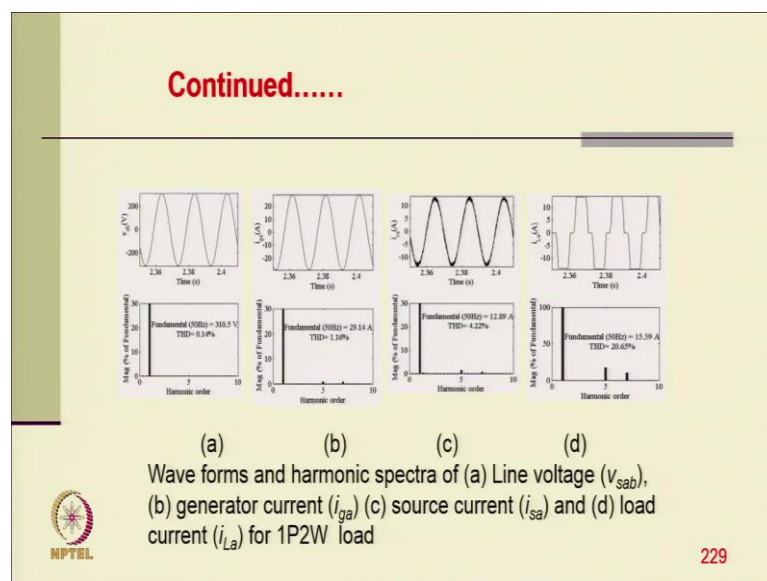
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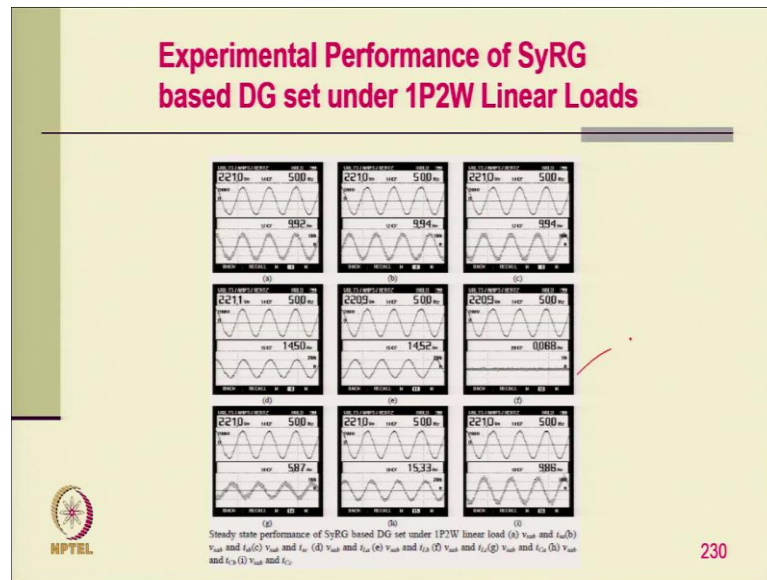
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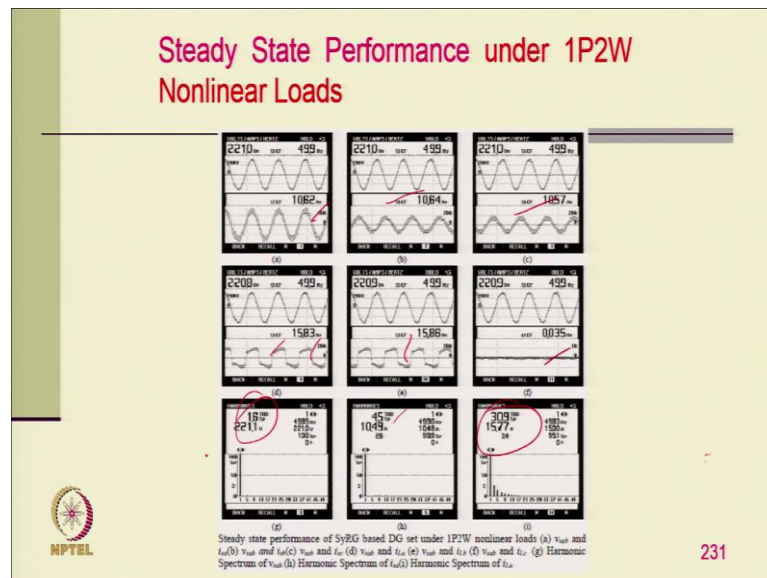


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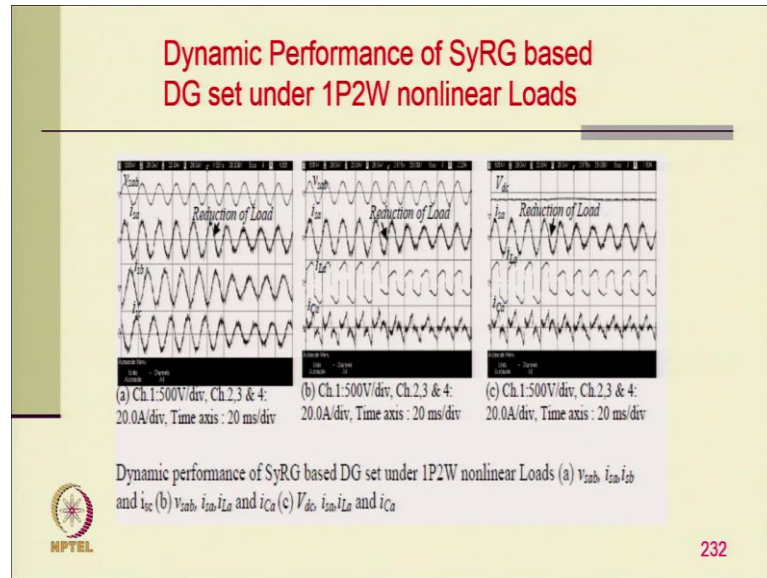
And this is the THD of load current 20.6 percent whereas the source current is 4.22 percent. And where the generator current THD 1.16 and the voltage THD 0.14 percent.

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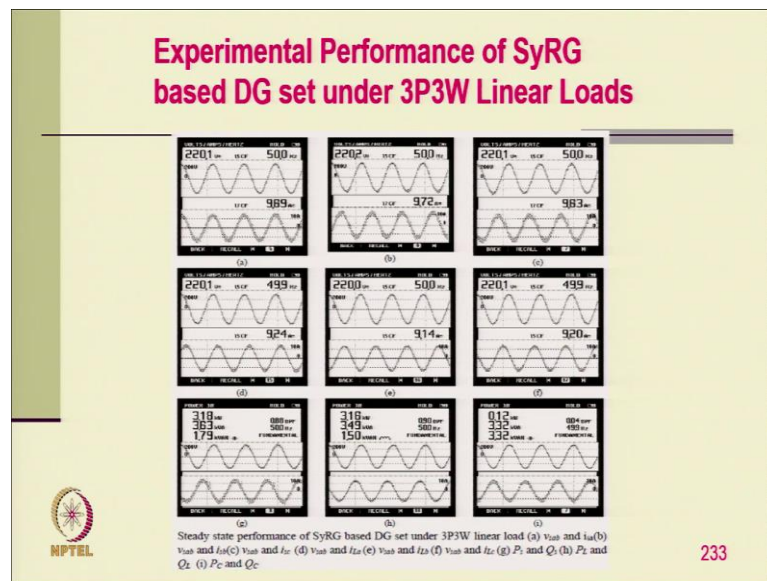




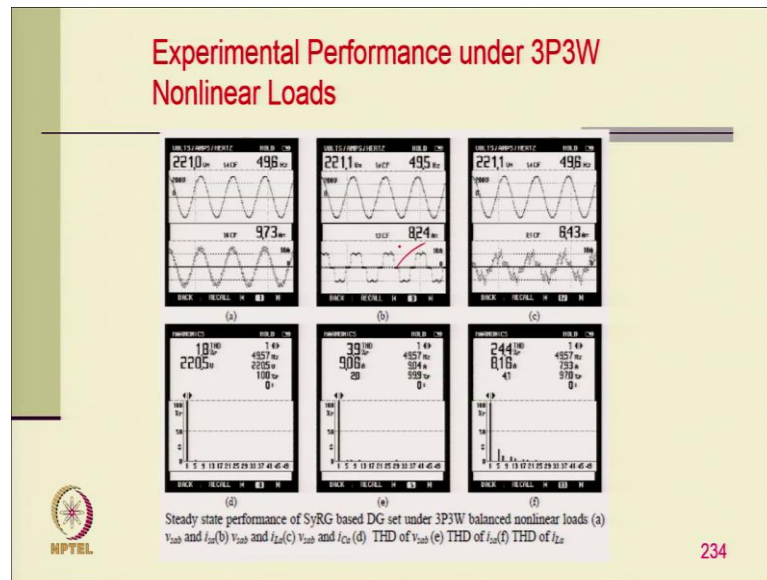
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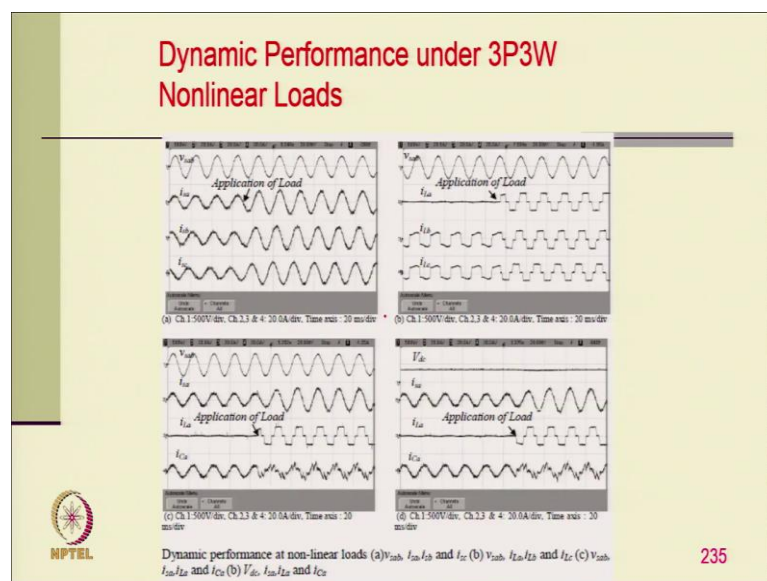
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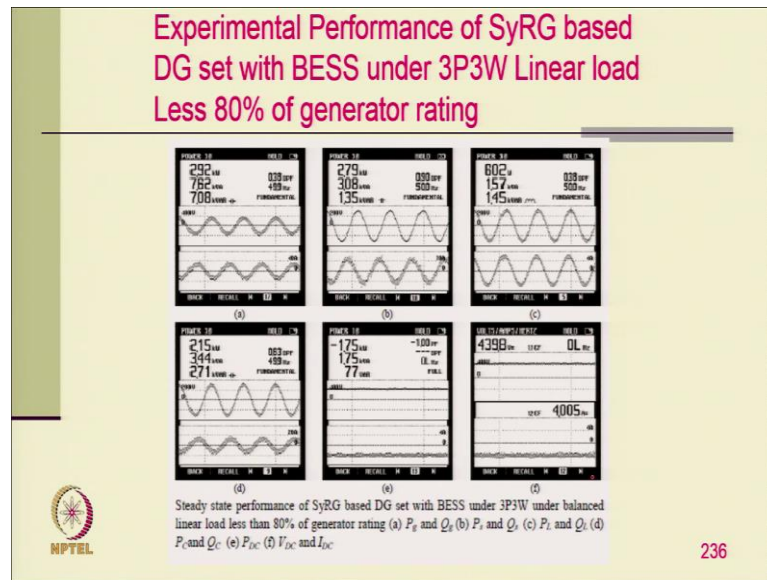
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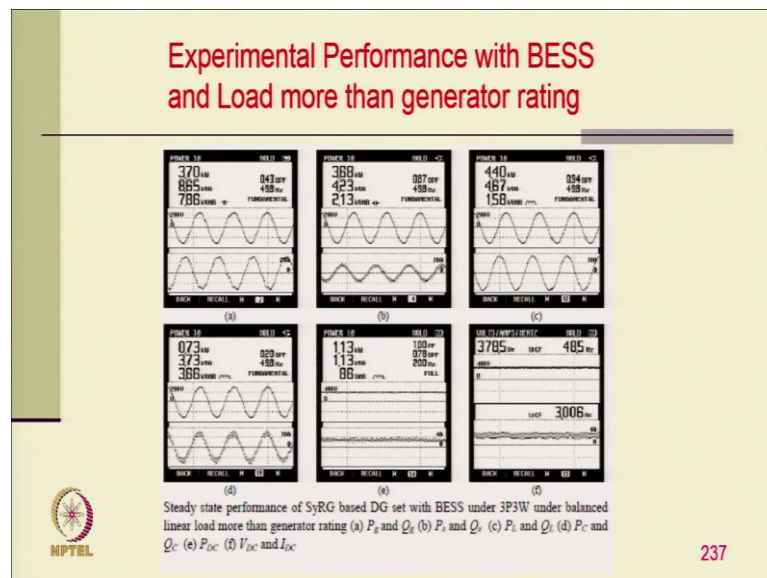
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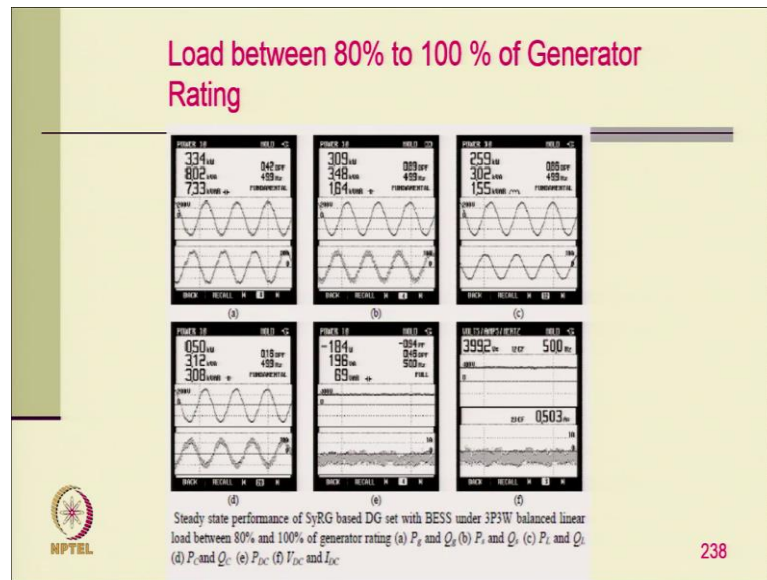
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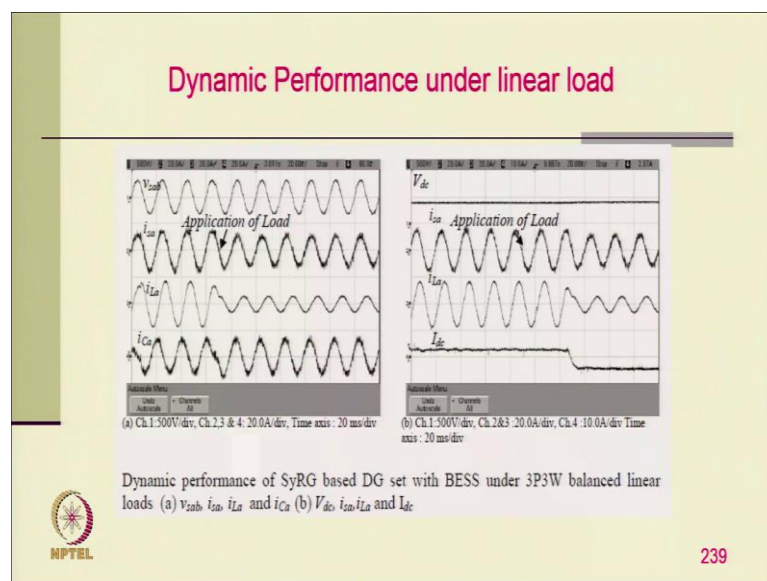
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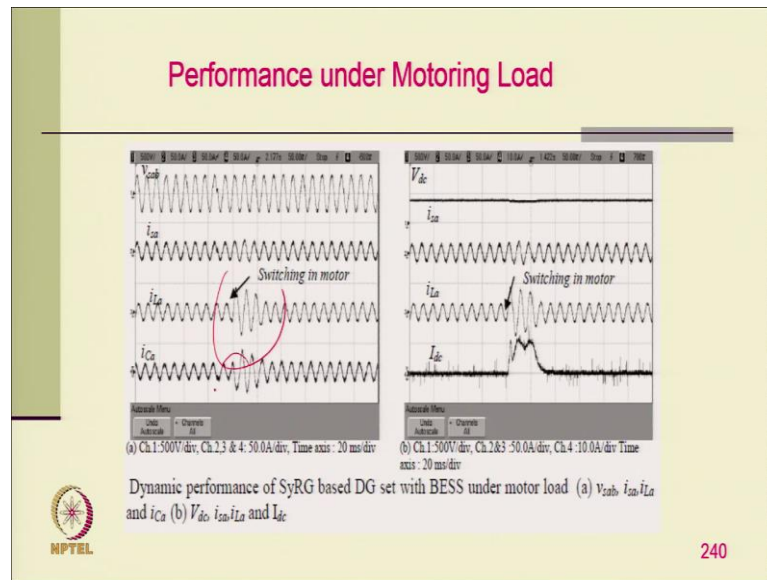
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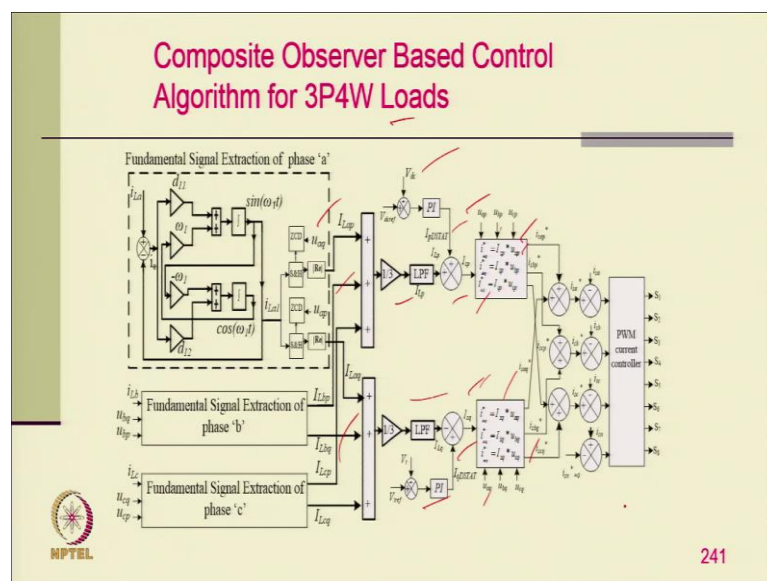
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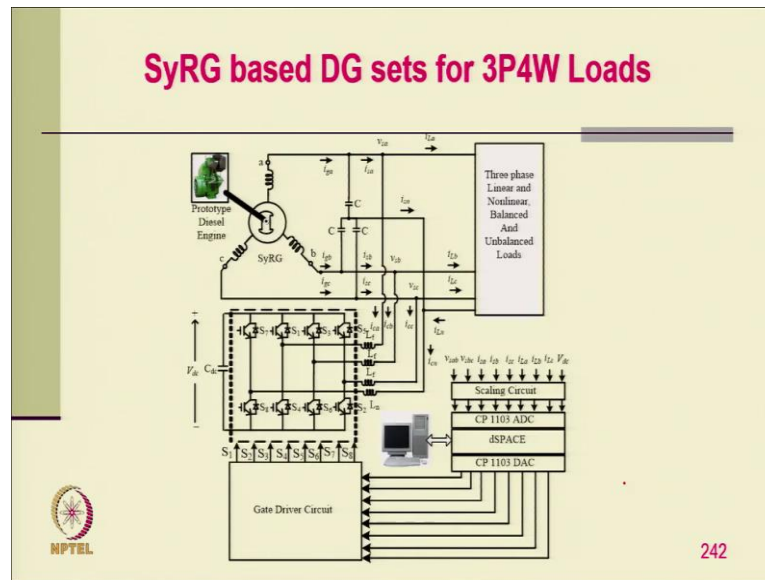
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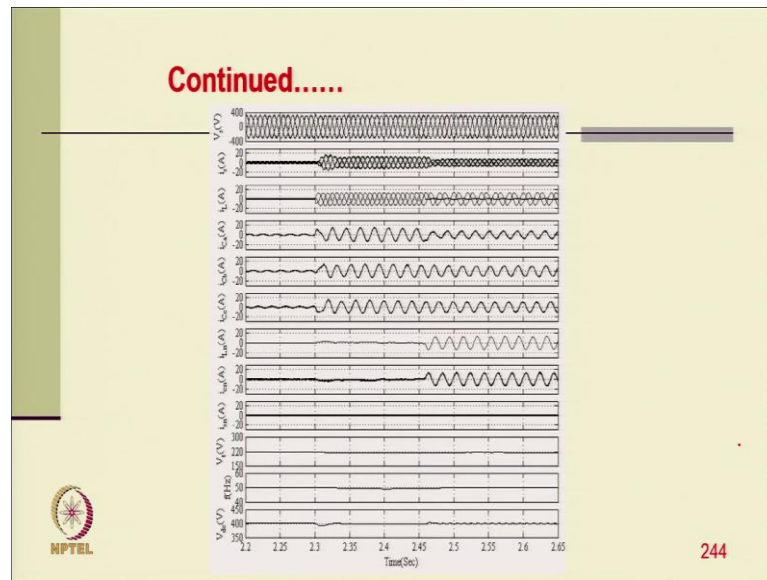
### Simulated Performance of SyRG based DG set under 3P4W Linear loads

- Initially system is at no load and it is subjected to a RL load of 3 kW at 0.8 lagging power factor at  $t = 2.3$  s.
  
- The system is subjected to unbalanced load by removing load from phase 'a' at  $t = 2.45$  s.



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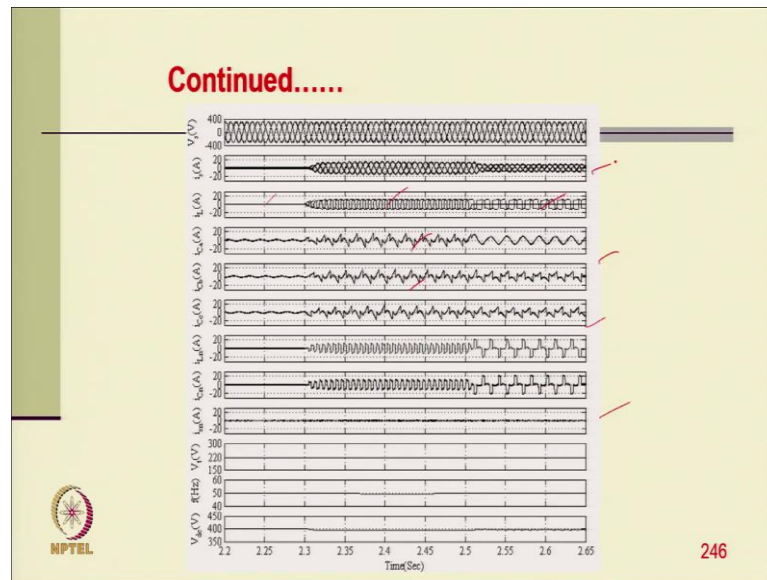
**Simulated Performance of SyRG based DG set under 3P4W Nonlinear loads**

- Initially system is at no load and it is subjected to a non-linear load of 3.7 kW at  $t = 2.3$  s.
- The system is subjected to unbalanced load by removing load from phase 'a' at  $t = 2.5$  s.

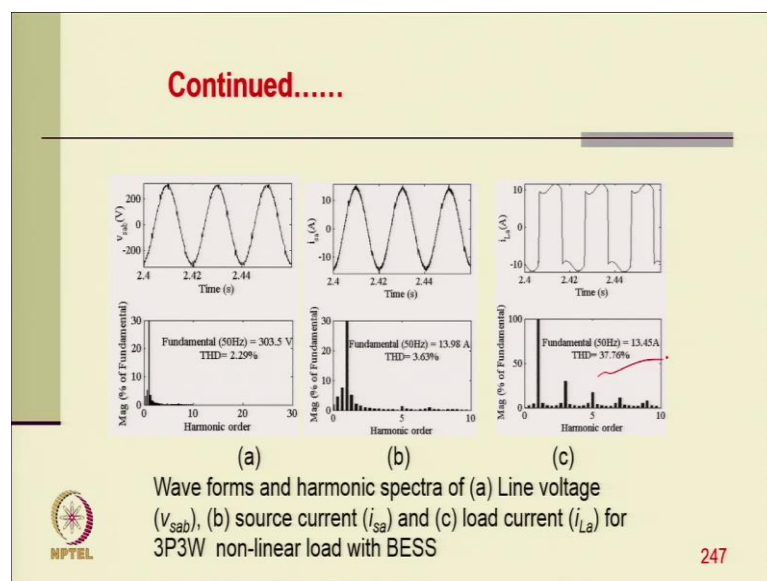
NPTEL

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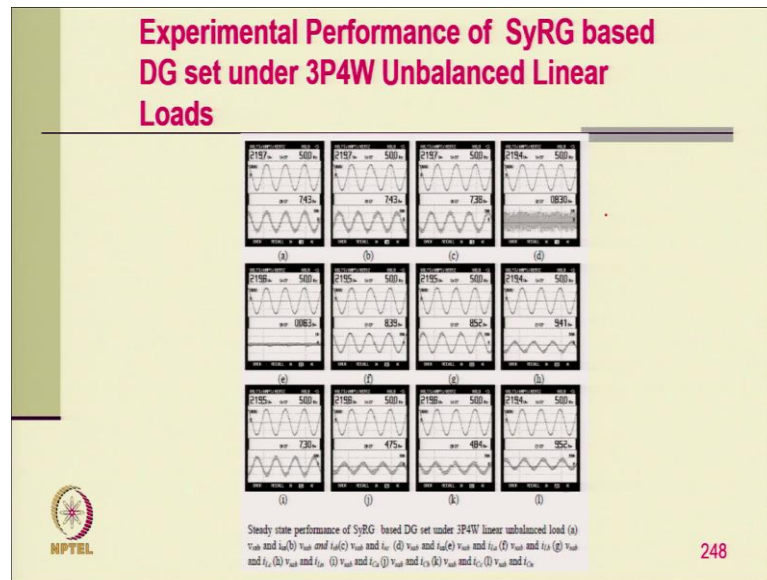
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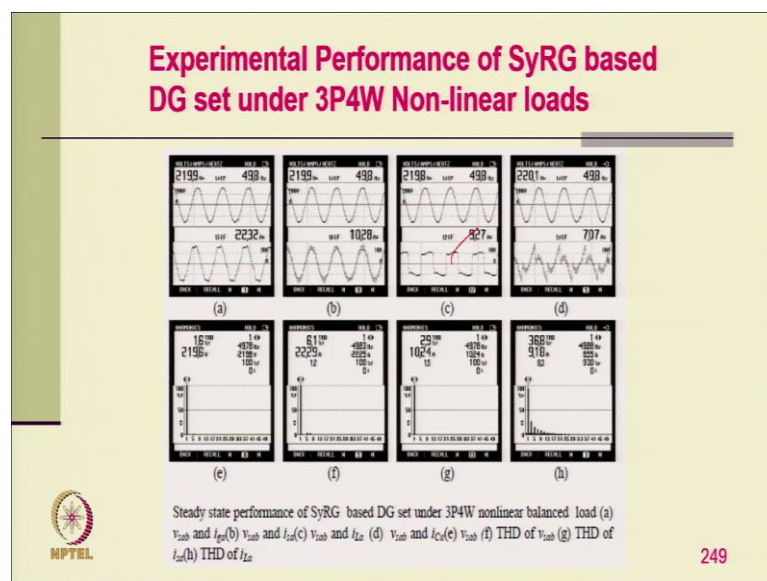
And the THD of the load current is 37.76 percent, where the THD of your generator current is 3.63 percent and terminal voltage THD 2.29 percent.



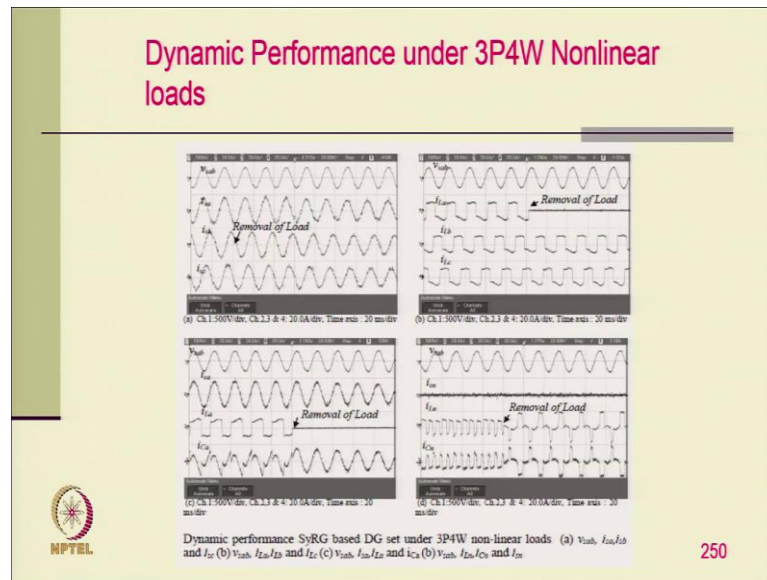
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## Numerical Problems

NPTEL 251

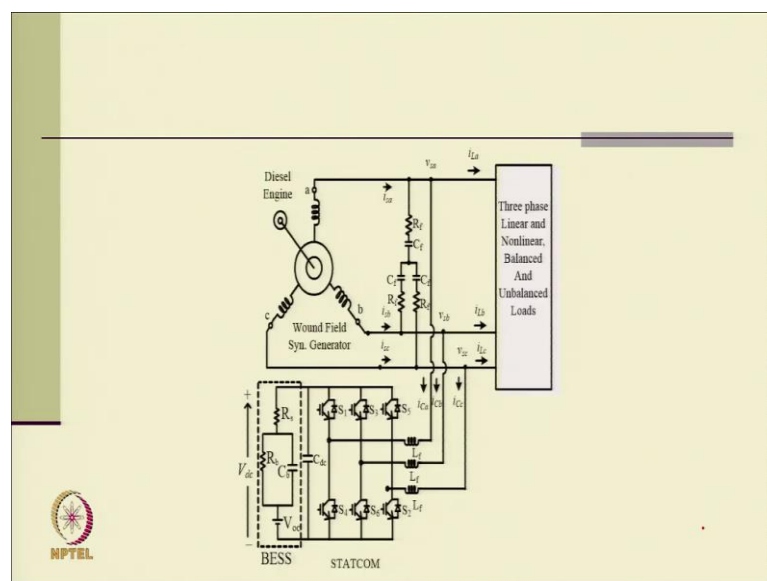
Now, coming to the numerical problems.

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**Q1.** A 415V 75kVA synchronous machine based isolated diesel generator (DG) system is integrated with a 660V battery through a VSI. This DG system is controlled such that the load on the system remains always between 80 and 100% of generator capacity to improve the efficiency of the DG system. If load is below 80%, the battery charging takes place; if the load is beyond 100%, discharging of the battery takes place; and in between 80 and 100% load, the battery remains in floating condition. There is a load shedding provision if load increases above 125%. Calculate the watt-hour rating and the current of the battery if at peak load (125%) a backup of 4 h is desired.



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**Solution:** Given that an isolated three-phase three-wire 415 V, 75 kVA diesel engine generating (DG) system based on synchronous generator is connected with a 660 V battery at the DC side of a VSC.


The watt-hour rating of the battery if at full load a backup of 4 h is desired is  $E = \% \text{ of the full load} \times PH = 0.25 \times 75 \times 4 = 75 \text{ kWh}$  (since the battery is required to feed 25% of the full load active power).

The battery current is  $I_b = E/V_b H = 75\ 000/(660 \times 4) = 28.41 \text{ A}$ .

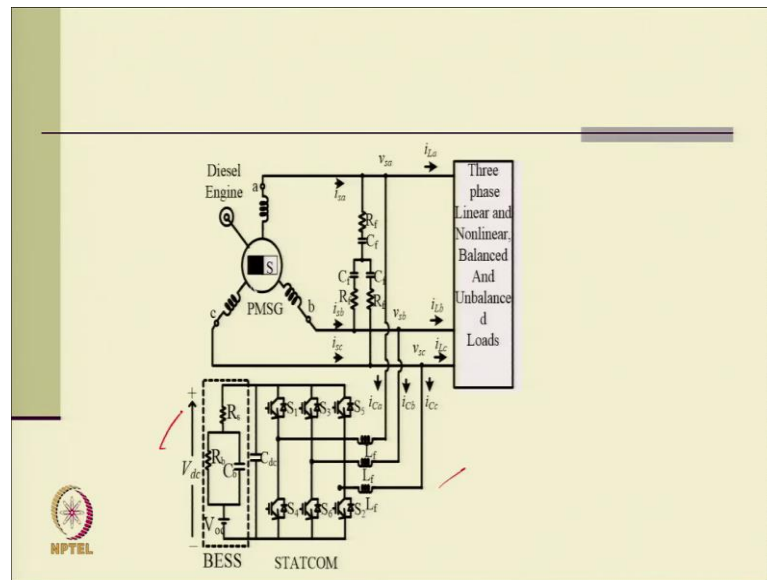


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**Q2.** A 400V 50kVA PMSG based isolated diesel generator (DG) system is integrated with a 720V battery through a VSI. This DG system is controlled such that the load on the system remains always between 80 and 100% of generator capacity to improve the efficiency of the DG system. If load is below 80%, the battery charging takes place; if the load is beyond 100%, discharging of the battery takes place; and in between 80 and 100% load, the battery remains in floating condition. Calculate the apparent power flow through the VSI if a 0.8 power factor linear load with (a) 50% of DG capacity (50% of 50kW), (b) 85% of DG capacity, and (c) 110% of DG capacity is connected to the DG set.



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This is the typical system with the battery which provide the power leveling.

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**Solution:** Given that an isolated three-phase three-wire 415 V, 50 kVA diesel engine generating (DG) system based on PMSG is connected with a 720 V battery at the DC side of a VSC.

(a) The active power of load = 50% of capacity =  $50 \times 0.5 = 25 \text{ kW}$   
 Reactive power of load =  $P \tan \Phi = 18.75 \text{ kVAR}$

Active power from DG set = 80% of capacity (for optimal fuel consumption) =  $50 \times 0.8 = 40 \text{ kW}$

Active power through the VSC is  $P_{VSI} = P_{dg} - P_l = 40 - 25 = 15 \text{ kW}$  (battery charging)

Reactive power through the VSC is  $Q_{VSI} = 18.75 \text{ kVAR}$


Apparent Power =  $S_{VSI} = \sqrt{P_{VSI}^2 + Q_{VSI}^2} = 24.01 \text{ kVA}$

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(b) The active power of load = 85% of capacity =  $50 \times 0.85$   
= 42.5 kW  
Reactive power of load =  $P \tan \Phi = 31.875$  kVAR

Active power from DG set = Equal to load (85% of capacity)  
= 42.5 kW

Active power through the VSC is  $P_{VSI} = 0$  kW (battery is floating)  
Reactive power through the VSC is  $Q_{VSI} = 31.875$  kVAR  
Apparent Power =  $S_{VSI} = \sqrt{P_{VSI}^2 + Q_{VSI}^2} = 31.875$  kVA




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(c) The active power of load = 110% of capacity =  $50 \times 1.1$   
= 55 kW  
Reactive power of load =  $P \tan \Phi = 41.25$  kVAR

Active power from DG set = 100% of capacity (for optimal fuel consumption) = 50 kW

Active power through the VSC is  $P_{VSI} = P_{dg} - P_l = 50 - 55 = -5$  kW (battery is discharging)  
Reactive power through the VSC is  $Q_{VSI} = 41.25$  kVAR  
Apparent Power =  $S_{VSI} = \sqrt{P_{VSI}^2 + Q_{VSI}^2} = 41.55$  kVA

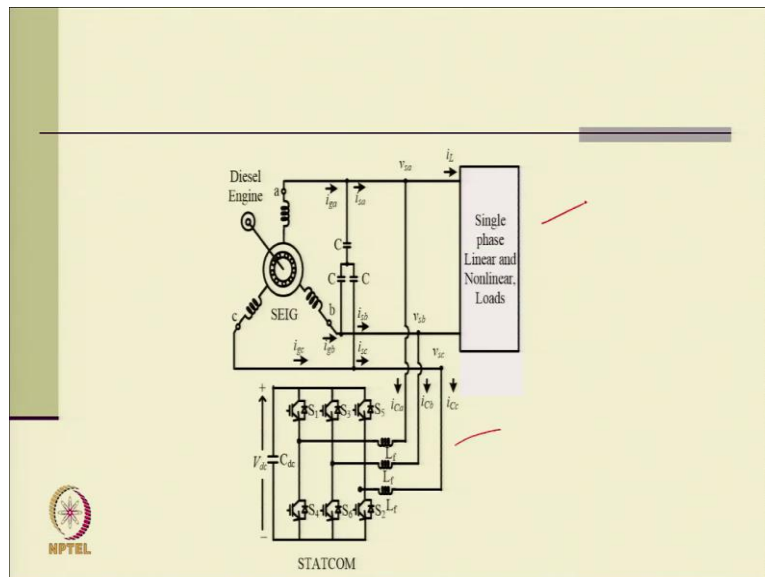


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**Q3** A three-phase 400 V, 22 kW, 50 Hz self-excited squirrel cage induction machine used for diesel generation needs an excitation of 9 kVAR at no load and 15 kVAR at a unity power factor full load. A self supporting PWM-based VSI is used for meeting the reactive power requirements of this induction generator. Considering fixed capacitor rating equal to no load excitation kVAR, calculate the reactive power flow and line current of the VSI at (a) no load, (b) unity power factor full load (22 kW), (c) 0.9 lagging power factor full load (22 kW), and (d) 0.9 leading power factor full load (22 kW).



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**Sol:** Given that a three-phase self-excited 400 V, 22 kW, 50 Hz, squirrel cage induction generator based G set needs the excitation of 9 kVAR at no load and 15 kVAR at a unity power factor full load.

The fixed capacitor kVAR rating is equal to no load excitation =  $Q_C = 9$  kVAR.

**(a) At no load:**

The reactive power flow through the VSI is  $Q_{VSI} = Q_0 - Q_C = 0$  kVAR.

The line current of the VSI is  $I_C = Q_{VSI} / \sqrt{3} V_s = 0 / (\sqrt{3} \times 400) = 0$  A.



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**(b) For a unity power factor full load (22 kW):**

The reactive power flow through the VSI is  $Q_{VSI} = Q_{fl} - Q_C = (15 - 9)$  kVAR = 6 kVAR.


The line current of the VSI is  $I_C = Q_{VSI} / \sqrt{3} V_s = 6000 / (\sqrt{3} \times 400) = 8.66$  A.

**(c) For a 0.9 lagging power factor full load (22 kW):**

Reactive power of load =  $P_t \tan \Phi = 10.65$  kVAR

The reactive power flow through the VSI is  $Q_{VSI} = Q_{fl} + Q_{load} - Q_C = (15 + 10.65 - 9)$  kVAR = 16.65 kVAR.

The line current of the VSI is  $I_C = Q_{VSI} / \sqrt{3} V_s = 22.69 / (\sqrt{3} \times 400) = 24.04$  A.






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(d) For a 0.9 leading power factor full load (22 kW):  
Reactive power of load =  $P_t \tan \phi = 10.65$  kVAR

The reactive power flow through the VSI is  $Q_{VSI} = Q_{fl} + Q_{load} - Q_C = (15 - 10.65 - 9)$  kVAR =  $-4.65$  kVAR.


The negative sign denotes that the VSI has to provide lagging reactive power to maintain unity power factor.

The line current of the VSI is  $I_C = Q_{VSI} / \sqrt{3} V_s = 4650 / (\sqrt{3} \times 400) = 6.71$  A.

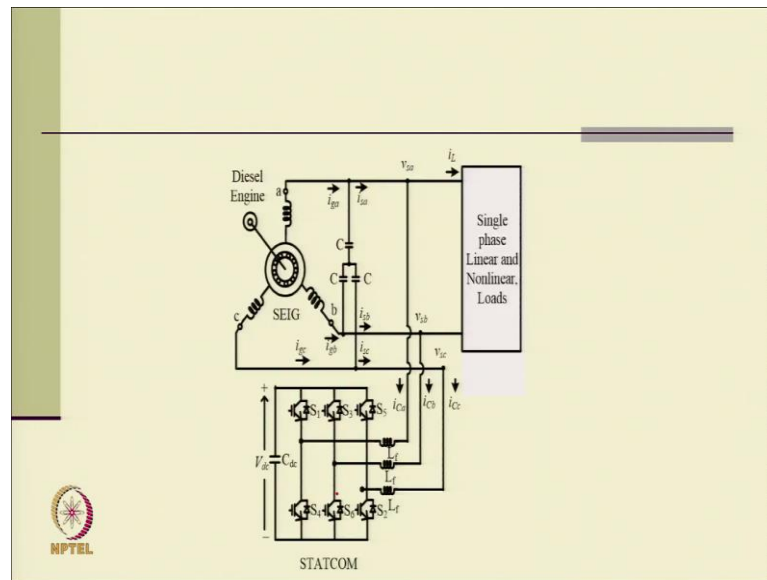


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**Q4** In the previous question, if a fixed capacitor bank is used for reducing the rating of the VSI and the VSI is used only for smooth control of voltage at rated value, then calculate the kVAR rating and line current of the VSI at (a) unity power factor full load (22 kW), (b) 0.9 lagging power factor full load (22 kW), and (c) 0.9 leading power factor full load (22 kW).



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This is the typical system.

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In a reduced rating VSI-based voltage regulator, as the VSI can work in leading and lagging reactive power modes depending on the extent of load, its rating can be reduced by using an appropriate rating AC capacitor at the induction generator terminals to cover total range of the operation.

In most of the cases, half the required rating (other than no load) can be selected as the rating of the VSI and full load required reactive power rating is selected as the rating of the AC capacitor.

At no load, the VSI works as an inductor and at full load it works as a capacitor.




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**(a) For a unity power factor full load (22 kW):**  
The kVAR rating of the DSTATCOM is  $Q_{VSI} = (Q_{fl} - Q_0)/2 = (15 - 9)/2 = 3$  kVAR.

Since the capacitor rating is  $Q_C = Q_0 + (Q_{fl} - Q_0)/2 = 9 + (15 - 9)/2 = 9 + 3 = 12$  kVAR.

At no load the VSI is to provide 3 kVAR lagging reactive power and at full load the VSI is to provide 3 kVAR leading reactive power to the diesel generator system

The line current of the VSI is  $I_{VSI} = Q_{VSI}/\sqrt{3}V_s = 3000/(\sqrt{3}\times 400) = 4.33$  A.



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**(b) For a 0.9 lagging power factor full load (22 kW)**  
Reactive power of load =  $P_t \tan \Phi = 10.65$  kVAR


The kVAR rating of the VSI is  $Q_{VSI} = (Q_{fl} + Q_{load} - Q_0)/2 = (15 + 10.65 - 9)/2 = 8.325$  kVAR.

The line current of the VSI is  $I_{VSI} = Q_{VSI}/\sqrt{3}V_s = 8325/(\sqrt{3}\times 400) = 12.02$  A.

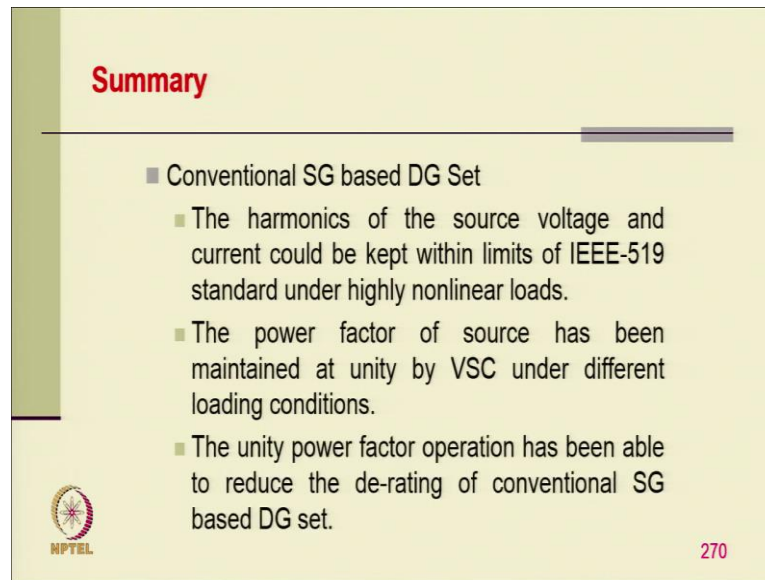
**(c) For a 0.9 leading power factor full load (22 kW)**  
Reactive power of load =  $P_t \tan \Phi = 10.65$  kVAR

The kVAR rating of the VSI is  $Q_{VSI} = (Q_{fl} + Q_{load} - Q_0)/2 = (15 - 10.65 - 9)/2 = -2.325$  kVAR.

The line current of the VSI is  $I_{VSI} = Q_{VSI}/\sqrt{3}V_s = 2325/(\sqrt{3}\times 400) = 3.35$  A.




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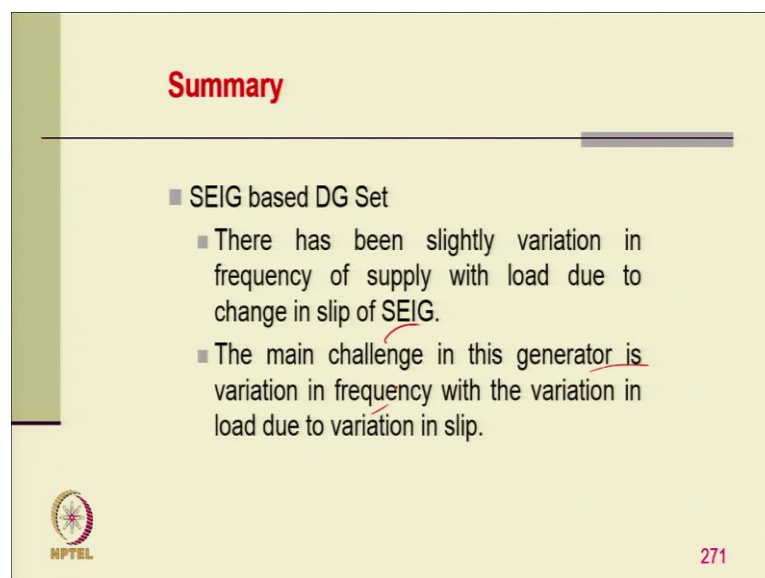
**Summary**

- Conventional SG based DG Set
  - The harmonics of the source voltage and current could be kept within limits of IEEE-519 standard under highly nonlinear loads.
  - The power factor of source has been maintained at unity by VSC under different loading conditions.
  - The unity power factor operation has been able to reduce the de-rating of conventional SG based DG set.

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So, with this, we like to summarize, the power quality improvement in DG set. We discussed conventional synchronous generator based DG set. The harmonics of the source voltage or generator voltage and the current are kept within the limit of IEEE 519 standard under highly non-linear load, and, the power factor of the source has been maintained at unity by voltage source converter operating under different conditions.

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**Summary**

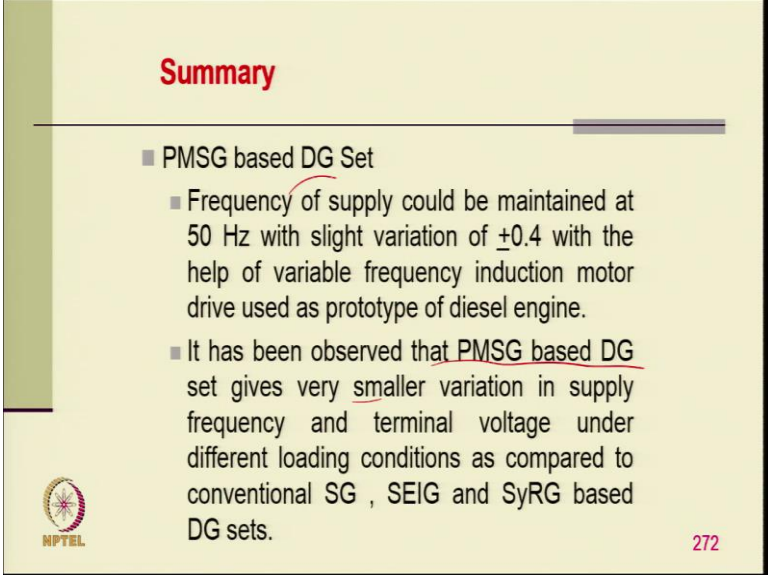
- SEIG based DG Set
  - There has been slightly variation in frequency of supply with load due to change in slip of SEIG.
  - The main challenge in this generator is variation in frequency with the variation in load due to variation in slip.

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Now, coming to self excited induction generator based DG set. There has been a slightly variation in the frequency of the supply with the load due to changing of the slip in the


self excited induction generator. The main challenge in this generator is to variation frequency with variation of load due to variation in slip.

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**Summary**

- PMSG based DG Set
  - Frequency of supply could be maintained at 50 Hz with slight variation of  $\pm 0.4$  with the help of variable frequency induction motor drive used as prototype of diesel engine.
  - It has been observed that PMSG based DG set gives very smaller variation in supply frequency and terminal voltage under different loading conditions as compared to conventional SG , SEIG and SyRG based DG sets.

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In case of permanent synchronous generator based DG set the frequency of supply could be maintained 50 percent with slight variation of plus minus 0.4 with the help of variable frequency drive used as a prototype. It has been observed that the PMSG based set DG set give the very smaller variation in the supply frequency and the terminal voltage under different loading conditions as compared to conventional synchronous, SEIG and synchronous generator set.

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## Summary

- SyRG based DG Set
  - It gives very small variation supply frequency under different loads unlike SEIG.
  - The variation in terminal voltage is also small.
  - The main disadvantage of this generator is that it requires heavy excitation current as compared to SEIG. So, the size of this generator is largest among conventional SG, SEIG and PMSG of the same rating

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Coming to synchronous reluctance generator set it give the very small variation in supply frequency under different loads unlike SEIG. And the variation in terminal voltage is also small. And the main disadvantage of this generator is that it requires a heavy excitation current as compared to self excitation. So, the size of the generator is larger among the conventional synchronous generators, self excitation and PMSG of same rating.

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These are the some of the references which we referred for typically for this power quality improvement of DG set and typically for different generators.

Thank you.