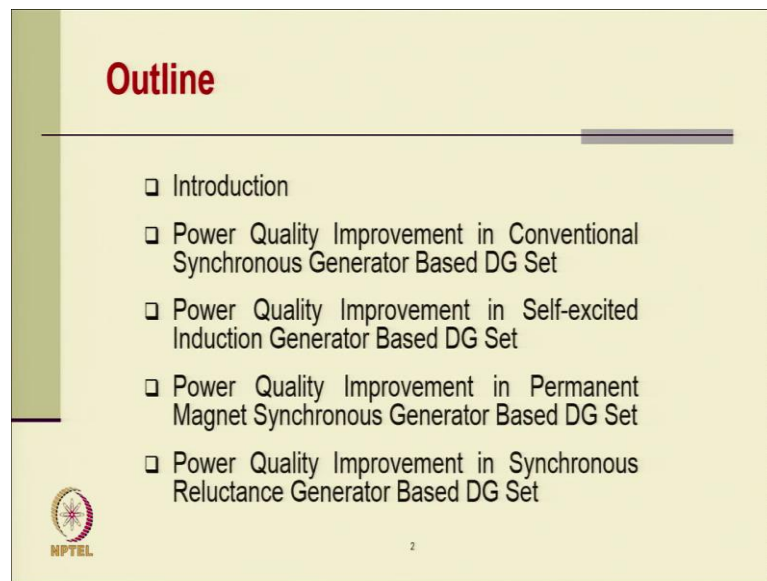


Power Quality
Prof. Bhim Singh
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Chapter - 15
Module - 03
Lecture - 43

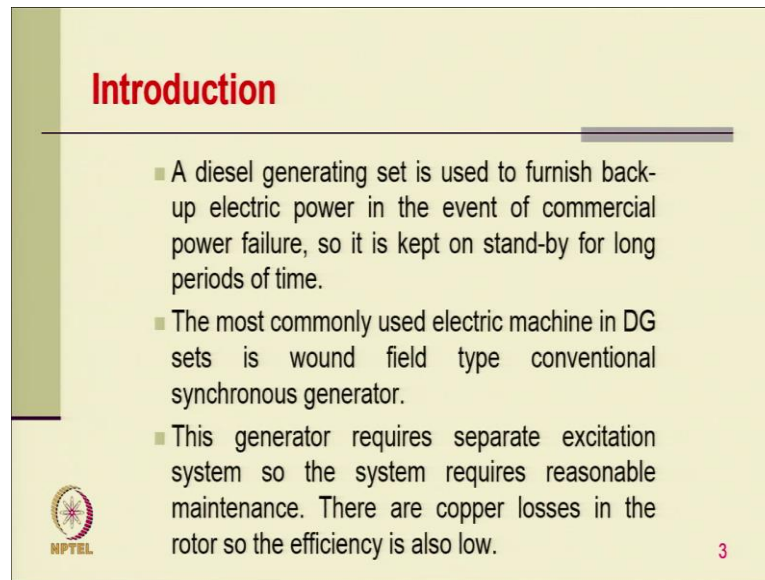
Power Quality Improvement in Diesel Generator Set Based Power Supply System

(Refer Slide Time: 00:30)




Welcome to the course on power quality. We will discuss today the Power Quality Improvement in Diesel Generator Set Based Power Supply System with the outline that will introduce the power quality improvement in conventional synchronous generator-based diesel generator set and power quality improvement in self excited induction generator based DG set. And power quality improvement in permanent synchronous generator based diesel generator set and the power quality improvement in synchronous reluctance based DG set.

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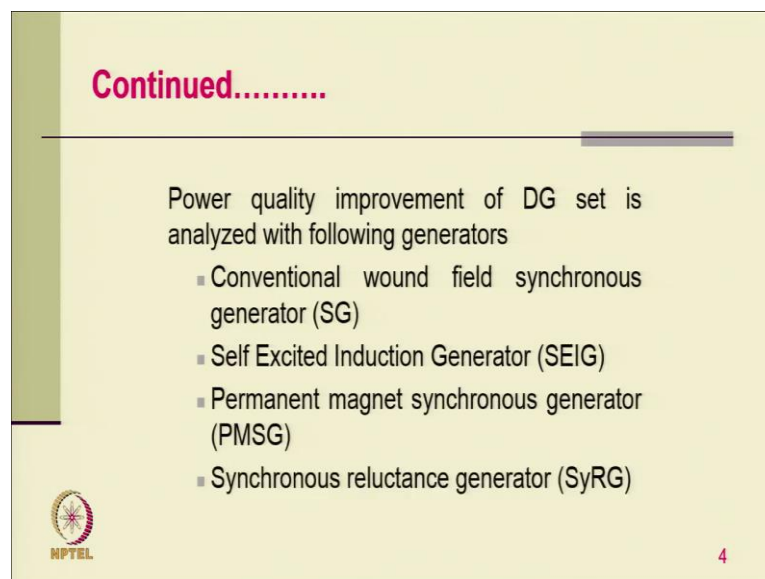
Introduction

- A diesel generating set is used to furnish back-up electric power in the event of commercial power failure, so it is kept on stand-by for long periods of time.
- The most commonly used electric machine in DG sets is wound field type conventional synchronous generator.
- This generator requires separate excitation system so the system requires reasonable maintenance. There are copper losses in the rotor so the efficiency is also low.

 NPTEL 3

Coming to introduction. A diesel generating set is used to furnish backup electric power to the event of commercial power failure, so it is kept on stand-by for long periods of time. The most commonly used electrical machines in DG sets is wound field type conventional synchronous generator. This generator requires separate excitations. So, the system requires reasonable maintenance and there are copper losses in the rotor so the efficiency is also low.


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Continued.....

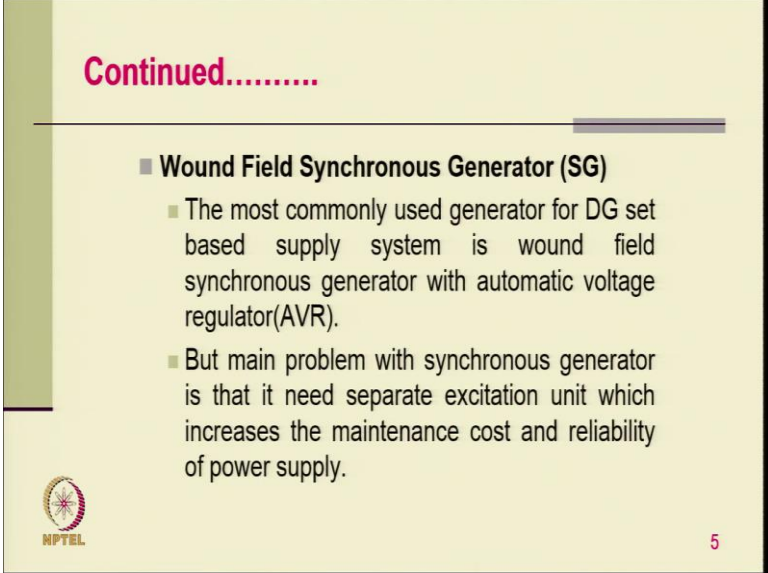
Power quality improvement of DG set is analyzed with following generators

- Conventional wound field synchronous generator (SG)
- Self Excited Induction Generator (SEIG)
- Permanent magnet synchronous generator (PMSG)
- Synchronous reluctance generator (SyRG)

 NPTEL 4


And power quality improvement of DG set is analyzed with the following generator with conventional wound field synchronous generator, with self-excited induction generator, with permanent synchronous generator, and synchronous reluctance generator.

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Continued.....

- **Wound Field Synchronous Generator (SG)**
 - The most commonly used generator for DG set based supply system is wound field synchronous generator with automatic voltage regulator(AVR).
 - But main problem with synchronous generator is that it need separate excitation unit which increases the maintenance cost and reliability of power supply.


 NPTEL 5

Well, coming to the wound field synchronous generator. The most commonly used generator for DG sets supply system is wound field synchronous generator with automatic voltage regulator, but the main problem is synchronous generator is that the need separate excitation unit which increases maintenance and cost and reliability of the supply.

(Refer Slide Time: 01:50)

Continued.....

- **Wound Field Synchronous Generator (SG)**
 - The advantage of self excited synchronous generator is that it does not draw any reactive power as in case of induction generator.
 - Has problem of hunting




6

And the advantage of self excited synchronous generator is that it does not draw any reactive power in case of as in generator. It has the problem of hunting.

(Refer Slide Time: 01:59)

Continued.....

- **Self Excited Induction Generator (SEIG)**
 - SEIG has rugged construction, less maintenance, no separate source of excitation is required, easy availability, no hunting, etc .
 - SEIG requires separate excitation capacitor bank.
 - The voltage and frequency regulation are the main challenges of SEIG.




7

And self excited induction generator has rugged construction, less maintenance, and no separate source of excitation is required, so, easy availability, and no hunting phenomena. The Self Excited induction generator requires separate excitation capacitor bank. Voltage and frequency regulation are main challenge of the self excited induction generator.

(Refer Slide Time: 02:18)

Continued.....

- **Permanent Magnet Synchronous Generator (PMSG)**
 - Construction of PMSG is simple and robust.
 - PMSG are brushless type. PMSG does not require the field winding and DC supply source.
 - Voltage regulation is main challenge because field excitation is constant. However, it has been observed that PMSG with capacitors has a voltage compensation function.




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Coming to permanent magnet synchronous generator. The construction of PMSG is simple and robust. The permanent generators are brushless type and does not require the field winding and DC supply source. Voltage regulation is the main challenge, because the field excitation is constant. However, it has been observed that PMSG with capacitor has the voltage compensation function.

(Refer Slide Time: 02:41)

Continued.....

- **Synchronous Reluctance Generator (SyRG)**
 - SyRG has rugged construction, less maintenance, no separate source of excitation is required, no hunting, etc .
 - Its frequency remains fixed if speed of prime mover is kept fixed.
 - SyRG requires separate excitation capacitor bank like SEIG.
 - Its size is more as compared to conventional generator of similar rating.



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And, the synchronous reluctance generator has rugged construction, less maintenance, and no separate source for excitation is required, and its frequency remains fixed, if the

speed of prime mover is fixed. The synchronous reluctance generator requires separate excitation capacitor like SEIG. Its size is more as compared to conventional generator of same rating.

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Continued.....

- **Synchronous Reluctance Generator (SyRG)**
 - It requires large excitation current.
 - The voltage regulation is the main challenge of SyRG.

NPTEL 10

This slide features a light green background with a dark green vertical bar on the left. The title 'Continued.....' is in red. Below it, a horizontal line is followed by a bullet point for 'Synchronous Reluctance Generator (SyRG)'. Underneath, two sub-bullets describe its characteristics: 'It requires large excitation current.' and 'The voltage regulation is the main challenge of SyRG.' The NPTEL logo and the number '10' are in the bottom left and right corners, respectively.

It requires large excitation current and voltage regulation is the main challenge of synchronous reluctance generator.

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State of Art

- Most of research work on DG sets has been focused on excitation control and voltage regulation of wound field synchronous generator.
- Some researchers the use of variable speed PMSG for improvement of power quality and enhancement of fuel efficiency of DG sets.
- Earlier an electronic converters is used with a central DC bus to increase efficiency of internal-combustion engine (ICE) for feeding a variable load.

NPTEL 11

This slide features a light green background with a dark green vertical bar on the left. The title 'State of Art' is in red. Below it, a horizontal line is followed by three bullet points describing research trends: 'Most of research work on DG sets has been focused on excitation control and voltage regulation of wound field synchronous generator.', 'Some researchers the use of variable speed PMSG for improvement of power quality and enhancement of fuel efficiency of DG sets.', and 'Earlier an electronic converters is used with a central DC bus to increase efficiency of internal-combustion engine (ICE) for feeding a variable load.' The NPTEL logo and the number '11' are in the bottom left and right corners, respectively.


Most of the research work on DG sets have been focused on excitation control and voltage regulation of wound field synchronous generator. Some researchers have used

the variable speed permanent magnet for improvement of power quality and enhancement of fuel efficiency of DG set. Earlier an electronics controller is used with central DC bus to increase efficiency of internal-combustion engine for feeding the variable load.

(Refer Slide Time: 03:33)

Continued.....

- The steady-state performance of a standalone permanent magnet synchronous generator driven by a diesel engine with a fixed capacitor-thyristor controlled reactor scheme has been used to maintain the load voltage and frequency constant under varying load conditions.
- Self excited SyRG(Synchronous Reluctance Generator) has been reported in the literature as good alternative to self excited IG due to its increased efficiency, low maintenance, rugged construction and constant frequency operation.




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The steady-state performance of a standalone permanent magnet generator driven by diesel engine with a fixed capacitor-thyristor controlled reactor scheme has been used to maintain the load voltage and frequency constant under varying condition. The self-excited synchronous generator has been reported in the literature as good alternative to self excited induction generator, due to its increased efficiency, low maintenance and rugged construction with constant frequency operation.

(Refer Slide Time: 03:57)

OBJECTIVES

- Unity power factor operation and power quality improvement of wound field synchronous generator based set using three-leg and four-leg VSC.
- Power quality improvement and voltage control of SEIG, PMSG and SyRG based DG sets using STATCOM.
- Load compensation of SG, SEIG, PMSG and SyRG based DG sets using battery energy storage system (BESS).




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Now, coming to the objectives. The unity power factor operation and power quality improvement of wound field synchronous generator-based set using three-leg and four-leg voltage source converter. The power quality improvement and voltage control of self excited induction generator, permanent synchronous reluctance generator using static compensators. Load compensation of synchronous generator self exciting permanent generator and synchronous reluctance-based DG sets using the battery energy storage system.

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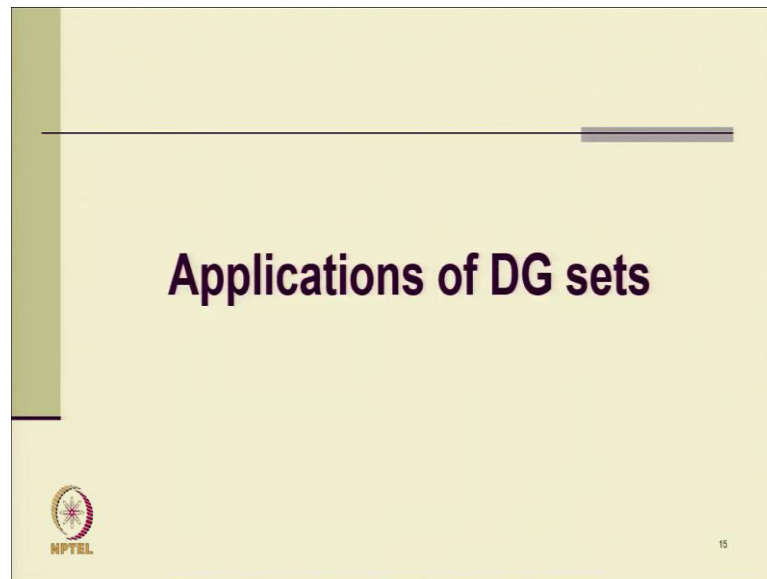
A typical DG set



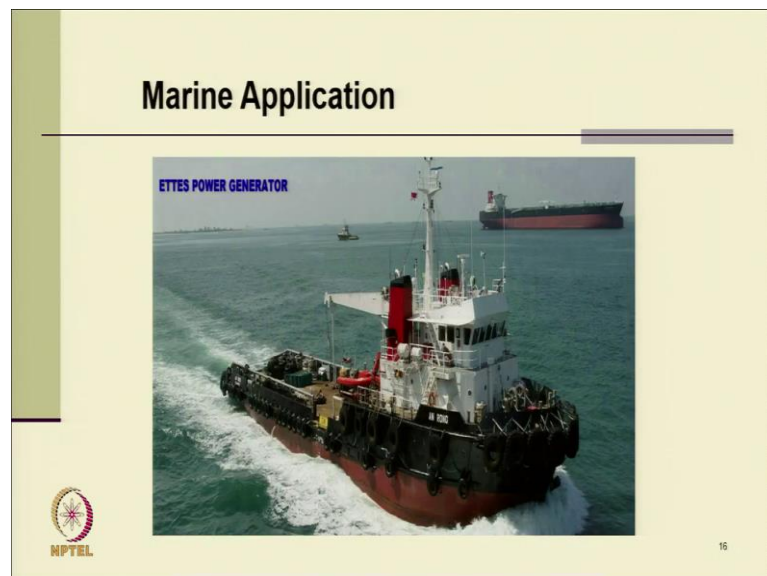
14

Well, this is the typical example of diesel generating set.

(Refer Slide Time: 04:30)




(Refer Slide Time: 04:32)




(Refer Slide Time: 04:37)

Military Application



The image shows a large, camouflaged generator mounted on a truck in a field. Several soldiers in military uniforms are standing around the truck, and one is holding a cable connected to the generator. The background shows a clear sky and some distant structures.




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(Refer Slide Time: 04:40)

Salient DG for Bank and Insurance




The image shows a large green generator unit in an industrial setting. The unit has a sign that reads "TAMBAL RENTAL POWER" and lists contact information: "Tambal Rental Power", "9872240197", "01782-021187", and "01782-021187".




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High performance Data Centers



A leading data center in the southern city of Shenzhen is using 17 C2500D5A PowerBox containerized generator sets to meet its standby power requirement – the largest PowerBox order Cummins Power Generation China has fulfilled.



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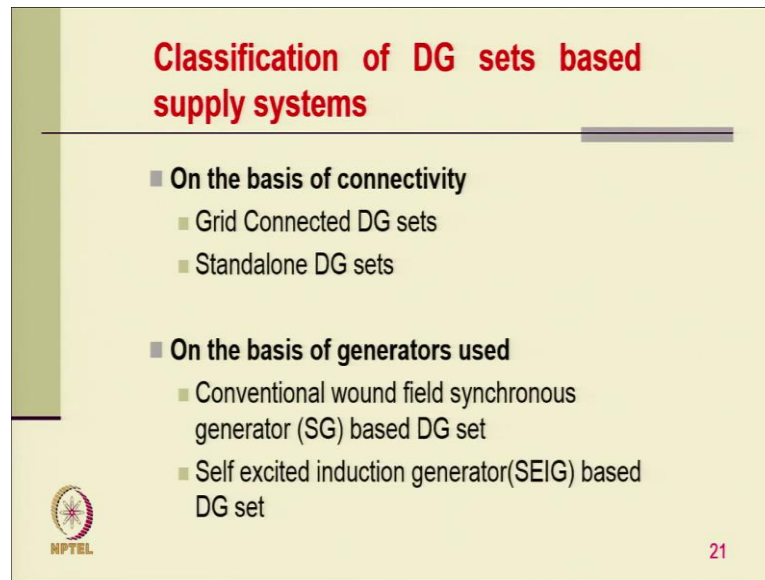
Many More Applications.....

- Sales infrastructure
- Agriculture-food and pharmaceutical industries
- Healthcare: Hospitals, clinics and retirement homes
- Water treatment facilities
- Transportation and logistics
- Constructions sites



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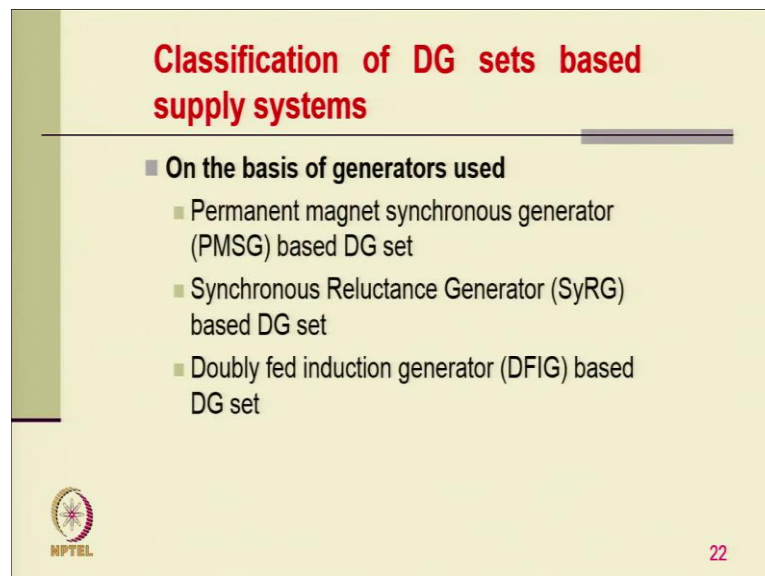
Classification of DG sets based supply systems

- **On the basis of connectivity**
 - Grid Connected DG sets
 - Standalone DG sets
- **On the basis of generators used**
 - Conventional wound field synchronous generator (SG) based DG set
 - Self excited induction generator(SEIG) based DG set

NPTEL 21

This is the classification of DG sets based supply systems.

(Refer Slide Time: 05:25)



Classification of DG sets based supply systems

- **On the basis of generators used**
 - Permanent magnet synchronous generator (PMSG) based DG set
 - Synchronous Reluctance Generator (SyRG) based DG set
 - Doubly fed induction generator (DFIG) based DG set


NPTEL 22

This is the classification of DG sets based supply systems.

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Continued.....

- On the basis of speed
 - Fixed speed
 - Variable speed
- On the basis of load
 - Single phase
 - Three phase

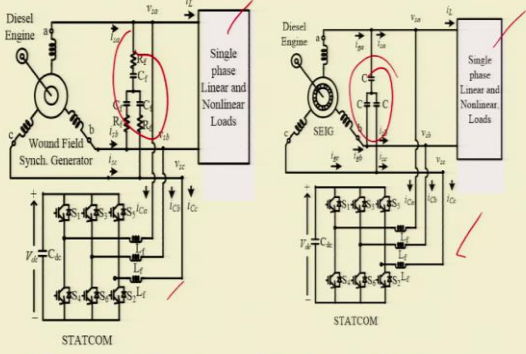


23

This is the classification of DG sets based supply systems.

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Configurations of DG sets feeding single-phase two wire (1P2W) loads



STATCOM

STATCOM

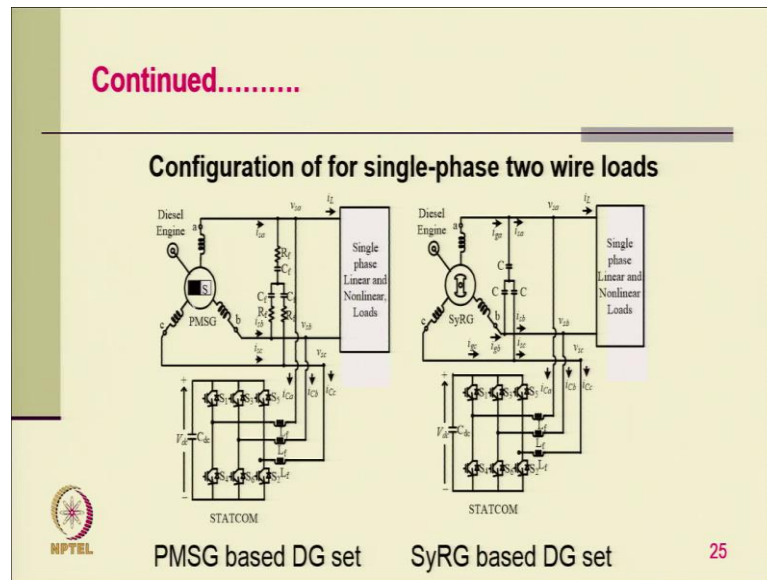
SG based DG set SEIG based DG set



24

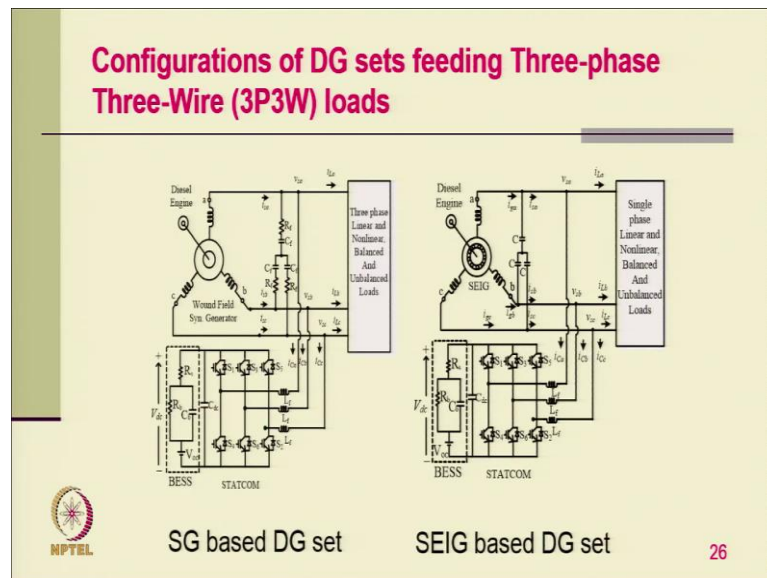
These are the configurations of SG and SEIG based DG sets feeding single phase two wire (1P2W) loads.

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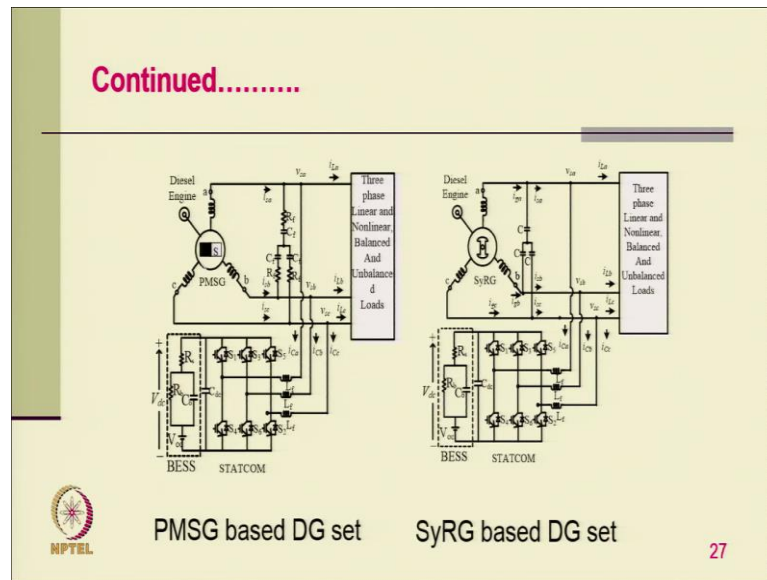
These are the configurations of PMSG and SyRG based DG sets feeding single phase two wire (1P2W) loads.

(Refer Slide Time: 08:58)



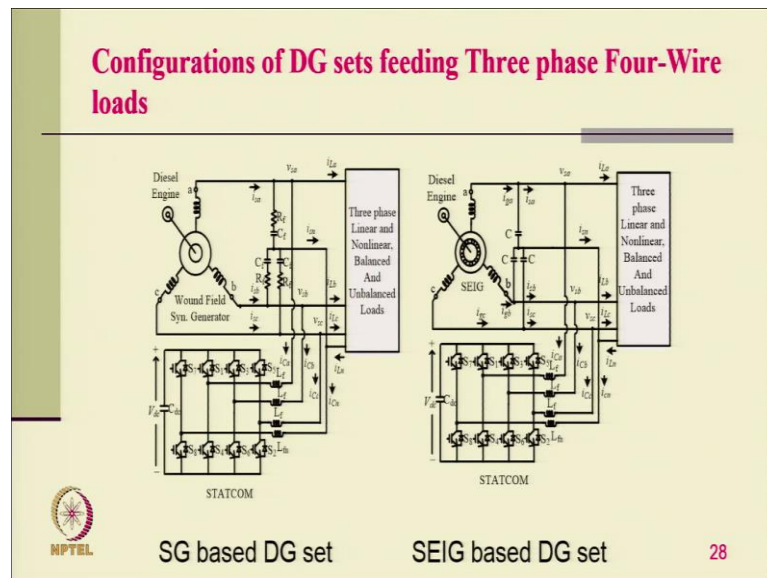
These are the configurations of SG and SEIG based DG sets feeding Three phase Three wire (3P3W) loads.

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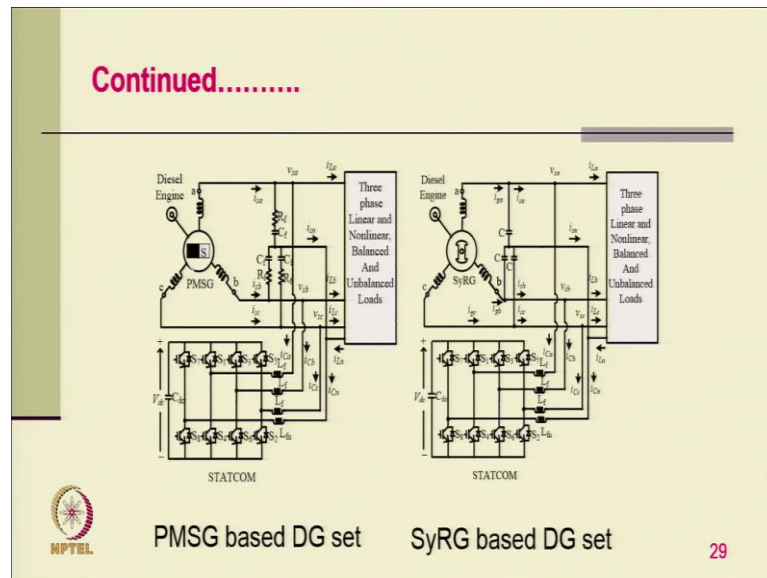
These are the configurations of PMSG and SyRG based DG sets feeding Three phase Three wire (3P3W) loads.

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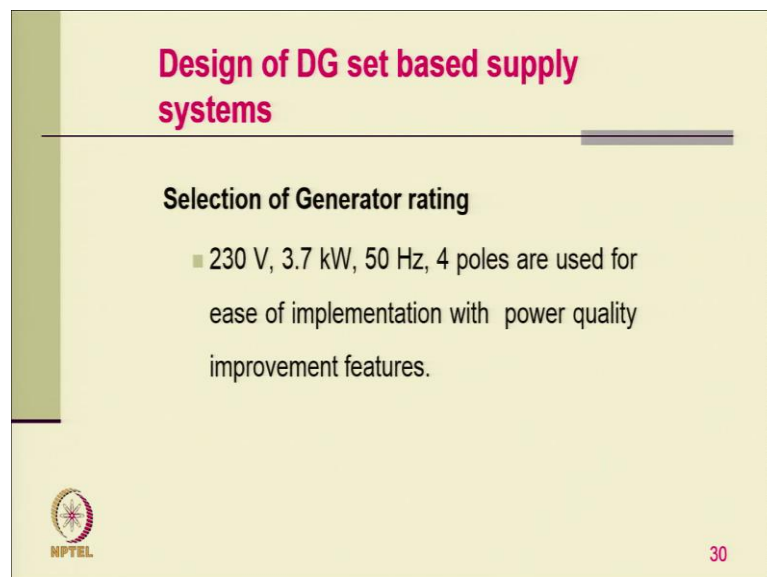
These are the configurations of SG and SEIG based DG sets feeding Three phase Four wire (3P4W) loads.

(Refer Slide Time: 12:47)



These are the configurations of PMSG and SyRG based DG sets feeding Three phase Four wire (3P4W) loads.

(Refer Slide Time: 13:27)



Now, coming to the design part of the DG sets. We have taken a case study that has 3.7 kW, 230 V, 50 Hz, 4 pole generator set is used for the power quality improvement features.

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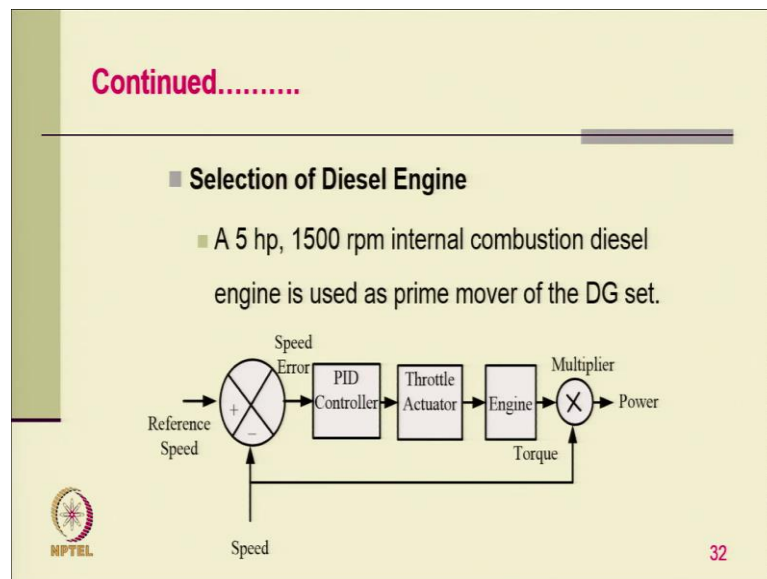
Design of DG set based supply systems

| Generators | Selected rating | Parameters of the generator |
|----------------|--|--|
| Wound field SG | Three phase, 5 kVA, 400 V, 50 Hz, 4 poles, star connected | $R_s = 0.163 \Omega$, $L_l = 0.2 \text{ mH}$, $L_{md} = 8.4 \text{ mH}$, $L_{mq} = 0.9 \text{ mH}$ |
| SEIG | Three phase, 3.7 kW, 230 V, 14.5 A 50 Hz, 4 poles, star connected | $R_s = 0.394 \Omega$, $L_s = 2 \text{ mH}$, $R_r = 0.48 \Omega$, $L_r = 2.5 \text{ mH}$, $L_m = 76.6 \text{ mH}$ |
| PMSG | Three phase, 3.7 kW, 230 V, 13 A, 50 Hz, 4 poles, star connected | $X_d = 4.669 \Omega$, $X_q = 5.573 \Omega$, $R_s = 0.2747 \Omega$ |
| SyRG | Three phase, 3.7 kW, 230 V, 22.7 A, 50 Hz, 4 poles, star connected | $X_d = 22.51 \Omega$, $X_q = 5.47 \Omega$, $R_s = 0.188 \Omega$ |

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These are the parameters and selected rating of all four machine based DG sets.

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Continued.....

■ Selection of DC Link Capacitor

$$\frac{1}{2} C_{dc} [V_{dc}^2 - V_{dcmin}^2] = 3V(aI)t$$

- Considering $V_{dcmin} = 400$ V, $V_{dc} = 395$ V, $V = 132.79$ V, $I = 10$ A, $t = 750$ ms, $a = 1.2$
- The calculated value of C_{dc} is 1793 μ F and it is selected as 1650 μ F.



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Continued.....

■ Selection of Interfacing Inductors

$$L_f = \frac{\sqrt{3} m V_{dc}}{12 a f_s i_{pp}}$$

- Considering $m=1$, $V_{dc}=400$ V, $a = 1.2$, $i_{pp} = 1.5$ A of rated VSC current and $f_s = 10$ kHz.
- The value of L_f is obtained as 3.2 mH. A round off value of 3.5 mH is used in this work.




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Continued.....

- **Selection of DC link battery voltage**
$$V_{dc} \geq (2\sqrt{2}/\sqrt{3}m)V_L$$
 - Assuming m to be 1, the DC link voltage is obtained as 376 V for V_L (230 V) and it is selected as 420V.
 - For a nominal battery voltage of 420V, 35 cell units of 12V, 7Ah are connected in series.



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Continued.....

- **Selection of Excitation Capacitors**
$$C = Q / (6\pi f V^2)$$

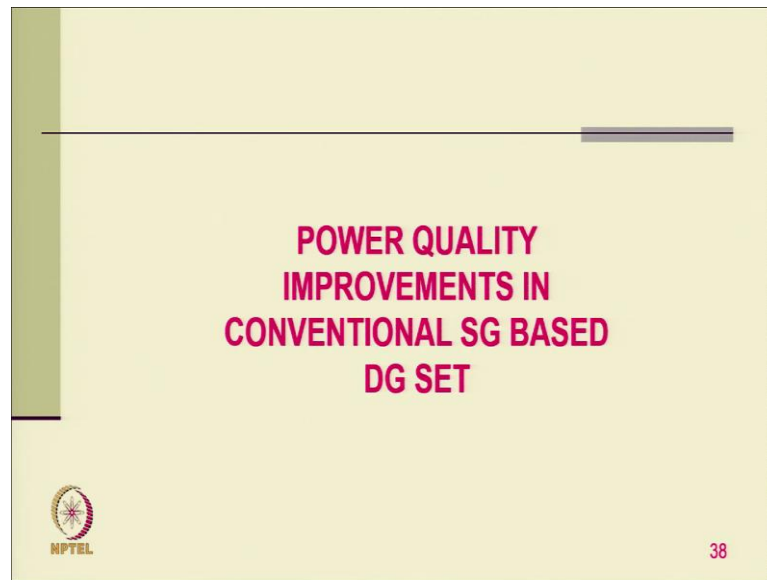
where V is rms phase voltage.

 - ~~SEIG of 3.7 kW requires 2.51 kVAR~~
 - SyRG of 3.7 kW requires a 6.3 kVAR at no load to maintain line voltage at 220V.



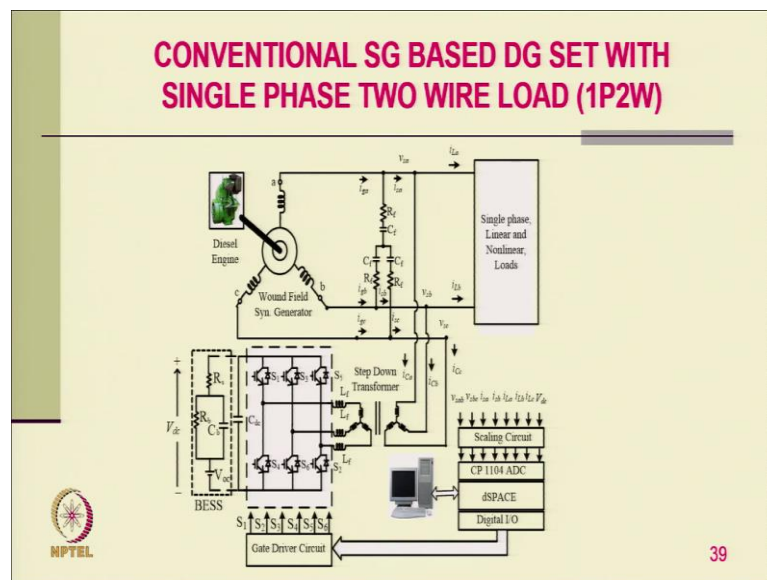
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Now, coming to power quality improvement in conventional synchronous generator-based DG set.

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This is the typical configuration of conventional SG based DG set with 1-Phase two wire load (1P2W).

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Control algorithms verified experimentally for SG based DG set

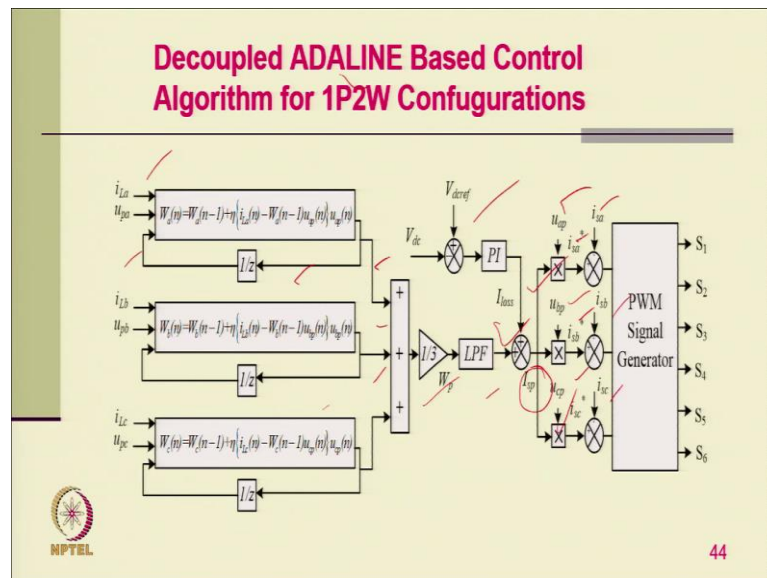
- Decoupled ADALINE Based Control Algorithm for 1P2W configuration with self Supported
- Composite Observer based Control Algorithm for 3P3W Loads with BESS
- Adaptive Theory Based Notch Filter Control Algorithm for 3P4W Loads



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These are the control algorithms which has been verified experimentally for the control of conventional SG based DG sets.

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This is the block diagram of decoupled ADALINE based control algorithm for 1P2W configurations.

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Continued.....

- Estimation of Instantaneous Phase Voltages
$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$
- The amplitude of phase voltages $V_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$
- Estimation of In-Phase Unit-Templates
$$U_{ap} = v_{sa}/V_t, U_{bp} = v_{sb}/V_t, U_{cp} = v_{sc}/V_t$$




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Continued.....

- Estimation of Amplitude of Fundamental of Active Power Component of Load Current
$$W_a(n) = W_a(n-1) + \eta \{i_{La}(n) - W_a(n-1)u_{ap}(n)\}u_{ap}(n),$$
$$W_b(n) = W_b(n-1) + \eta \{i_{Lb}(n) - W_b(n-1)u_{bp}(n)\}u_{bp}(n),$$
$$W_c(n) = W_c(n-1) + \eta \{i_{Lc}(n) - W_c(n-1)u_{cp}(n)\}u_{cp}(n),$$

where h is called the coefficient of convergence and its value can vary from 0.01 to 1 depending of the rate of convergence



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Continued.....

- Final weight vector
$$W_p(n) = \frac{W_a(n) + W_b(n) + W_c(n)}{3}$$
- DC Link Voltage PI Controller

$$I_{loss}(n) = I_{loss}(n-1) + K_{pdc} \{V_{dcerr}(n) - V_{dcerr}(n-1)\} + K_{idc} V_{dcerr}(n)$$

where, K_{pdc} and K_{idc} are proportional and integral controller parameters respectively and V_{dcerr} is error in dc link voltage. 47




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Continued.....

- Estimation of Amplitude of Reference Source Currents

$$I_{sp} = W_p(n) + I_{loss}(n)$$


- Instantaneous Reference Source Currents

$$i_{sa}^* = I_{sp} * u_{ap}, i_{sb}^* = I_{sp} * u_{bp}, i_{sc}^* = I_{sp} * u_{cp}$$


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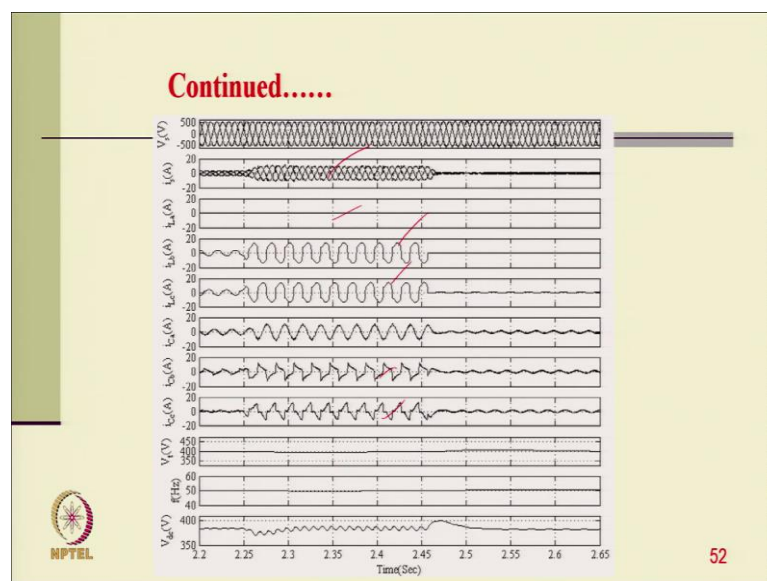
Simulated Performance of SG based DG set under 1P2W Nonlinear Loads

- The system is subjected to a load of 1 kW and then it is subjected to load of 4.2 kW at $t = 2.25$ s between phases 'b' and 'c'.
- The generator is unloaded at $t = 2.45$ s.



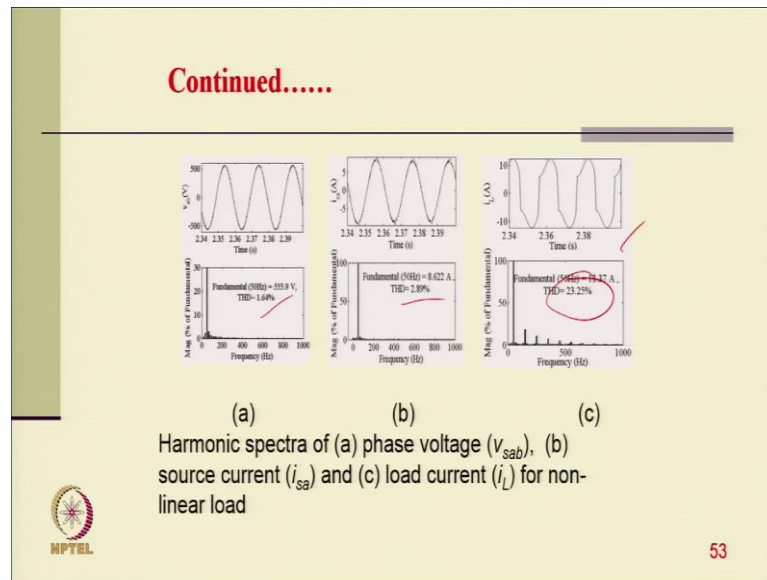
51

(Refer Slide Time: 19:48)



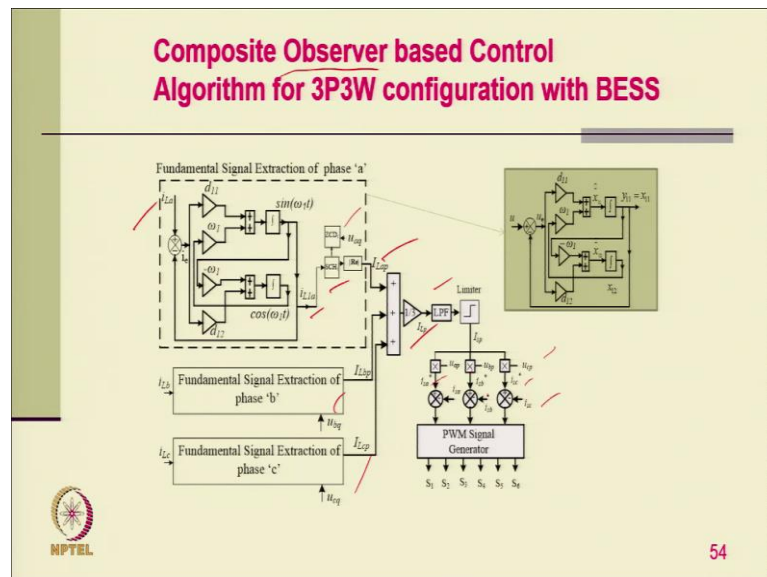
This is the simulated performance of SG based DG sets under 1P2W non-linear loads.

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And these are the harmonic spectrum. The load current have a quite high THD, but you can see the generator current THD is quite low as well as voltage THD is also quite low, at the point of common coupling. But if you do not put this compensator certainly, the load currents will become your generator current.

(Refer Slide Time: 20:36)




This is another control algorithm.

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Continued.....

- Estimation of Instantaneous Phase Voltages
$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$
- The amplitude of phase voltages
$$V_i = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$$
- Estimation of In-Phase Unit-Templates
$$u_{ap} = v_{sa}/V_t, u_{bp} = v_{sb}/V_t, u_{cp} = v_{sc}/V_t$$




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(Refer Slide Time: 21:41)

Continued.....

- Estimation of Active Power Component of Reference Source Current
$$\begin{bmatrix} x_{11} \\ x_{12} \end{bmatrix} = \begin{bmatrix} 0 & \omega_1 \\ -\omega_1 & 0 \end{bmatrix} \begin{bmatrix} x_{11} \\ x_{12} \end{bmatrix} + \begin{bmatrix} d_{11} \\ d_{12} \end{bmatrix} u_e$$
$$\begin{bmatrix} y_{11} \\ y_{12} \end{bmatrix} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_{11} \\ x_{12} \end{bmatrix}$$




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Continued.....

- Error signal $u_e = u - y_{11}$, u is input signal, y_{11} is fundamental component of extracted by the composite observer.
- For the proposed state observer, the optimum values of gain vectors d_{11} and d_{12} are 40 and -2 respectively for extraction of fundamental component of load current.




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(Refer Slide Time: 21:58)

Continued.....

- Overall Amplitude of Fundamental component of load current
$$I_{Lp} = \frac{I_{Lap} + I_{Lbp} + I_{Lcp}}{3}$$
- Estimation of Amplitude of Reference Source Currents
$$I_{sp} = I_{Lp}; \text{ For load between 80\% and 100\% of generator rating}$$
$$I_{sp} = 0.8 \times I_{g, rated}; \text{ For load less than 80\% of generator rating}$$
$$I_{sp} = I_{g, rated}; \text{ For load more than 100\% of generator rating}$$




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(Refer Slide Time: 22:34)

Continued.....

- Instantaneous Reference Source Currents


$$\underline{i_{sa}^* = I_{sp}^* u_{aq}, i_{sb}^* = I_{sp}^* u_{bp}, i_{sc}^* = I_{sp}^* u_{cp}}$$


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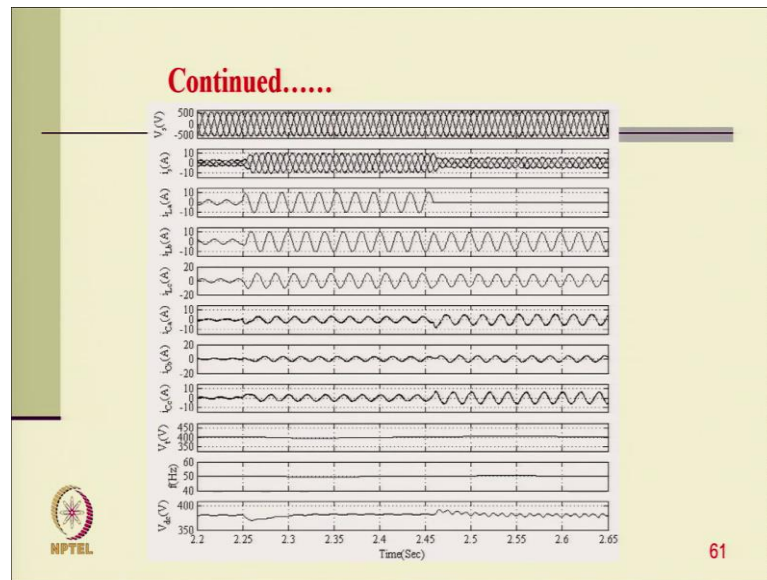
Simulated Performance of SG based DG set under 3P3W Linear Loads

- Initially the system is subjected to an inductive load of 1 kW
- Then it is subjected to load of 4.2 kW with power factor of 0.8 at t = 2.25 s.
- At t = 2.45 s the system is subjected to unbalanced load by removing load from phase 'a'.



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These are the simulated performance of SG based DG set under 3P3W linear loads.

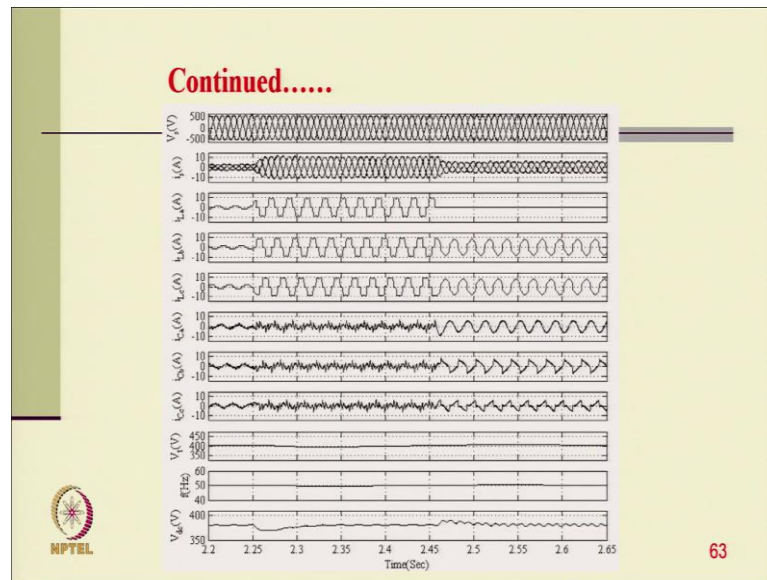
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Simulated Performance of SG based DG set under 3P3W Nonlinear Loads

- The system is subjected to loads of 1kW and 4.2kW and finally unbalanced load.

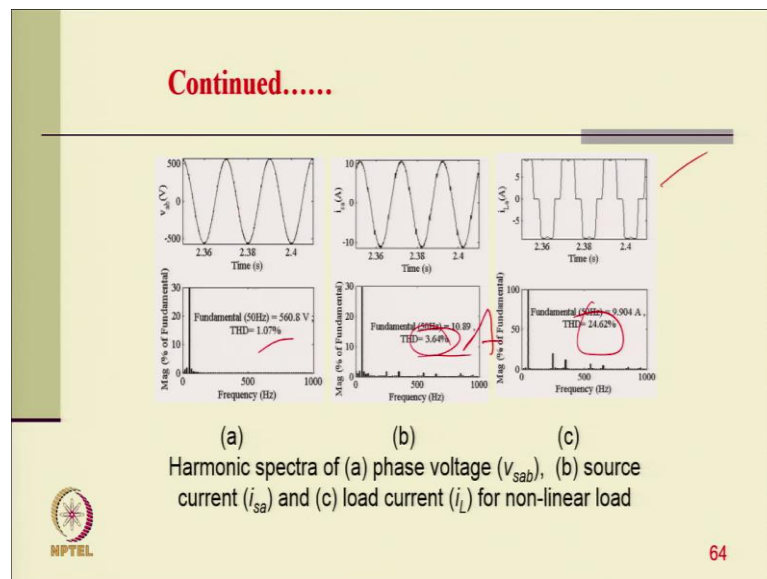
62

(Refer Slide Time: 23:19)



These are the simulated performance of SG based DG set under 3P3W non-linear loads.

(Refer Slide Time: 23:35)




And these are harmonic the spectrum, when the load current THD is 24%; you are able to get the generator current THD only typically of 3.64% and the voltage THD is maintained 1.07%.

(Refer Slide Time: 24:00)

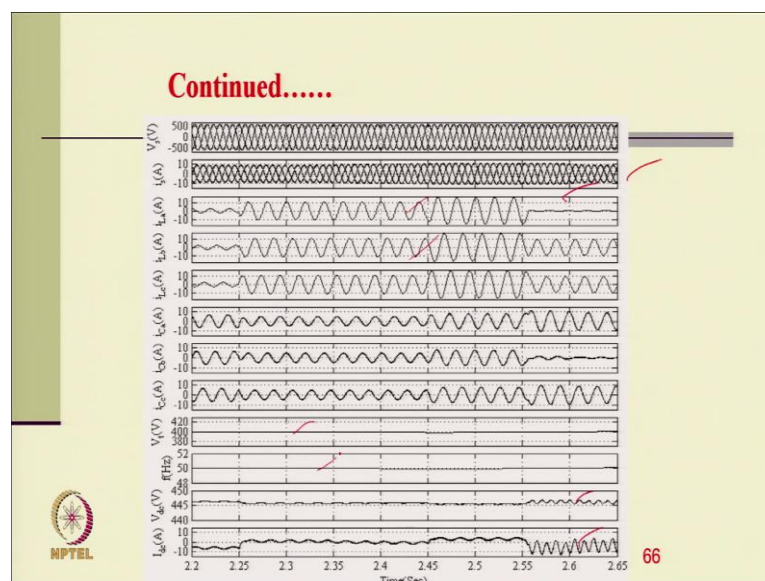
Simulated Performance of SG based DG set with BESS under 3P3W Linear Loads

- Initially system is subjected to a load of 1 kW at 0.8 lagging power factor and which is less than 80 % of generator rating so battery is taking a charging current.
- At $t = 2.25$ s a load of 4.2 kW is connected to the system . This load is slightly more than 80% of rating of generator so the generator supplies the load current and battery supplies no current.
- At $t = 2.45$ s a load of 6.2 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.



65

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These are the simulated performance of SG based DG set with BES system under 3P3W linear loads.

(Refer Slide Time: 24:32)

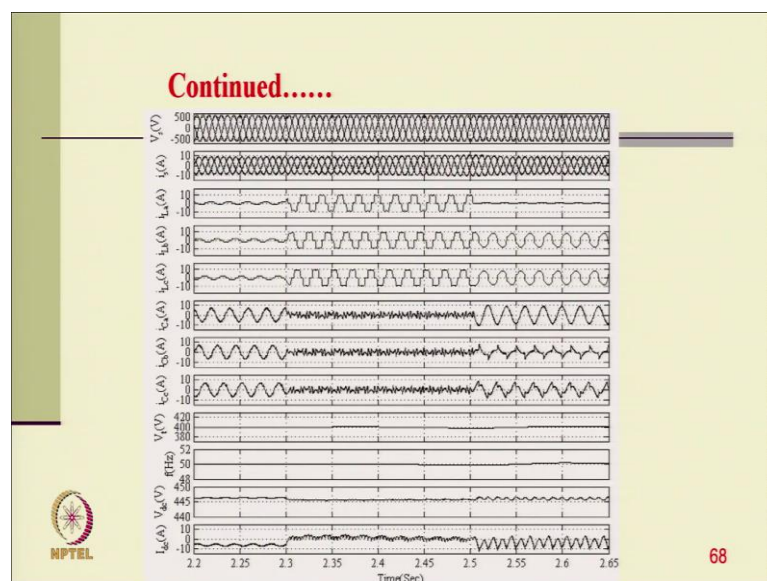
Simulated Performance of SG based DG set with BESS under 3P3W Nonlinear loads

- Initially system is subjected to a non-linear load of 1 kW and then it is subjected to non-linear load of 5 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'.



67

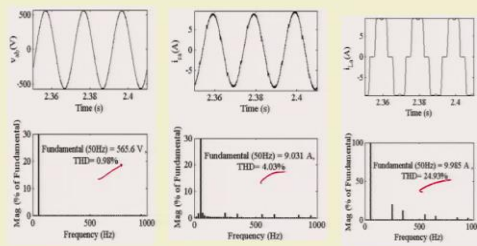
(Refer Slide Time: 24:45)



These are the simulated performance of SG based DG set with BES system under 3P3W non linear loads.

(Refer Slide Time: 25:05)

Continued.....



(a) (b) (c)
Harmonic spectra of (a) phase voltage (v_{sab}), (b) source current (i_{sa}) and (c) load current (i_l) for non-linear load



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Experimental Performance of SG based DG set under 1P2W Linear Loads

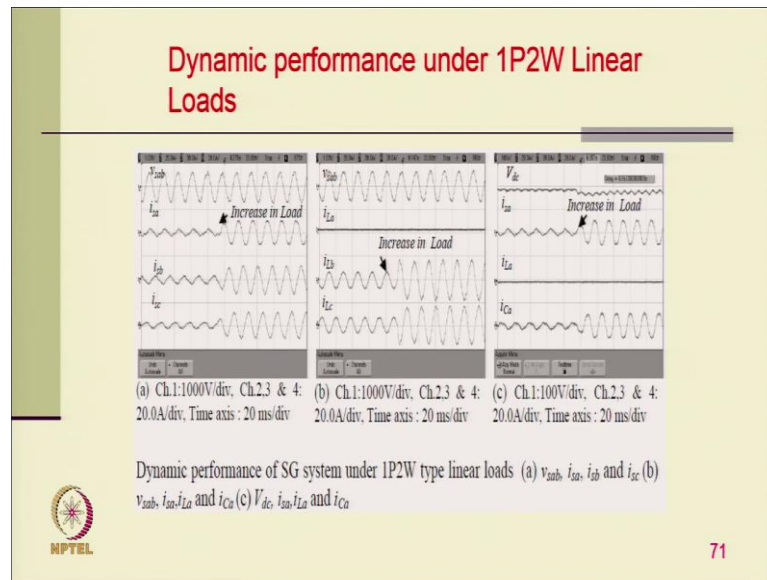


Performance of SG based DG set under 1P2W type linear load (a) v_{1a} and i_{1a} (b) v_{1b} and i_{1b} (c) v_{1c} and i_{1c} (d) v_{2a} and i_{2a} (e) v_{2b} and i_{2b} (f) v_{2c} and i_{2c} (g) v_{3a} and i_{3a} (h) v_{3b} and i_{3b} (i) v_{3c} and i_{3c}



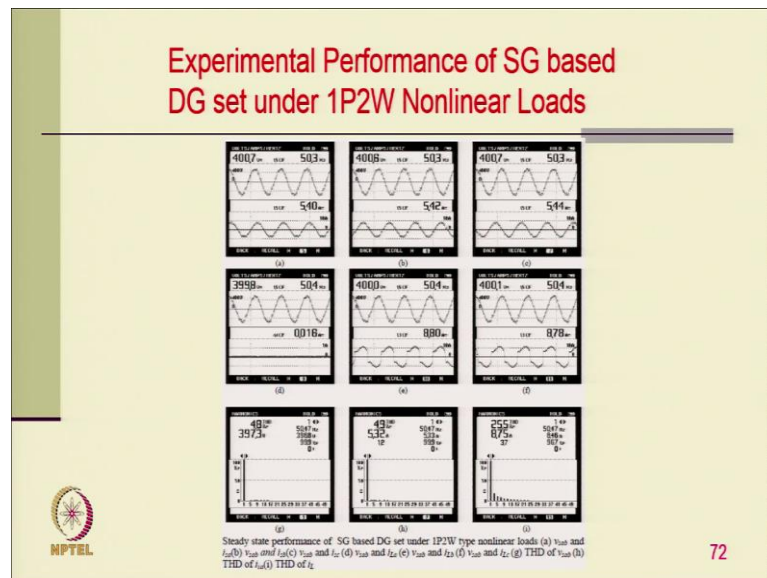
This is the experimental performance of SG based DG set under 1P2W linear loads.

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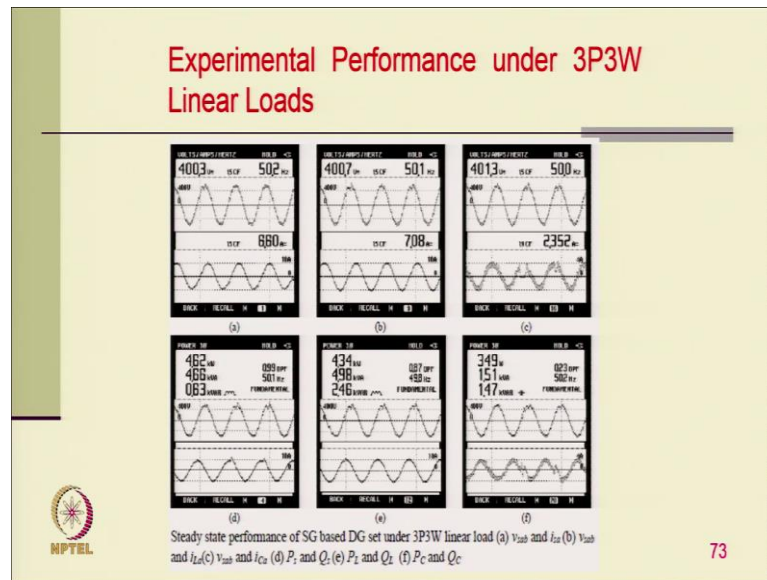
This is the experimental performance of SG based DG set under dynamic condition with 1P2W linear loads.

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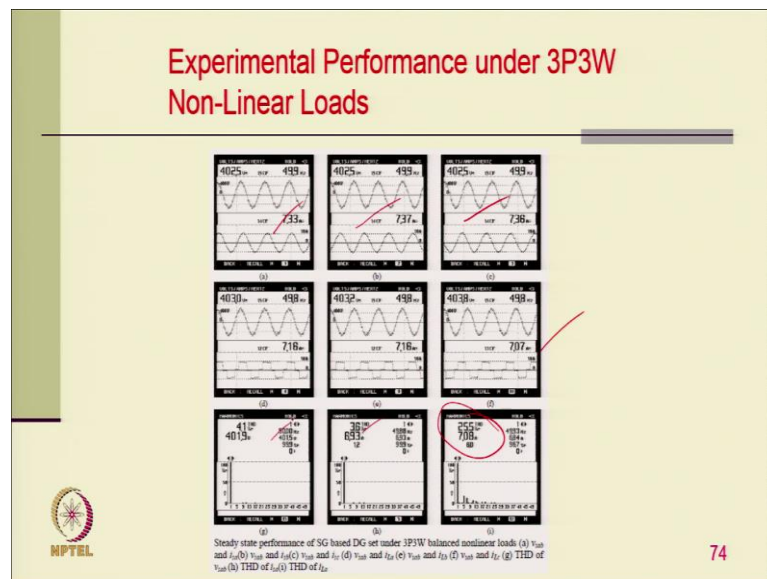
This is the experimental performance of SG based DG set under 1P2W non-linear loads.

(Refer Slide Time: 26:06)



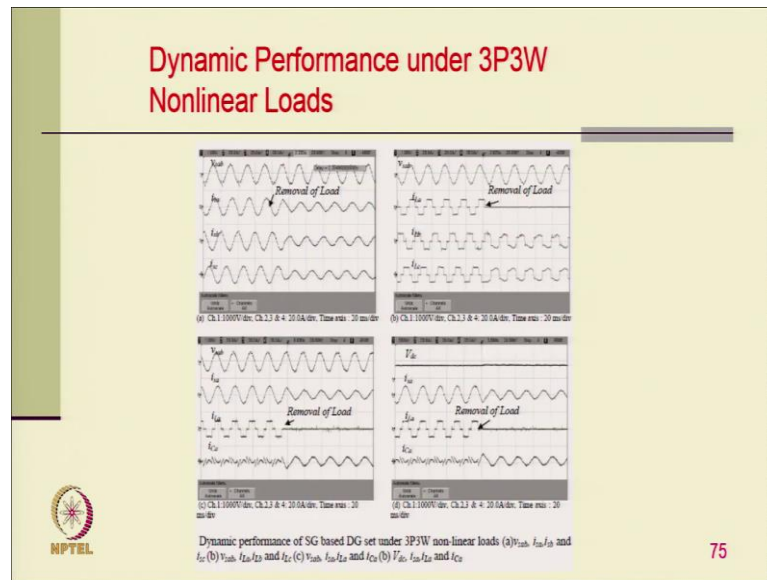
This is the experimental performance of SG based DG set under 3P3W linear loads.

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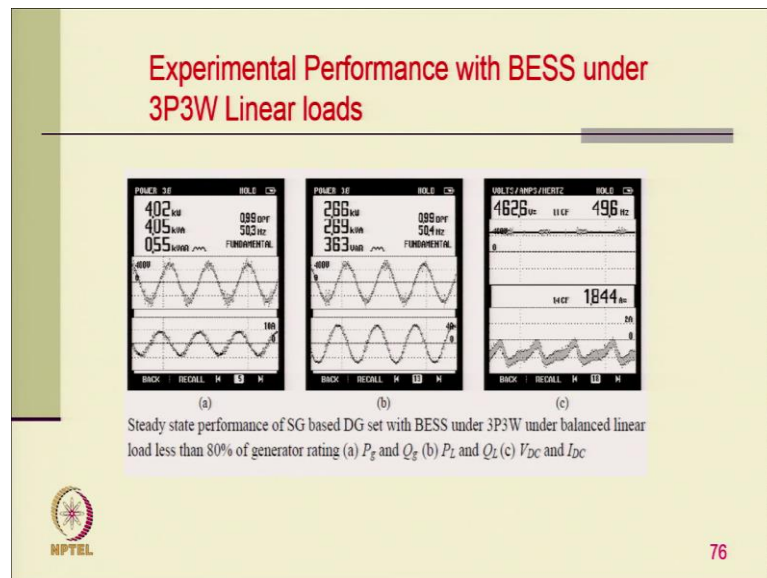
This is the experimental performance of SG based DG set under 3P3W non-linear loads.

(Refer Slide Time: 26:43)



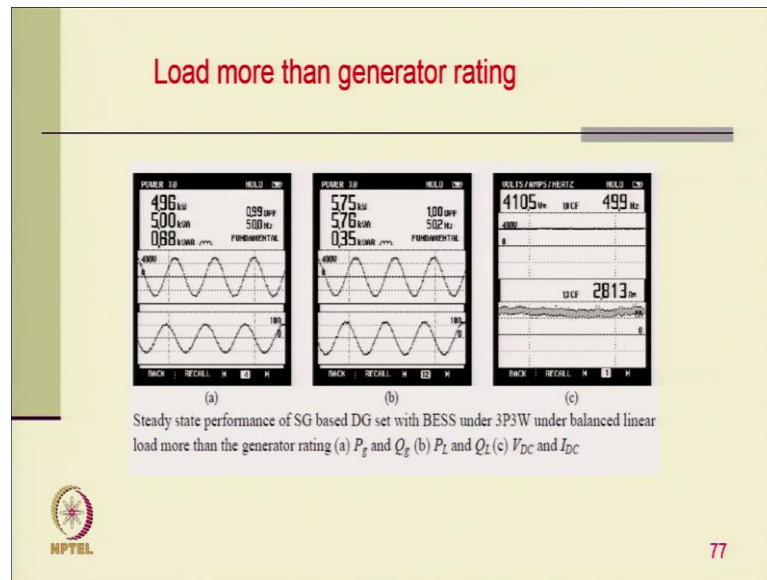
This is the experimental performance of SG based DG set under dynamic condition with 3P3W linear loads.

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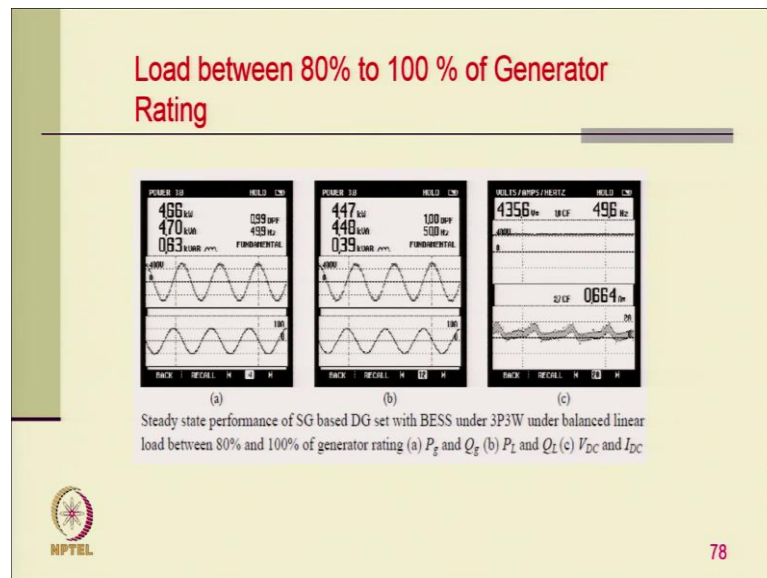
This is the experimental performance of SG based DG with BESS under 3P3W linear loads.

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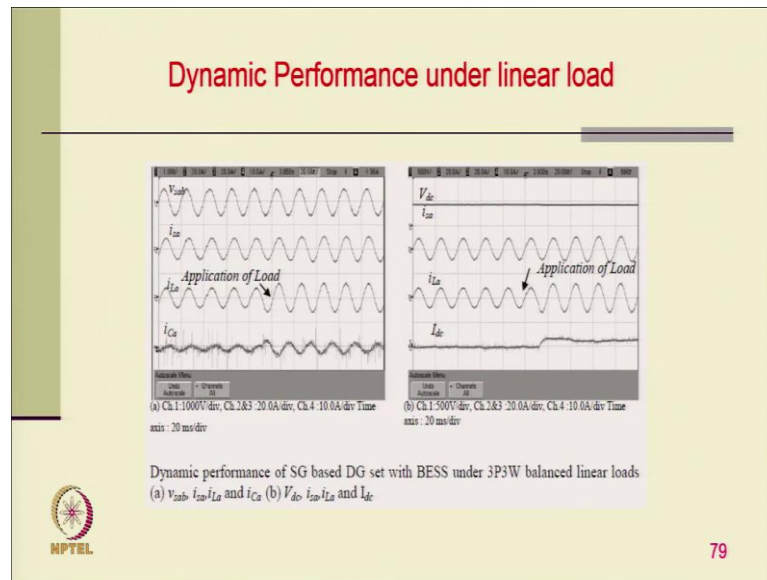
This is the experimental performance of SG based DG set under load more than generator rating.

(Refer Slide Time: 27:22)



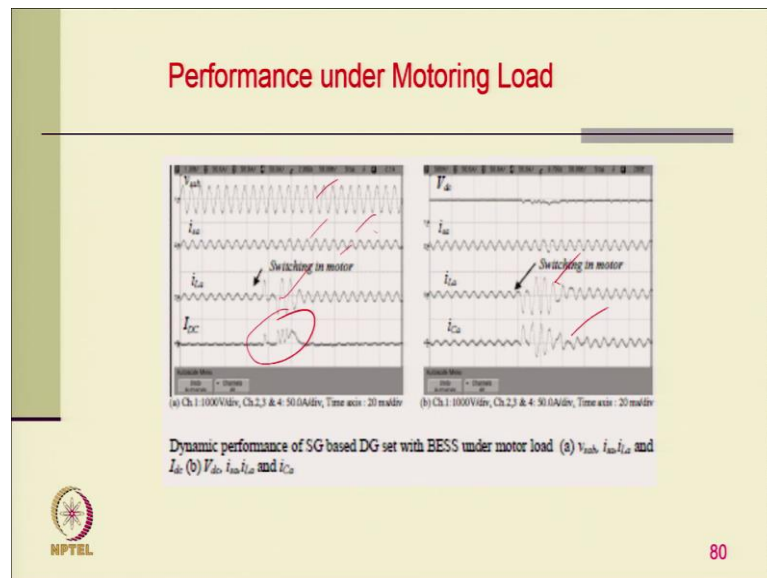
This is the experimental performance of SG based DG set under load between 80% to 100% generator rating.

(Refer Slide Time: 27:30)



This is the experimental performance of SG based DG set (with BESS) under dynamic condition with 3P3W linear loads.

(Refer Slide Time: 27:40)



This is the experimental performance of SG based DG set under motoring loads.


(Refer Slide Time: 29:18)

Continued.....

- Estimation of Instantaneous Phase Voltages

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$
- The amplitude of phase voltages $V_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$
- Estimation of In-Phase Unit-Templates

$$U_{ap} = v_{sa}/V_t, U_{bp} = v_{sb}/V_t, U_{cp} = v_{sc}/V_t$$



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Continued.....

- Estimation of Fundamental of Active Power Components of the Load Current with ANF

$$i_L(t) + k^2 \omega^2 \int i_L(t) dt = 2\zeta_k \omega e(t) \quad \dot{\omega} = -\gamma i_{L1}(t) \omega e(t)$$

$$e(t) = i_L(t) - \sum_{k=1}^n i_{Lk}(t)$$
- where, ω is estimated value of instantaneous fundamental frequency, ζ_k and γ are real and positive numbers which determine accuracy and convergence speed of ANF. $e(t)$ is error between input and its estimated signal.
- ζ_k and γ giving satisfactory performance of the system which are 0.375 and 10000 respectively.



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Continued.....


- Overall Amplitude of Fundamental component of load current

$$I_{Lp} = \frac{I_{Lap} + I_{Lbp} + I_{Lcp}}{3}$$

- DC Link Voltage PI Controller

$$I_{loss}(n) = I_{loss}(n-1) + K_{pdc} \{V_{dcerr}(n) - V_{dcerr}(n-1)\} + K_{idc} V_{dcerr}(n)$$

where, K_{pdc} and K_{idc} are proportional and integral controller parameters respectively and V_{dcerr} is error in dc link voltage.



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Continued.....

- Estimation of Amplitude of Reference Source Currents

$$I_{sp} = I_{Lp}(n) + I_{loss}(n)$$

- Instantaneous Reference Source Currents


$$i_{sa}^* = I_{sp}^* u_{ap}, i_{sb}^* = I_{sp}^* u_{bp}, i_{sc}^* = I_{sp}^* u_{cp}$$


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Continued.....

- Neutral Current Compensation
 - The neutral terminal of load is then connected at neutral point of RC filter and fourth leg of VSC through an inductor.
 - Fourth leg of VSC is used for source neutral current compensation.
 - It is therefore desired that no current should flow from the neutral point of RC filter to load neutral terminal.
 - This compensation is achieved by gating pulses of fourth leg of VSC using error signal which is a difference of source neutral current (i_{sn}) and its reference value (i.e. $i_{sn}^* = 0$).




87

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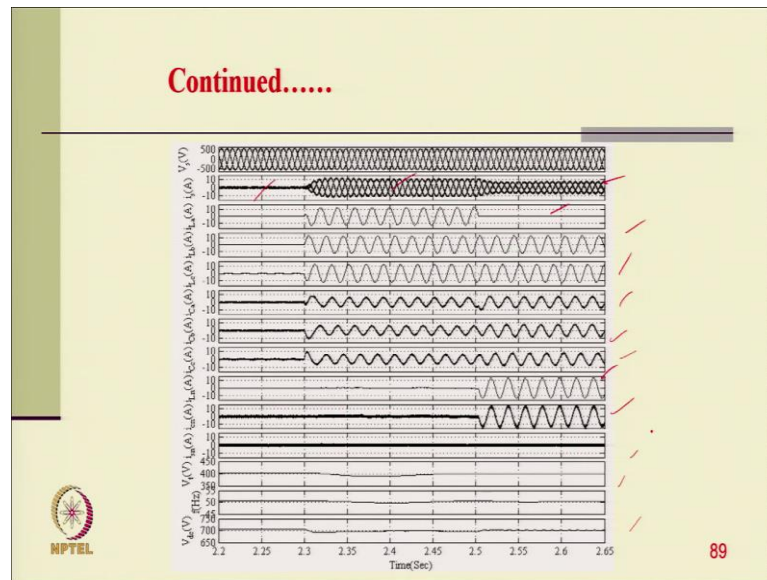
Simulated Performance of SG based DG set under 3P4W Linear loads

- Initially system is at no load and it is subjected to a RL load of 5 kW at 0.8 lagging power factor at $t = 2.3$ s.
- The system is subjected to unbalanced load at $t = 2.5$ s.



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(Refer Slide Time: 30:50)



This is the simulated performance of SG based DG set under 3P4W linear loads.

(Refer Slide Time: 31:27)

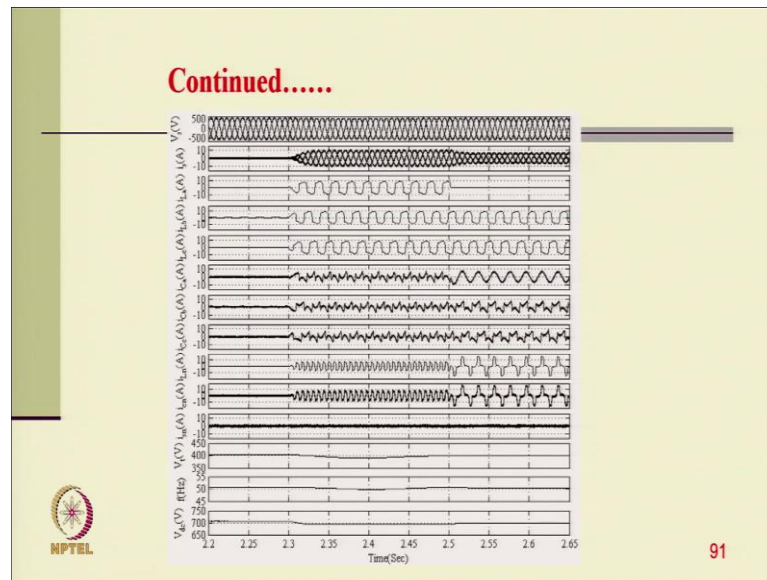
**Simulated Performance of SG based
DG set with BESS under 3P4W
Nonlinear loads**

- Initially system is subjected to no load and then at $t = 2.3\text{s}$ it is subjected to a non-linear load of 5 kW.

- The load is made unbalanced at $t = 2.5\text{ s}$.

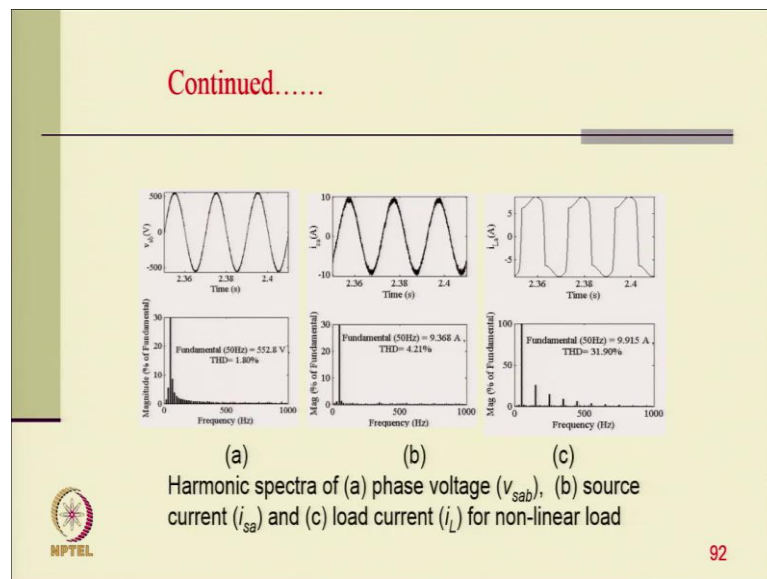
90

(Refer Slide Time: 31:29)



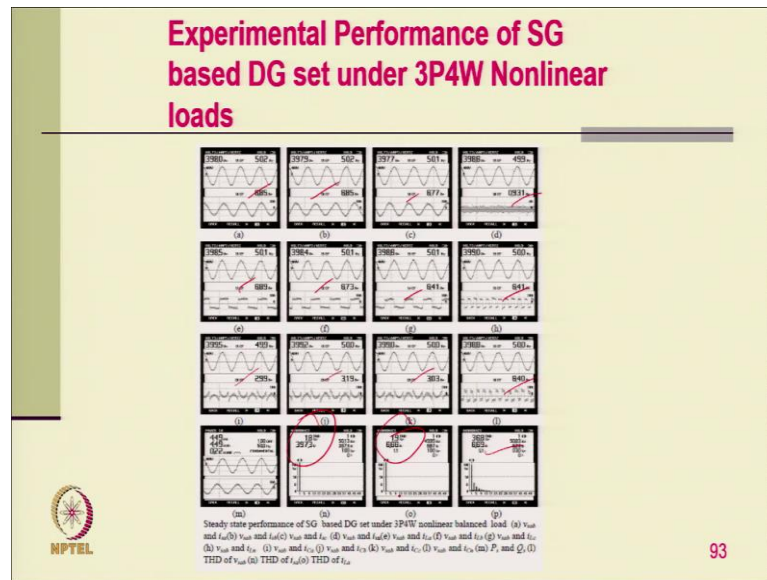
This is the simulated performance of SG based DG set under 3P4W non-linear loads.

(Refer Slide Time: 31:52)



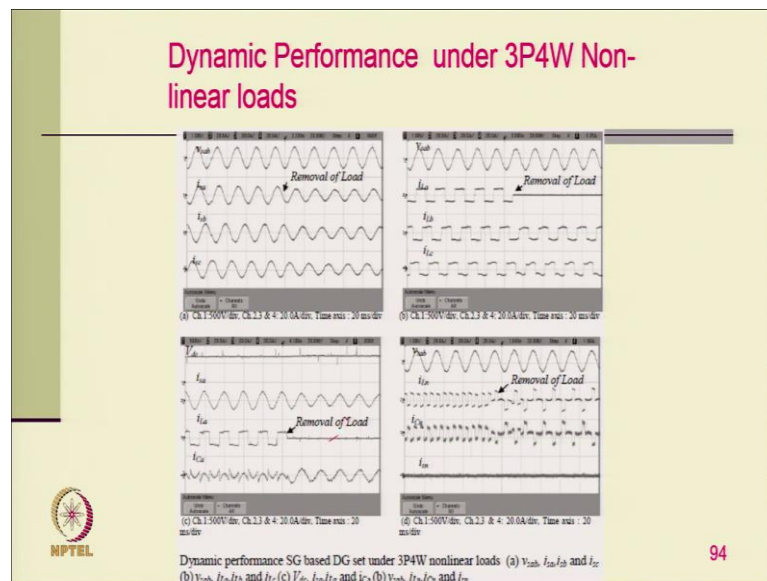
And you can see the THD of the load current is 31.9%, where the THD of your generator current is only 4.2% and it is a 1.8 % THD of the terminal voltage PCC voltage of the generator.

(Refer Slide Time: 32:07)



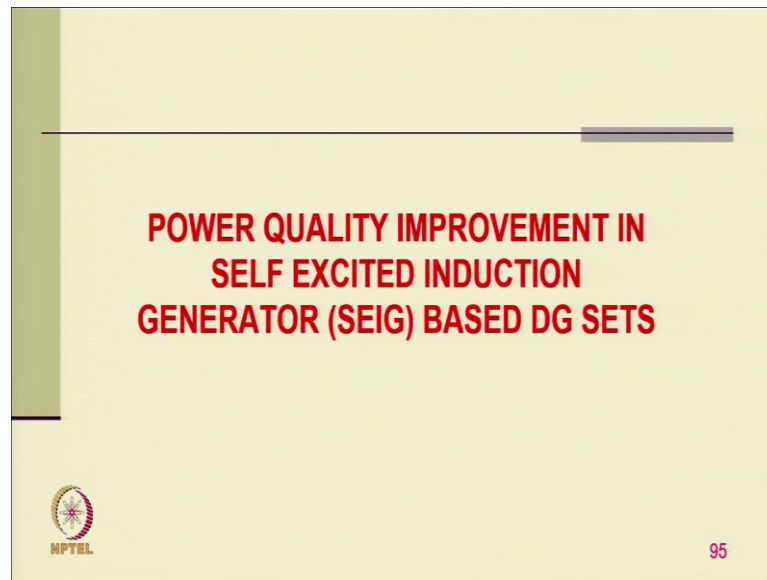
This is the experimental performance of SG based DG set under 3P4W nonlinear loads.

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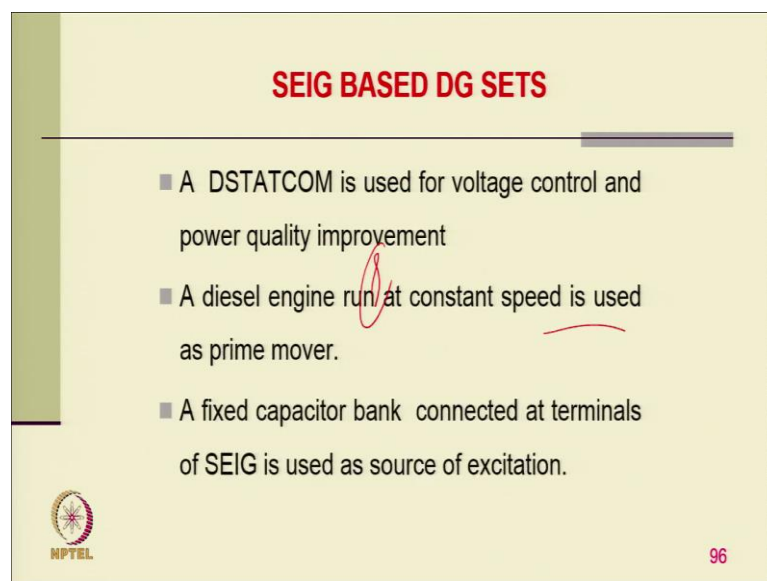


This is the experimental performance of SG based DG set under 3P4W nonlinear loads under dynamic conditions.

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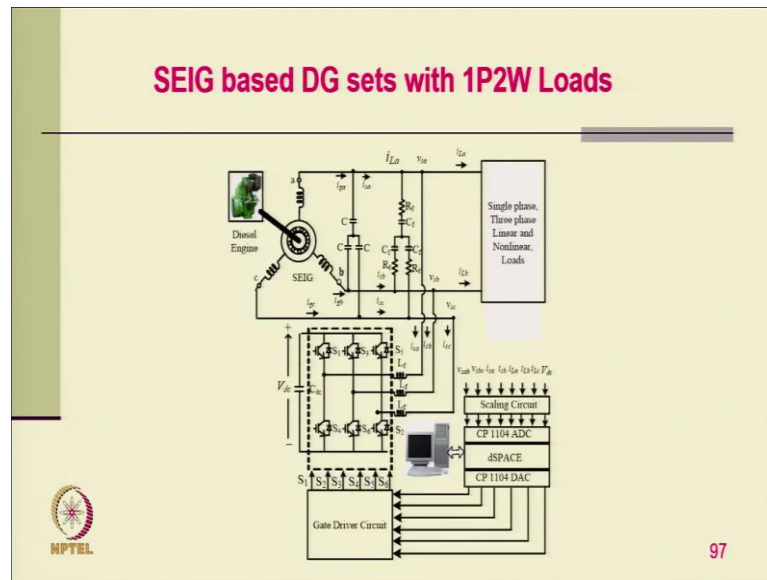


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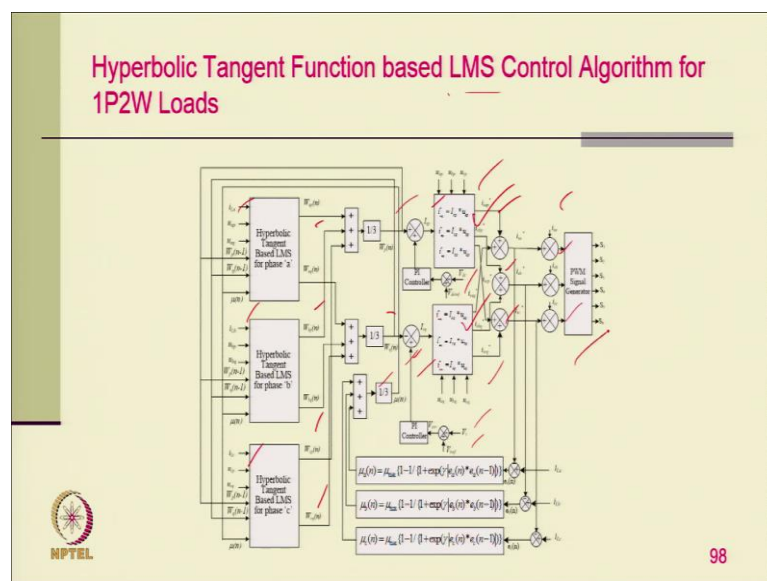


Now, coming to now performance of your power quality improvement in self excited induction generator, in based DG set. In self excited induction generator if you look into, we can use the DSTATCOM voltage. Here, we have to regulate the voltage also voltage control, because there is no other way as well as we have to improve the power quality by load balancing harmonic elimination and diesel engine runs at typically at constant speed. And the fixed capacitor bank is connected at the terminal of SEIG.

(Refer Slide Time: 33:18)




(Refer Slide Time: 33:48)



(Refer Slide Time: 34:49)

Continued.....

- Estimation of Instantaneous Phase Voltages
$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$
- The amplitude of phase voltages $V_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$
- Estimation of In-Phase Unit-Templates
$$u_{ap} = v_{sa}/V_t, u_{bp} = v_{sb}/V_t, u_{cp} = v_{sc}/V_t$$




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Continued.....

- Estimation of Active Power Component of Load Current
$$e(n) = i_L(n) - \{W_p(n) \times u_p(n)\}$$
$$W_p(n) = W_p(n-1) + \{\mu(n) * e(n) * u_p(n)\}$$
where, μ is the learning rate which depends upon the operating parameters and $e(n)$ is error signal.




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Continued.....

- Final weight vector $W_p(n) = \frac{W_a(n) + W_b(n) + W_c(n)}{3}$
- DC Link Voltage PI Controller
$$I_{loss}(n) = I_{loss}(n-1) + K_{pdc} \{V_{dcerr}(n) - V_{dcerr}(n-1)\} + K_{idc} V_{dcerr}(n)$$

where, K_{pdc} and K_{idc} are proportional and integral controller parameters respectively and V_{dcerr} is error in dc link voltage.




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Continued.....

- Estimation of amplitude of active power component of Reference Source Currents
$$I_{sp} = W_p(n) + I_{loss}(n)$$
- Instantaneous Reference Source Currents
$$i_{sap}^* = I_{sp} * u_{ap}, i_{sbp}^* = I_{sp} * u_{bp}, i_{scp}^* = I_{sp} * u_{cp}$$



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Continued.....


- Estimation of Reactive Power Component of Load Current

$$W_q(n) = W_q(n-1) + \{\mu(n) * e(n) * u_q(n)\}$$

$$e(n) = i_L(n) - \{W_{qI}(n) \times u_q(n)\}$$
- Final weight vector

$$W_q(n) = \frac{W_{aq}(n) + W_{bq}(n) + W_{cq}(n)}{3}$$

where $W_{aq}(n)$, $W_{bq}(n)$ and $W_{cq}(n)$ are weighted components of phase 'a', phase 'b' and phase 'c' respectively.



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Continued.....


- Computation of Learning Rate

$$\mu_{a,b,c}(n) = \mu_{max} \{1 - 1 / \{1 + \exp(\gamma |e_{a,b,c}(n) * e_{a,b,c}(n-1)|)\}\}$$

To meet the fast convergence the learning rate is at beginning is kept at maximum (μ_{max}). The optimal value of μ_{max} and γ for experiment are chosen as 0.6 and 10.
- The output of the terminal voltage PI controller at the nth sampling instant is given as,

$$I_{qSTAT}(n) = I_{qSTAT}(n-1) + K_{pV} \{V_{err}(n) - V_{err}(n-1)\} + K_{iV} V_{err}(n)$$

where, K_{pV} and K_{iV} are parameters terminal voltage PI controller and $V_{err}(n)$ is error in terminal voltage




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Continued.....

- Estimation of reactive component of Reference Source Currents
$$I_{sq} = I_{qSTAT}(n) - W_q(n)$$
- Instantaneous reactive component of Reference Source Currents
$$i_{saq}^* = I_{sq}^* * u_{aq}, i_{sbq}^* = I_{sq}^* * u_{bq}, i_{scq}^* = I_{sq}^* * u_{cq}$$
- Estimation of Total Reference Source Currents
$$i_{sa}^* = i_{sap}^* + i_{saq}^* \quad i_{sb}^* = i_{sbp}^* + i_{sbq}^* \quad i_{sc}^* = i_{scp}^* + i_{scq}^*$$




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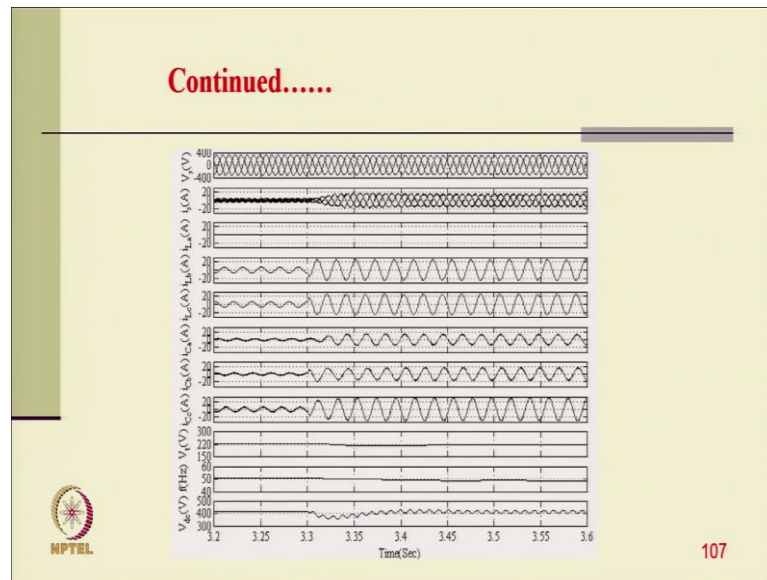
Simulated Performance of SEIG based DG set under 1P2W Linear Loads

- The DG set is initially loaded with a single phase load of 2.4 kW at lagging power factor of 0.8 connected between phases 'b' and 'c'.
- Then it subjected to a load of 3.4 kW at t = 3.3 s.



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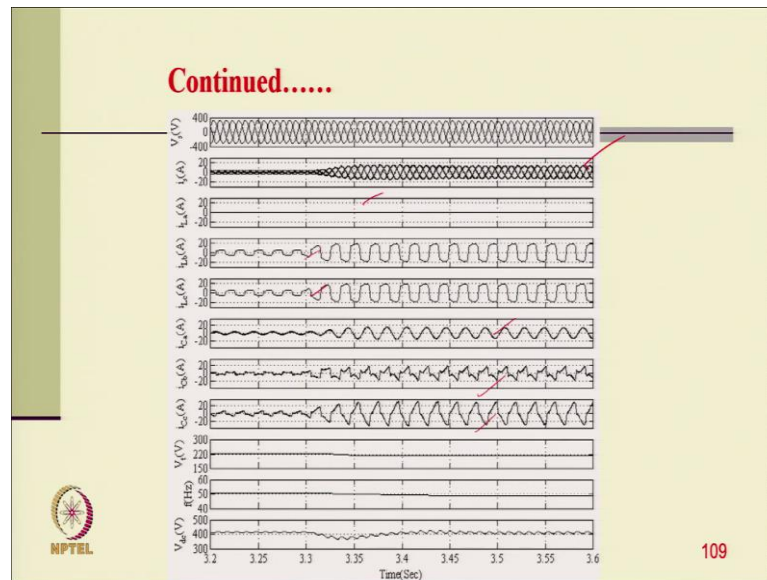
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Simulated Performance of SEIG based DG set under 1P2W Nonlinear Loads

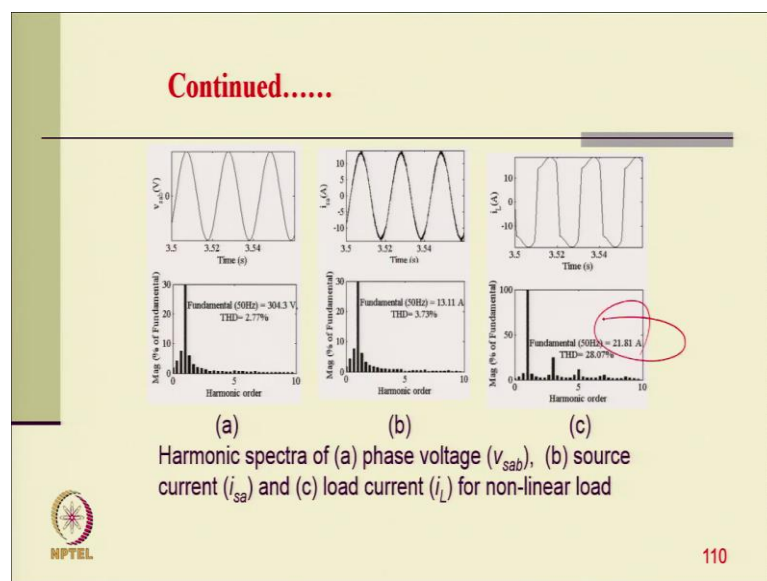
- Single phase load is connected between phase 'b' and 'c'
- Initially system is subjected to a load of 1 kW and then it is subjected to load of 3.6 kW at $t = 3.3$ s.

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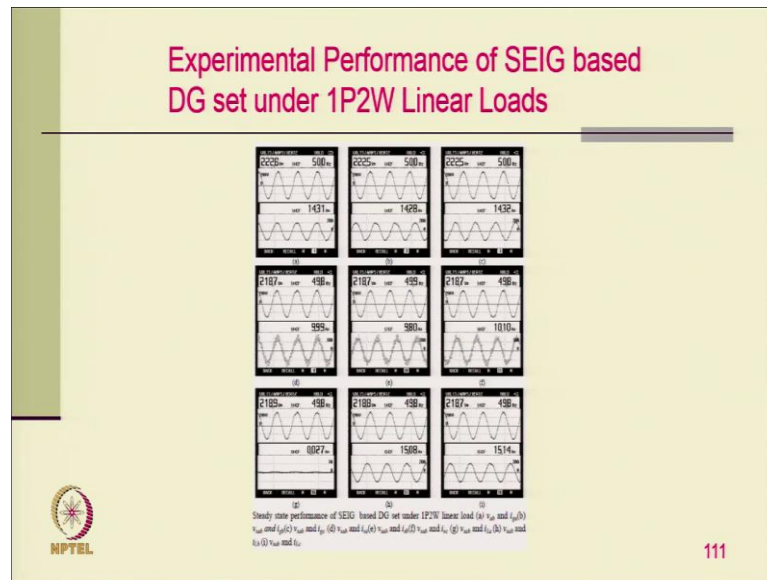


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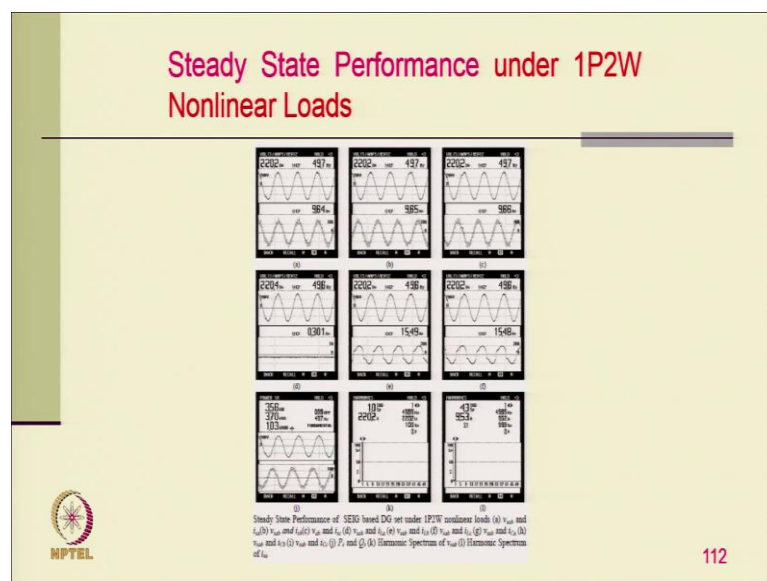


And here, the THD of the load is typically of 28%, but the THD of current generator current is 3.73 % and you can call it that THD voltage of only 2.77 %.

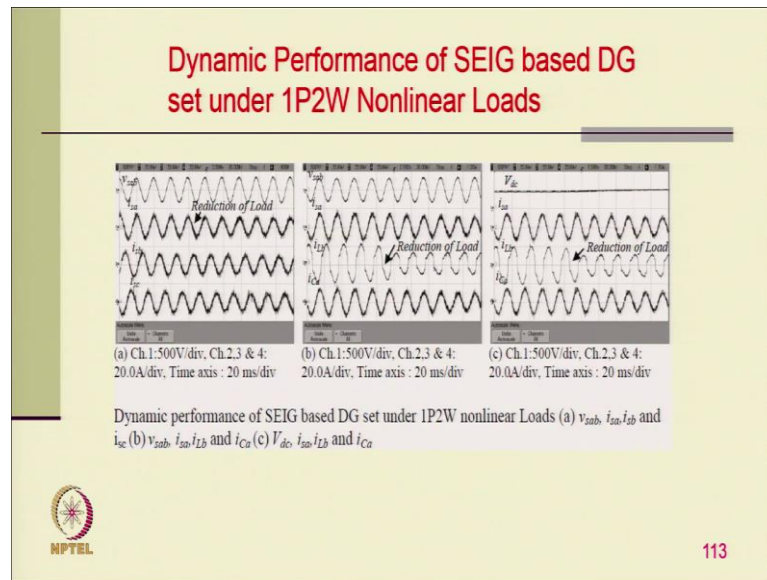
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(Refer Slide Time: 37:35)

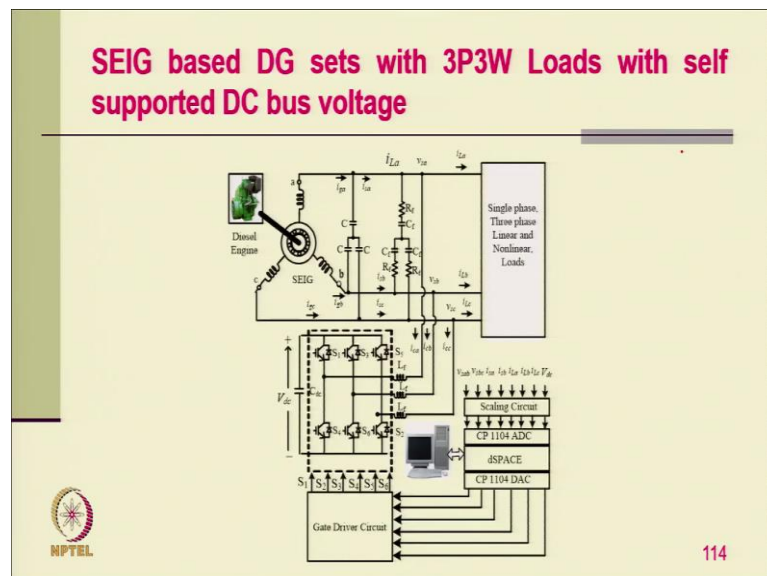


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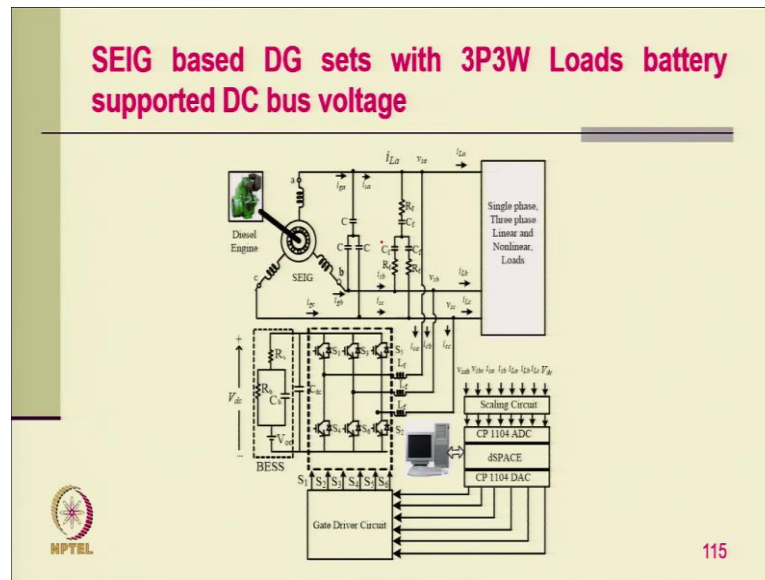


These are the dynamic performance of SEIG based DG set under 1P2W nonlinear loads.

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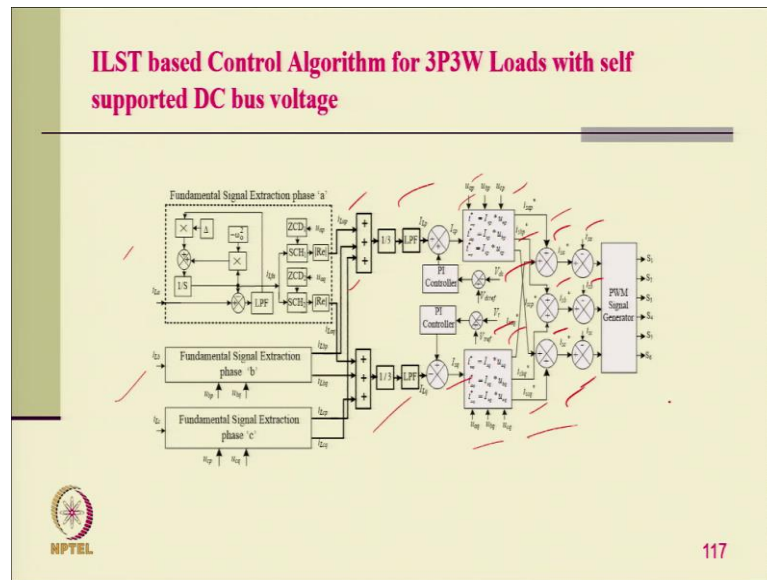
(Refer Slide Time: 38:16)



(Refer Slide Time: 38:21)

- ### Experimentally verified Control algorithms for SEIG based DG sets
- Improved linear sinusoidal tracer (ILST) based Control Algorithm for 3P3W Loads with self supported
 - Instantaneous Symmetrical Component Theory (ISCT) based control algorithm for 3P3W Loads with BESS
- NPTEL
- 116

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(Refer Slide Time: 39:07)

Continued.....

- Estimation of Instantaneous Phase Voltages

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sabc} \\ v_{sbc} \end{bmatrix}$$
- The amplitude of phase voltages $V_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$
- Estimation of In-Phase Unit-Templates

$$u_{ap} = v_{sa}/V_t, \quad u_{bp} = v_{sb}/V_t, \quad u_{cp} = v_{sc}/V_t$$

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Continued.....


- Estimation of Active Power Component of Load Current

$$I_{Lp} = \frac{I_{Lap} + I_{Lbp} + I_{Lcp}}{3}$$

DC Link Voltage PI Controller

$$I_{loss}(n) = I_{loss}(n-1) + K_{pdc} \{V_{dcerr}(n) - V_{dcerr}(n-1)\} + K_{idc} V_{dcerr}(n)$$

where, K_{pdc} and K_{idc} are proportional and integral controller parameters respectively and V_{dcerr} is error in dc link voltage.



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Continued.....

- Estimation of amplitude of active power component of Reference Source Currents

$$I_{sp} = I_{Lp}(n) + I_{loss}(n)$$

- Instantaneous Reference Source Currents

$$i_{sap}^* = I_{sp}^* u_{ap}, i_{sbp}^* = I_{sp}^* u_{bp}, i_{scp}^* = I_{sp}^* u_{cp}$$


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Continued.....

- Estimation of Reactive Power Component of Load Current

$$I_{Lq} = \frac{I_{Laq} + I_{Lbq} + I_{Lcq}}{3}$$
- The output of the terminal voltage PI controller at the nth sampling instant is given as,

$$I_{qSTAT}(n) = I_{qSTAT}(n-1) + K_{pv}\{V_{err}(n) - V_{err}(n-1)\} + K_{iv}V_{err}(n)$$

where, K_{pv} and K_{iv} are parameters terminal voltage PI controller and $V_{err}(n)$ is error in terminal voltage



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(Refer Slide Time: 39:36)


Continued.....

- Estimation of reactive component of Reference Source Currents

$$I_{sq} = I_{qSTAT}(n) - I_{Lq}(n)$$
- Instantaneous reactive component of Reference Source Currents

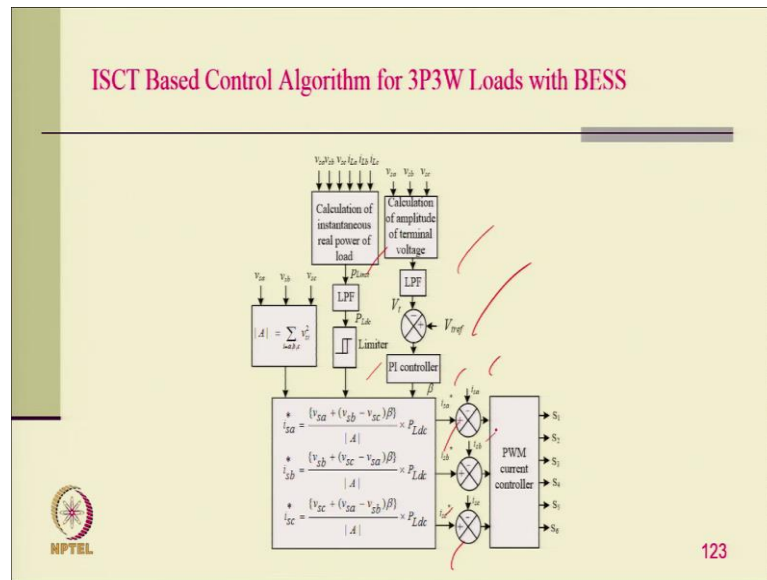
$$i_{saq}^* = I_{sq}^* * u_{aq}, i_{sbq}^* = I_{sq}^* * u_{bq}, i_{scq}^* = I_{sq}^* * u_{cq}$$
- Estimation of Total Reference Source Currents

$$i_{sa}^* = i_{sap}^* + i_{saq}^* \quad i_{sb}^* = i_{sbp}^* + i_{sbq}^* \quad i_{sc}^* = i_{scp}^* + i_{scq}^*$$



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(Refer Slide Time: 40:25)

Continued.....

- This algorithm uses phase voltages (v_{sa}, v_{sb}, v_{sc}), average load power (P_{Ldc}) and source power factor angle (f) for estimation of reference source currents
- Estimation of Instantaneous Phase Voltages

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$


■ The amplitude of phase voltages $V_t = \sqrt{\frac{2}{3} (v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$

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Continued.....

- Estimation Reference Source Current


$$i_{sa}^* = \frac{\{v_{sa} + (v_{sc} - v_{sb})\beta\}}{\sum_{i=a,b,c} v_{si}^2} * p_s \quad i_{sb}^* = \frac{\{v_{sb} + (v_{sa} - v_{sc})\beta\}}{\sum_{i=a,b,c} v_{si}^2} * p_s$$
$$i_{sc}^* = \frac{(v_{sc} + (v_{sb} - v_{sa})\beta)}{\sum_{i=a,b,c} v_{si}^2} * p_s$$


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Continued.....

- The parameter b is given by, $\beta = \frac{q_s}{\sqrt{3} p_s} = \frac{\tan \phi}{\sqrt{3}}$
- ϕ is power factor angle of load
- The parameter b is function of reactive power to be supplied by the source which directly relates to the terminal voltage of the system. So, b can be used to control the terminal voltage.
- It can be generated using a PI controller which fed with the terminal voltage error.




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Continued.....

- Output of terminal voltage PI controller ,
$$b(n) = b(n-1) + K_{pv}\{V_{err}(n) - V_{err}(n-1)\} + K_{iv}V_{err}(n)$$
where, K_{pv} and K_{iv} gain parameters of PI controller and $V_{err}(n)$ error voltage.
- The terminal voltage error can be given as,
$$V_{err}(n) = V_{ref}(n) - V_t(n)$$




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(Refer Slide Time: 40:52)

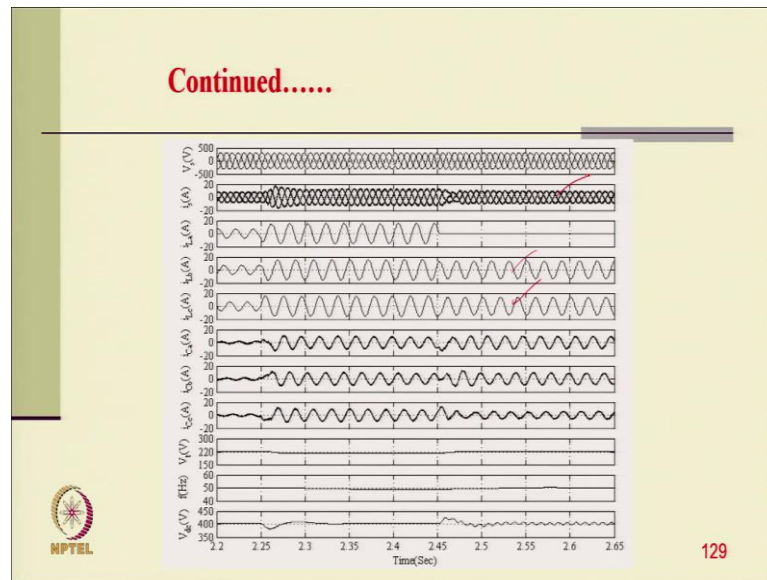
Simulated Performance of SEIG based DG set under 3P3W Linear Loads

- Initially system is subjected to a inductive load of 2 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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These are the simulated performance of the SEIG based DG set under 3P3W linear loads.

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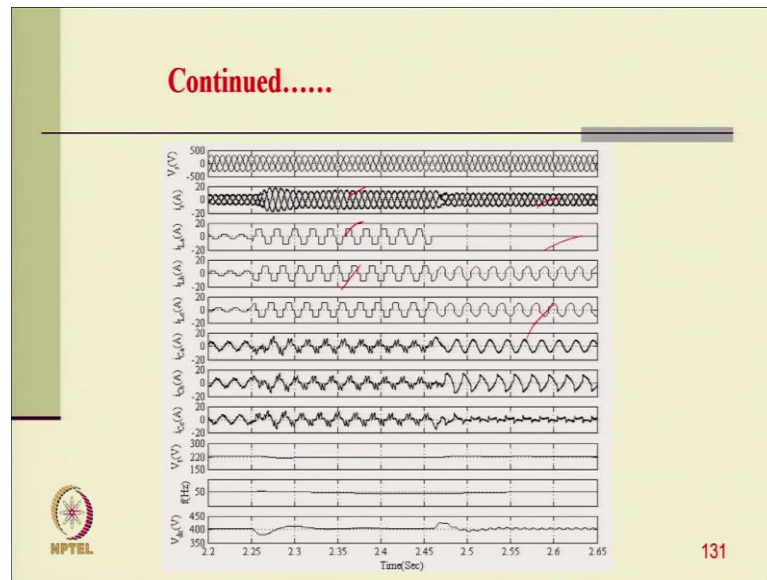
Simulated Performance of SEIG based DG set under 3P3W Non-linear Loads

- The system is initially subjected to a non-linear load of 2 kW and then it is subjected to non-linear load of 3.6 kW at $t=2.25$ s.

- The system is subjected to an unbalanced load from from $t=2.45$ s to 2.65s.

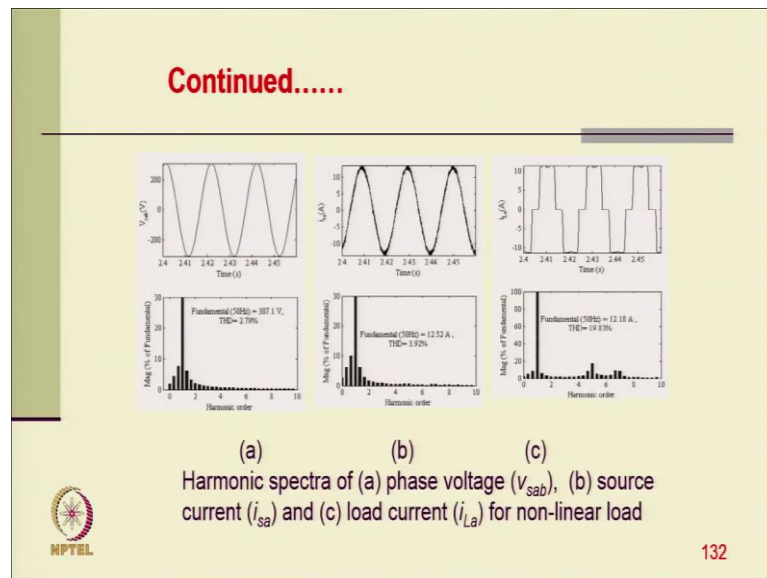
130

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These are the simulated performance of the SEIG based DG set under 3P3W non-linear loads.

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Here, we have a THD of the load; typically order of 19%, but the current THD in generator is only 3.92 % where the voltage THD is only 2.79 %.

(Refer Slide Time: 41:28)

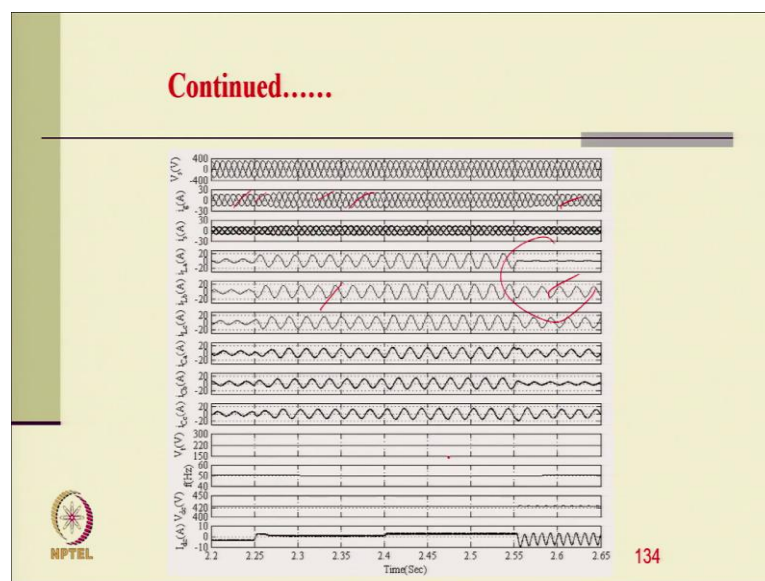
Simulated Performance of SEIG based DG set with BESS under 3P3W Linear Loads

- The system is initially 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 4.4 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'. It is observed that the source current is still balanced.



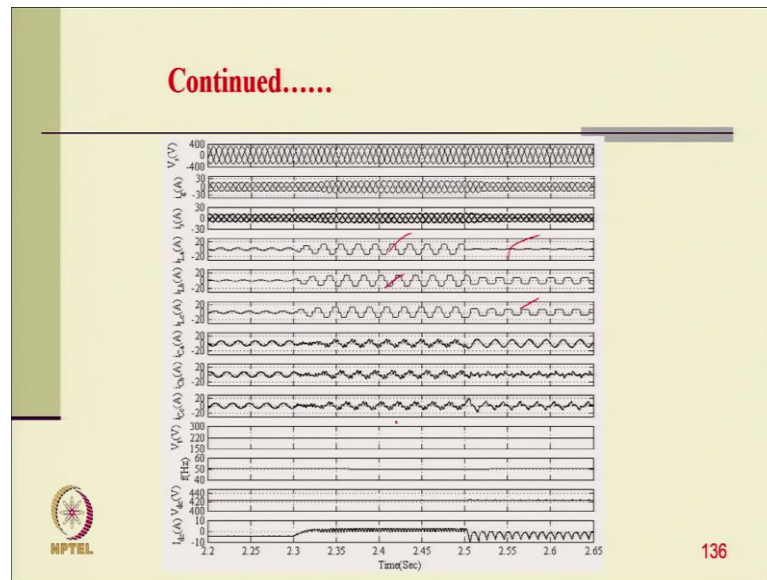
133

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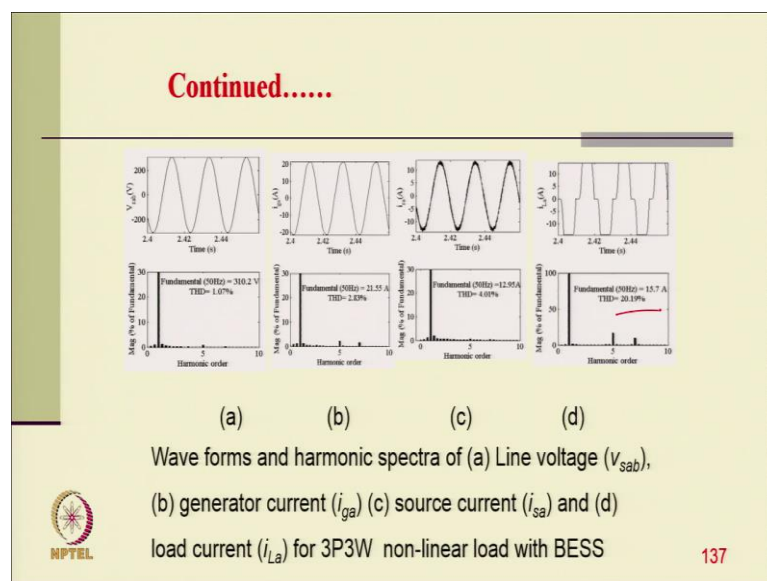


These are the simulated performance of the SEIG based DG set with BESS under 3P3W linear loads.

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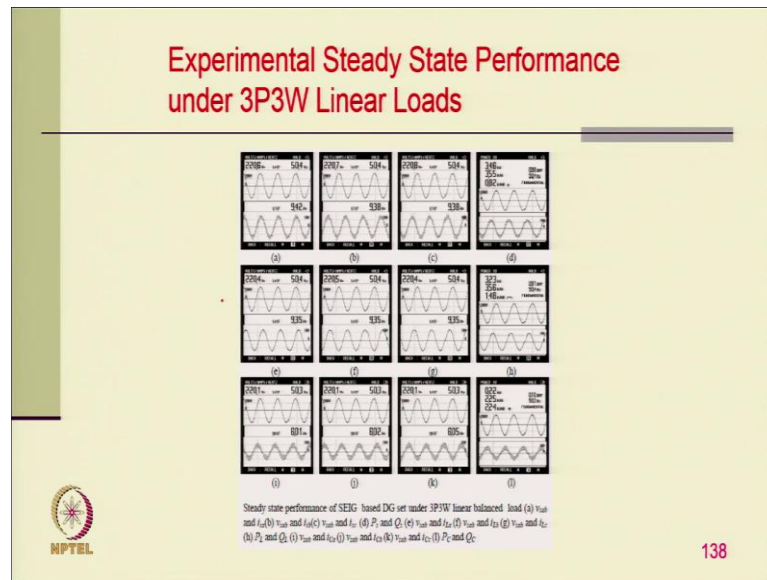


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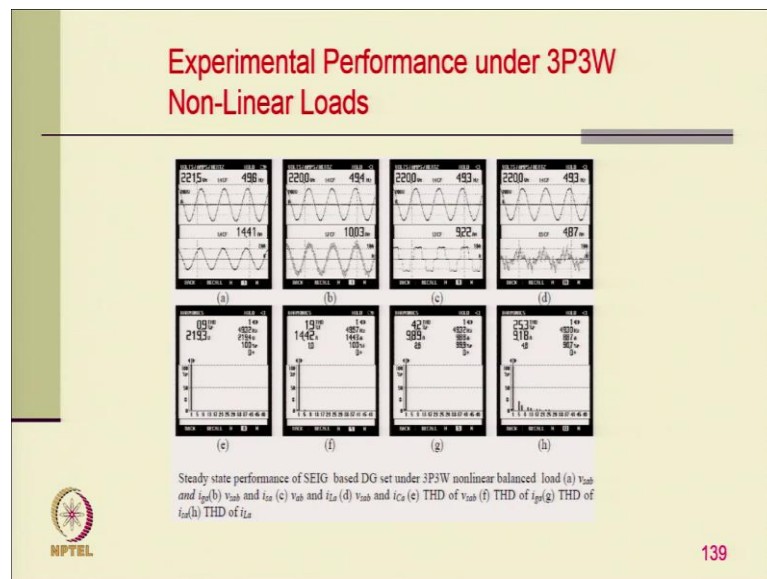
Here, we have the THD of the load current, 20%, whereas, the THD of generator current is 4 % where voltage THD is only 1%.

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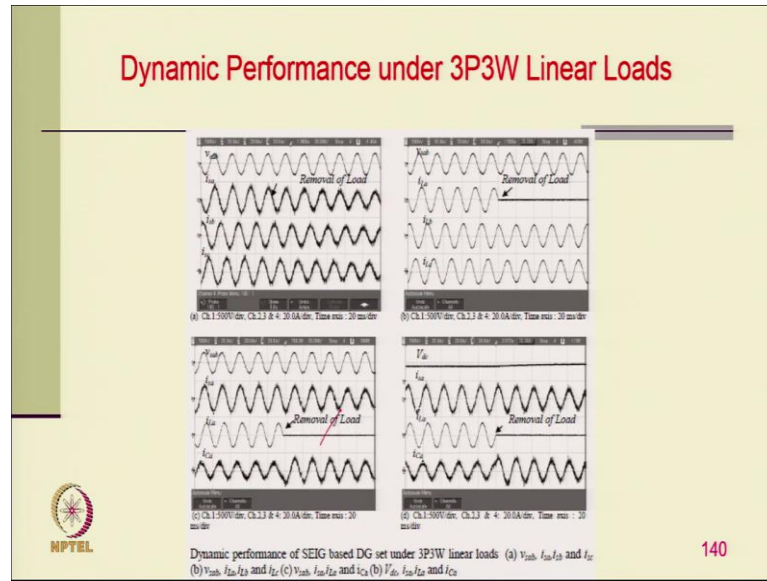
These are the experimental steady state performance under 3P3W linear loads.

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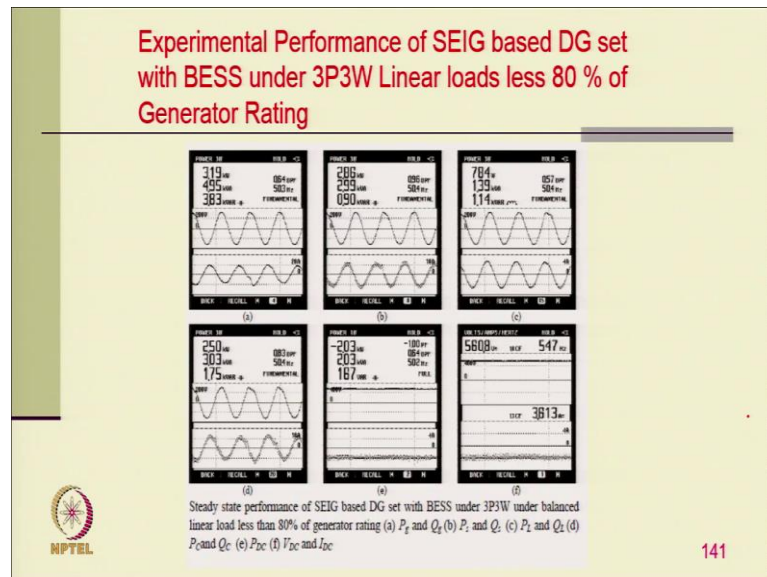
These are the experimental steady state performance under 3P3W non-linear loads.

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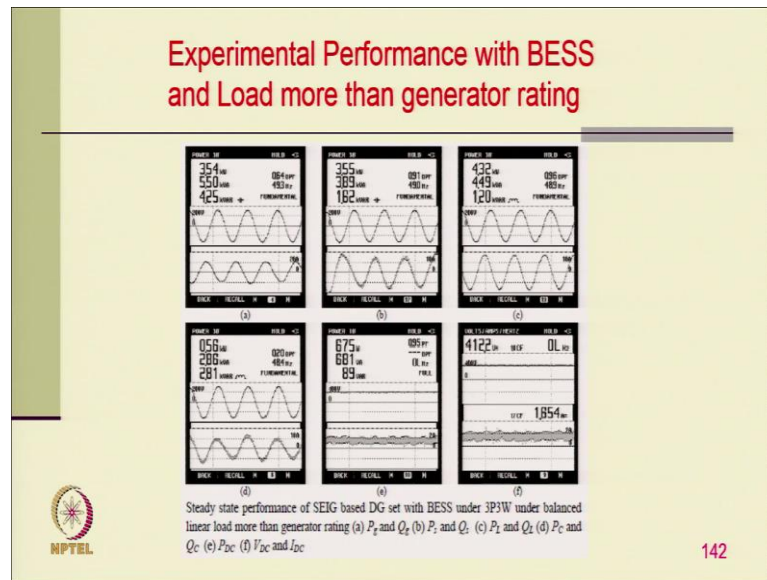


These are the experimental dynamic performance under 3P3W linear loads.

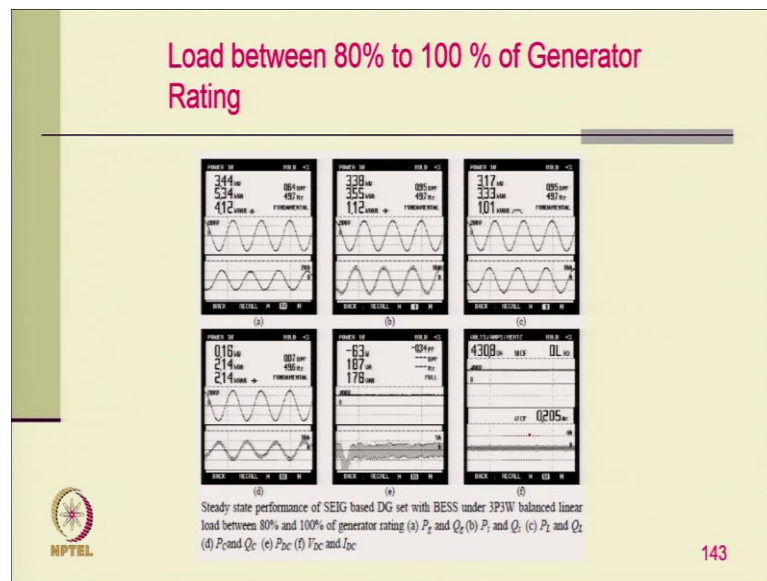
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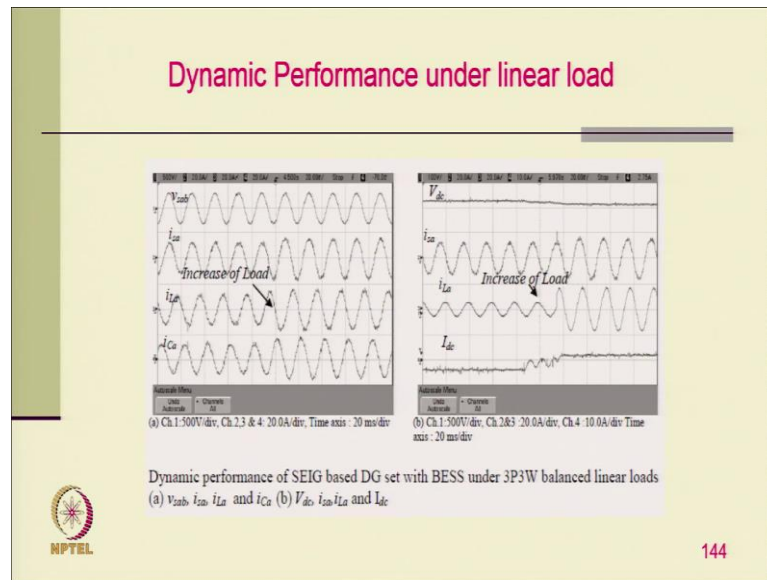
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(Refer Slide Time: 43:17)

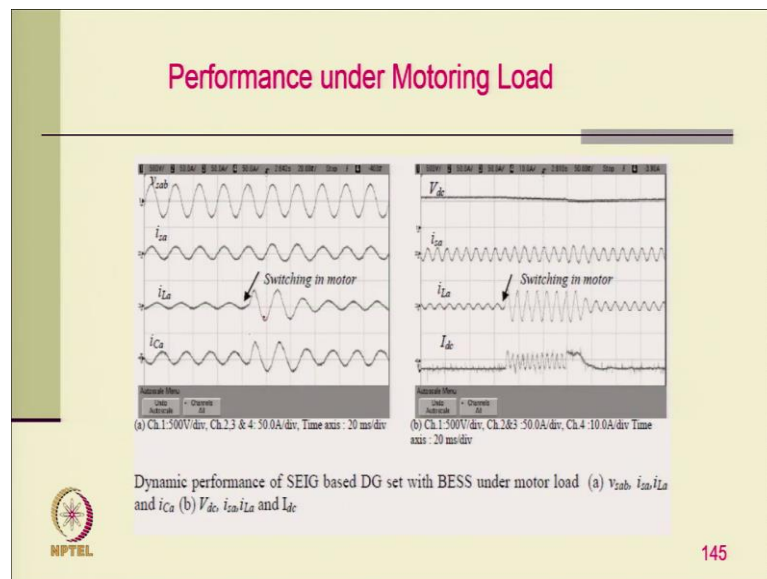


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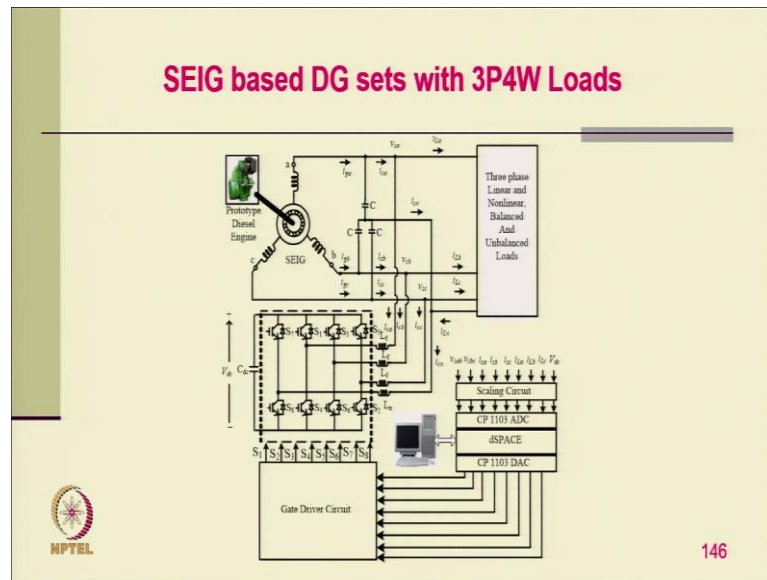
These are the experimental dynamic performance under linear loads.

(Refer Slide Time: 43:28)



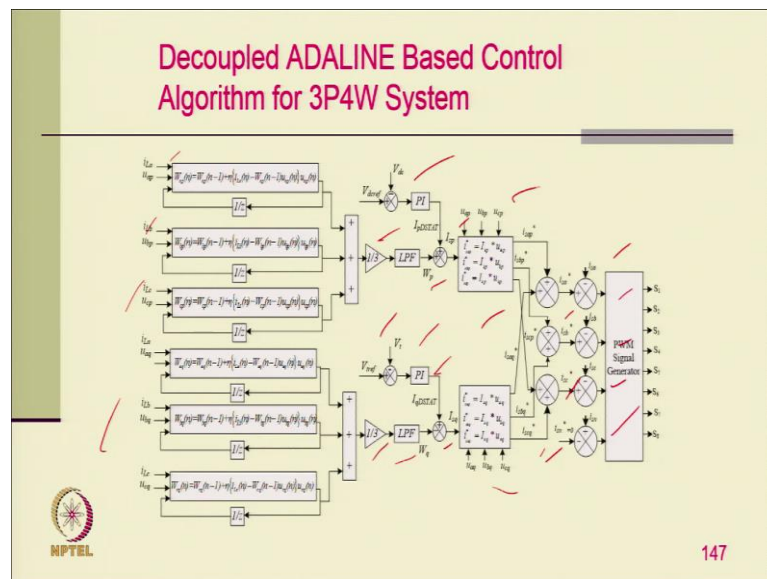
These are the experimental performance under motoring load.

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This is the circuit configuration of SEIG Based DG sets with 3P4W loads.

(Refer Slide Time: 44:13)




This is control algorithms applied for the control of the DG sets.

(Refer Slide Time: 45:07)

Continued.....

- Estimation of Instantaneous Phase Voltages
$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$
- The amplitude of phase voltages
$$V_t = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$$
- Estimation of In-Phase Unit-Templates
$$u_{ap} = v_{sa}/V_t, u_{bp} = v_{sb}/V_t, u_{cp} = v_{sc}/V_t$$




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Continued.....

- Final weight active power component
$$W_p(n) = \frac{W_{ap}(n) + W_{bp}(n) + W_{cp}(n)}{3}$$
- DC Link Voltage PI Controller
$$I_{loss}(n) = I_{loss}(n-1) + K_{pdc} \{V_{dcerr}(n) - V_{dcerr}(n-1)\} + K_{idc} V_{dcerr}(n)$$

where, K_{pdc} and K_{idc} are proportional and integral controller parameters respectively and V_{dcerr} is error in dc link voltage.



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Continued.....

- Estimation of amplitude of active power component of Reference Source Currents

$$I_{sp} = W_p(n) + I_{loss}(n)$$

- Instantaneous Reference Source Currents

$$i_{sap}^* = I_{sp}^* u_{ap}, i_{sbp}^* = I_{sp}^* u_{bp}, i_{scp}^* = I_{sp}^* u_{cp}$$


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Continued.....

- Estimation of Reactive Power Component of Load Current


$$W_{aq}(n) = W_{aq}(n-1) + \eta \{i_{La}(n) - W_{aq}(n-1)u_{aq}(n)\}u_{aq}(n),$$

$$W_{bq}(n) = W_{bq}(n-1) + \eta \{i_{Lb}(n) - W_{bq}(n-1)u_{bq}(n)\}u_{bq}(n),$$

$$W_{cq}(n) = W_{cq}(n-1) + \eta \{i_{Lc}(n) - W_{cq}(n-1)u_{cq}(n)\}u_{cq}(n),$$

- Final weight vector $W_q(n) = \frac{W_{aq}(n) + W_{bq}(n) + W_{cq}(n)}{3}$

where $W_{aq}(n)$, $W_{bq}(n)$ and $W_{cq}(n)$ are weighted components of phase 'a', phase 'b' and phase 'c' respectively.



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Continued.....

- The output of the terminal voltage PI controller at the nth sampling instant is given as,

$$I_{qSTAT}(n) = I_{qSTAT}(n-1) + K_{pv}\{V_{err}(n) - V_{err}(n-1)\} + K_{iv}V_{err}(n)$$

where, K_{pv} and K_{iv} are parameters terminal voltage PI controller and $V_{err}(n)$ is error in terminal voltage



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Continued.....

- Estimation of reactive component of Reference Source Currents

$$I_{sq} = I_{qSTAT}(n) - W_q(n)$$
- Instantaneous reactive component of Reference Source Currents

$$i_{saq}^* = I_{sq} * u_{aq}, i_{sbq}^* = I_{sq} * u_{bq}, i_{scq}^* = I_{sq} * u_{cq}$$
- Estimation of Total Reference Source Currents

$$i_{sa}^* = i_{sap}^* + i_{saq}^* \quad i_{sb}^* = i_{sbp}^* + i_{sbq}^* \quad i_{sc}^* = i_{scp}^* + i_{scq}^*$$




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Continued.....

- Neutral Current Compensation
 - The neutral terminal of load is then connected at neutral point of RC filter and fourth leg of VSC through an inductor.
 - Fourth leg of VSC is used for source neutral current compensation.
 - It is therefore desired that no current should flow from the neutral point of RC filter to load neutral terminal.
 - This compensation is achieved by gating pulses of fourth leg of VSC using error signal which is a difference of source neutral current (i_{sn}) and its reference value (i.e. $i_{sn}^* = 0$).




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Selected parameters

| Component | Rating |
|----------------------------|--|
| Prototype of Diesel Engine | 7.5 hp variable frequency induction motor drive |
| SEIG | 3.7 kW, three phase, 230V, 50Hz, 1435 rpm, 4-pole, |
| VSC | Semikron's make, 25 kVA |
| DC Link Capacitor | 1650 µF <i>µF</i> |
| Interfacing Inductors | 3.3 mH <i>mH</i> |
| Ripple Filter | 5W 30F <i>30F</i> |
| DC link battery | nominal voltage of 420V, 35 cell units of 12V, 7Ah |
| Current Sensors | LEM make LA-55P |
| Voltage sensors | LEM make LV-25 P |
| dSPACE | dSPACE 1103 |




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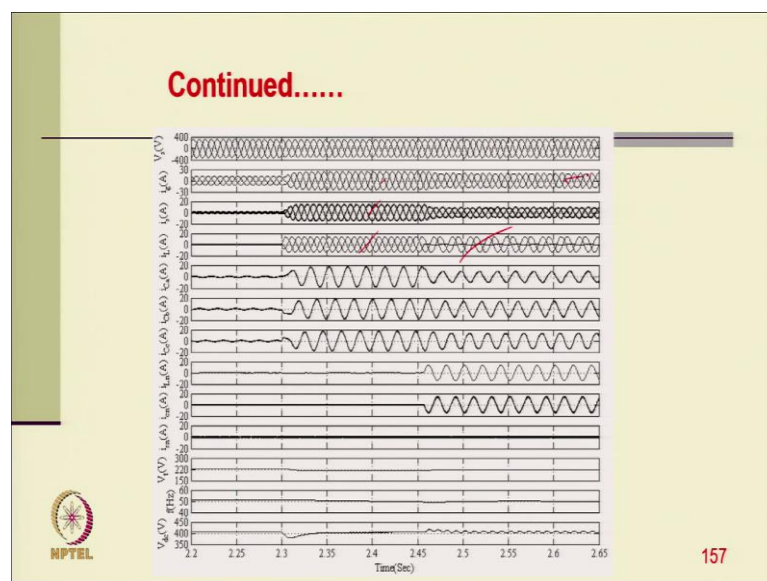
Simulated Performance of SEIG based DG set under 3P4W Linear loads

- Initially system is at no load and then at $t = 2.3\text{s}$, it is subjected to a RL load of 3 kW at 0.8 lagging power factor.
- The system is subjected to unbalanced load at $t = 2.45\text{ s}$.



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These are the simulated performance of SEIG based DG set under 3W4P linear loads.

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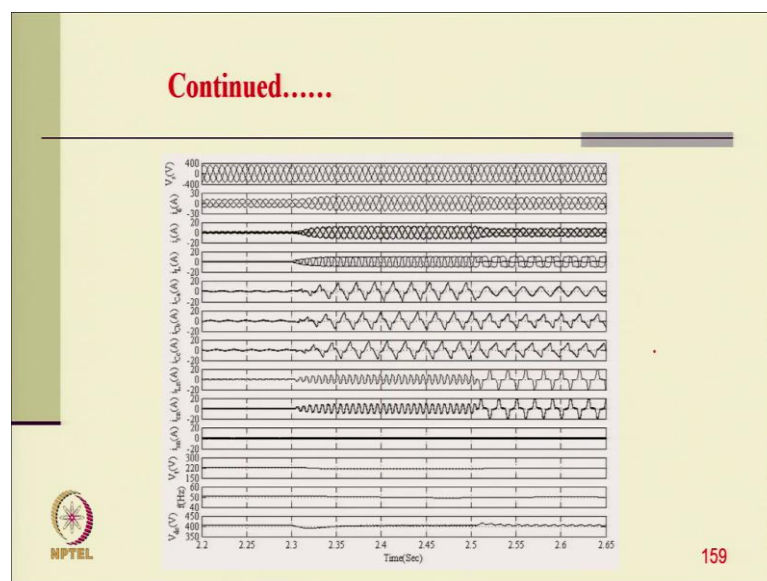
Simulated Performance of SEIG based DG set under 3P4W Nonlinear loads

- The DG set is subjected to a nonlinear load of 3.7 kW at $t = 2.3$ s and then load is made unbalanced $t = 2.5$ s.



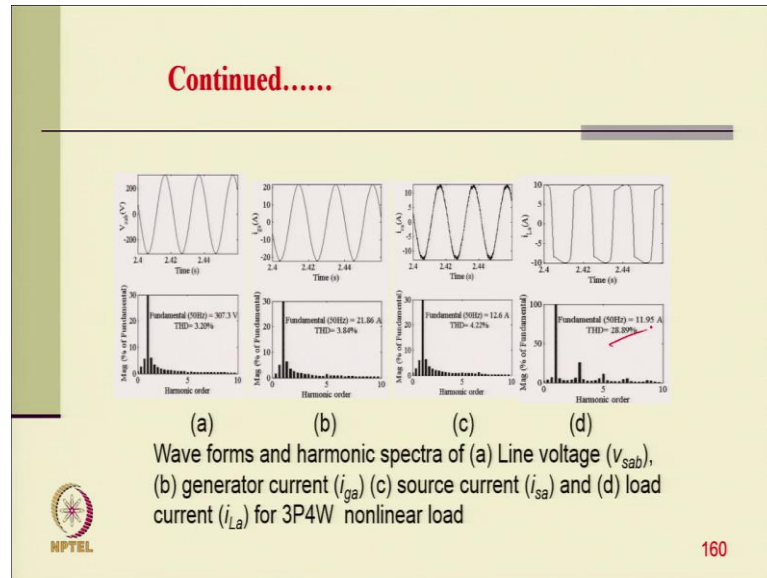
158

(Refer Slide Time: 46:35)



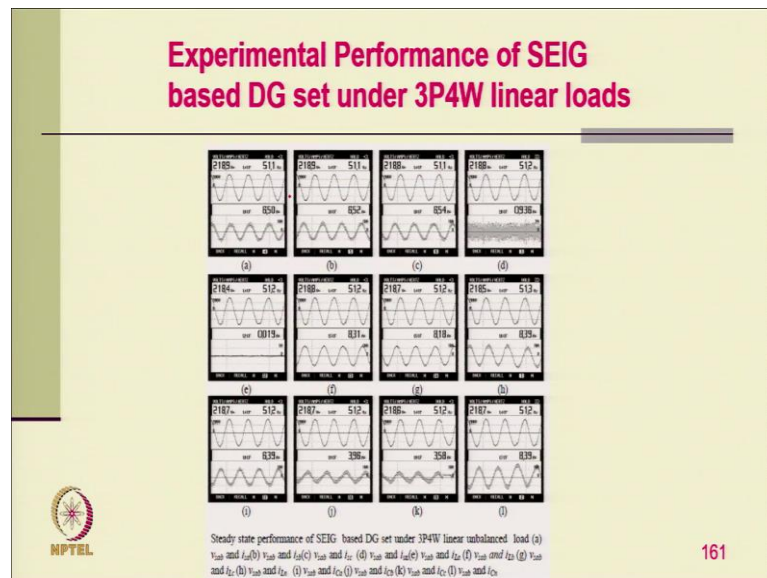
These are the simulated performance of SEIG based DG set under 3W4P non-linear loads.

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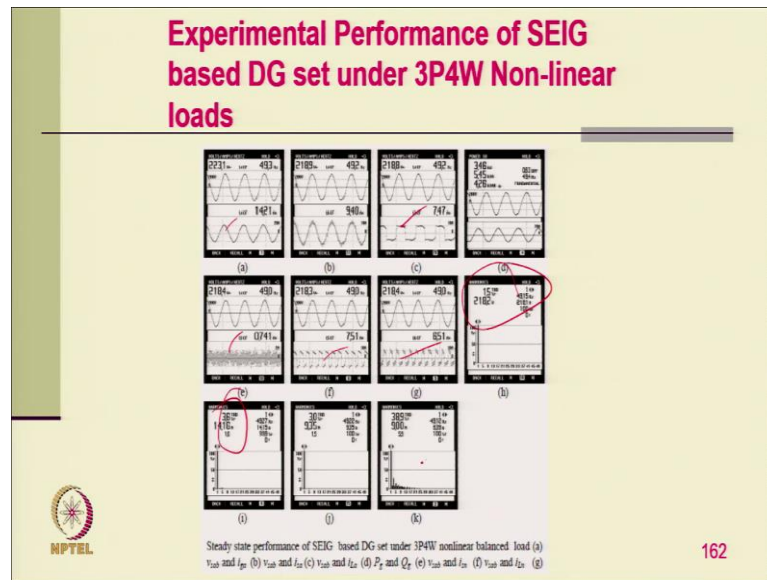


Here, the load current THD is 28.8%, whereas, the generator current THD is 3.8% and the point of common coupling voltage THD is only 3.2 %.

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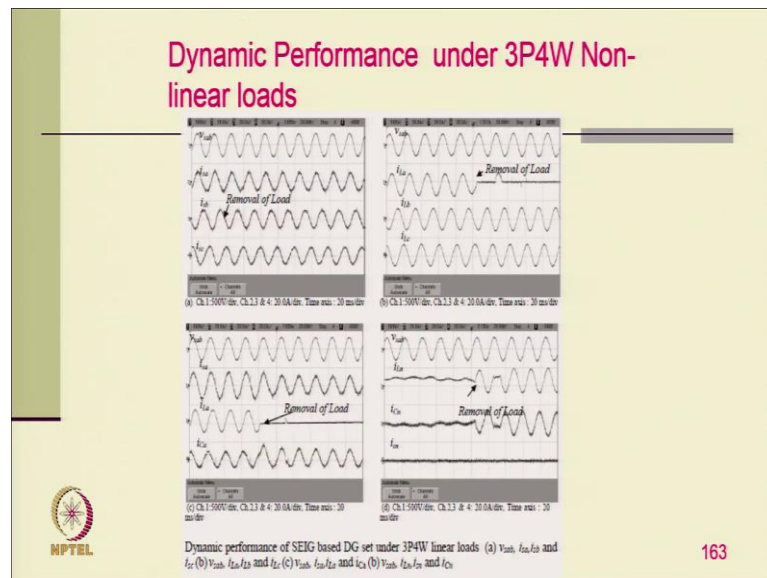


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These are the experimental performance of SEIG based DG set under 3P4W non-linear loads.

(Refer Slide Time: 47:28)



These are the experimental dynamic performance under 3P4W non-linear loads.