Power Quality

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Lecture - 04
Passive Shunt and Series Compensations

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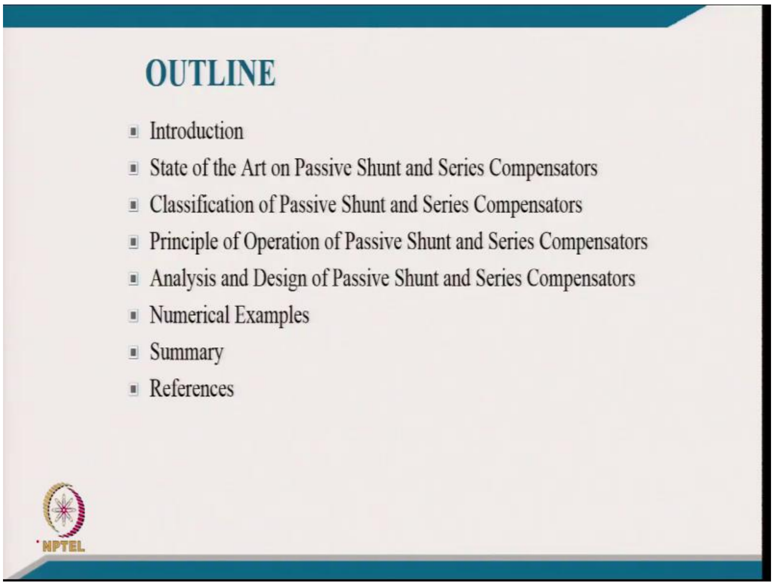

Welcome to this lecture on the part of Power Quality on Passive Shunt and Series Compensators. The passive shunt and series compensators are customarily used when you have a sinusoidal supply voltage. So, we would like to talk about the introduction, then state of the art on passive shunt and series compensators.

We classify the passive and shunt series compensators and discuss the principle of operation of passive shunt and series compensators. We discuss an analysis and the design of the passive series compensator, with the then followed by numerical examples and a summary and the references with that.

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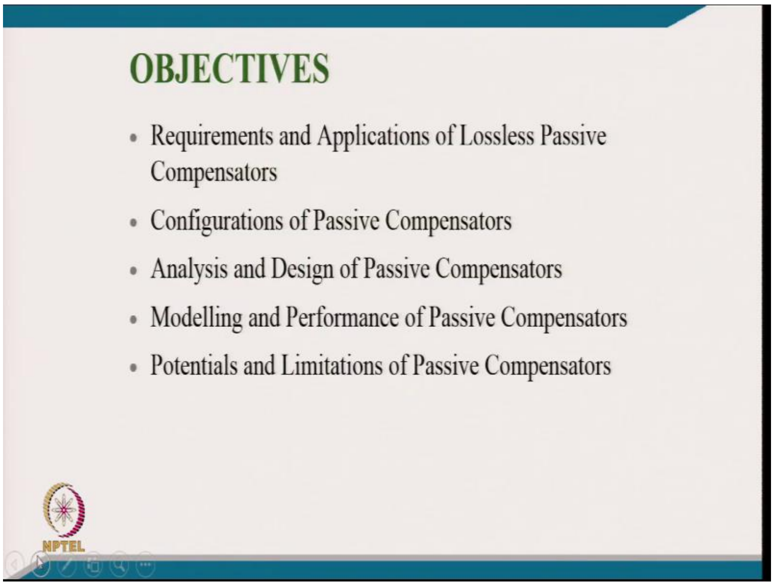

So, the very objective of this today's lecture is the requirement and application of lossless passive compensators. We will talk about the configuration of passive shunt compensators and analyze and design these passive compensators. Of course, we will discuss this passive compensator's modeling and performance and its potential and limitations.

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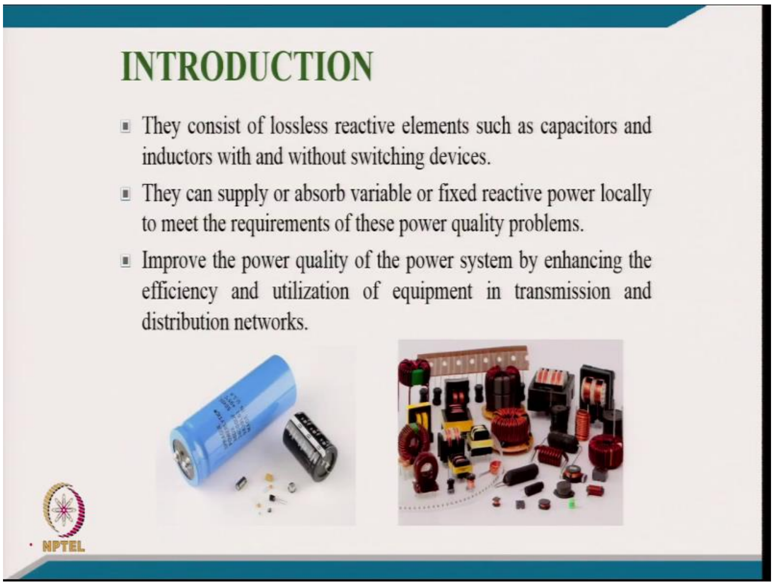

The passive compensator consists of lossless reactive elements such as capacitors and inductors with and without switching devices. And they can supply or absorb variable or fixed reactive power locally to meet the requirement of these power quality problems. And improve the power quality of the power system by enhancing the efficiency and utilization of equipment in transmission and distribution networks. And this consists mainly of different reactors or inductors and AC capacitors.

So, we are talking about this kind of compensation when we have a sinusoidal supply voltage and a sinusoidal supply current. But, indeed, we have a problem like the typically reduced voltage or reactive power problem.

We might have a load unbalanced if it is a type of your three-wire system and four-wire system, and we might have an even neutral current because of an unbalanced load. So we will be talking about only the typical compensation by this lossless component in this such a linear environment. They are inductors and capacitors, storing energy in one-half cycle, relieving energy, and complementing each other.

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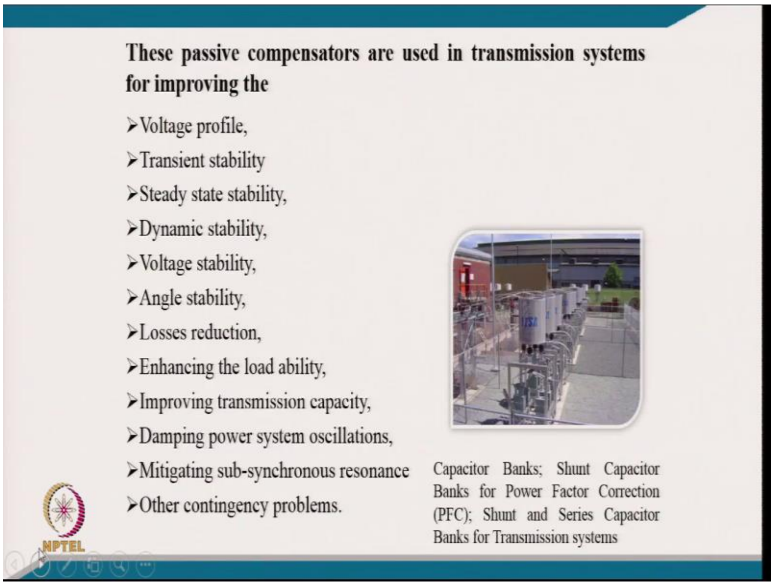

In this chapter, we consider no harmonics and other things in the system. So, these passive compensators are used in transmission systems; typically, they improve the different performance parameters, improve the voltage profile, and then improve the transient stability. They are also used to improve the steady state stability, dynamic stability, voltage stability, angular stability, and of course, the losses reduction by compensating for reactive power.

They are also used to enhance the load ability, improve the transmission network's transmission capacity, dampen the power system oscillation, and mitigate sub-synchronous resonance and other contingency problems. This photograph shows the capacitor banks of huge ratings for power factor correction and series and shunt and series compensator banks for the transmission system for compensating the transmission line and the substation.

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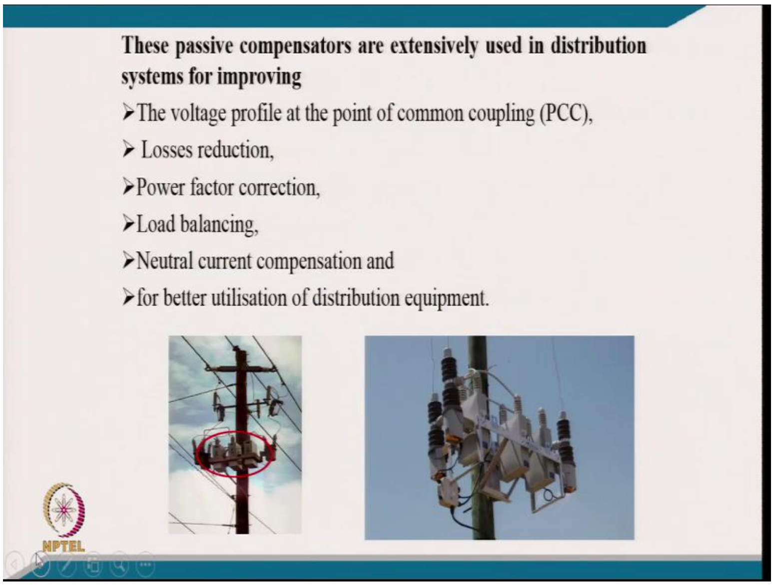

The passive compensators are extensively used in the distribution system for improving the voltage profile at the point of common coupling. And of course, for loss reduction, the power factor correction, the load balancing, a neutral current compensation, and better distribution equipment utilization.

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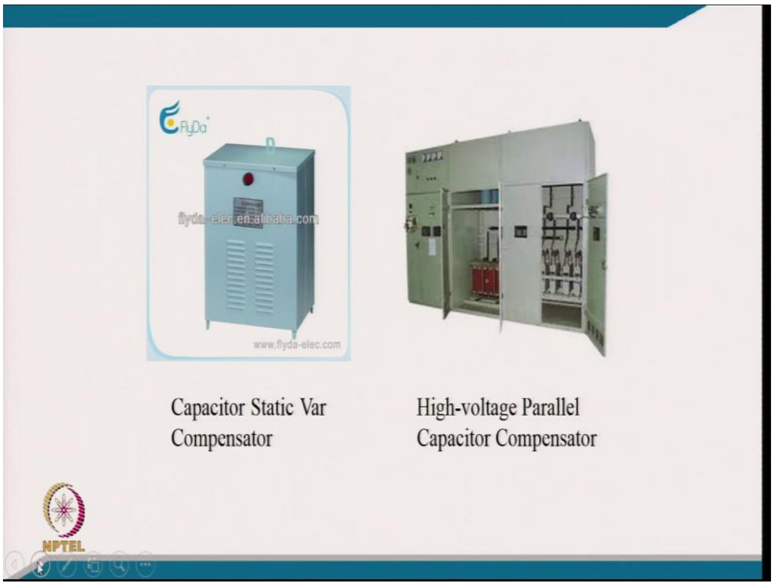

It can be seen clearly in the photograph, how the Capacitor Static Var Compensator looks and how the High-voltage Parallel Capacitor Compensator looks.

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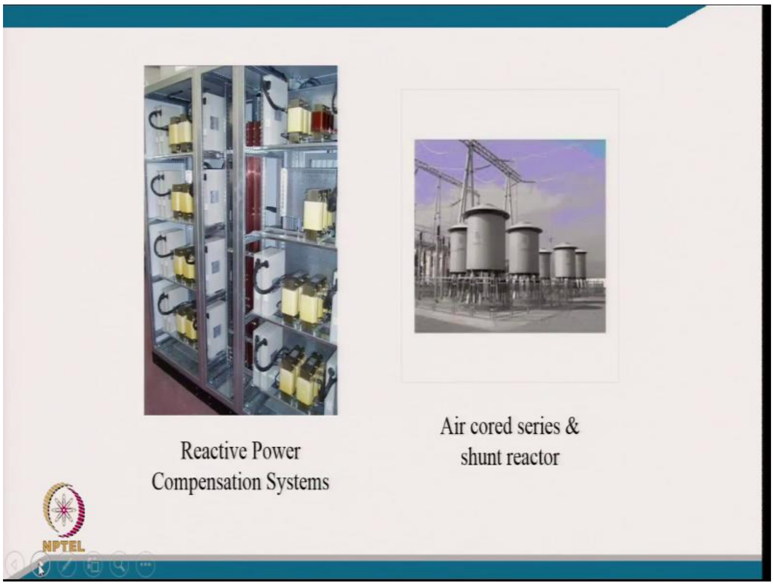

The photograph on the left side is a reactive power compensation system and on the right side is an air cored series and shunt reactors used in a very high voltage network-like transmission system.

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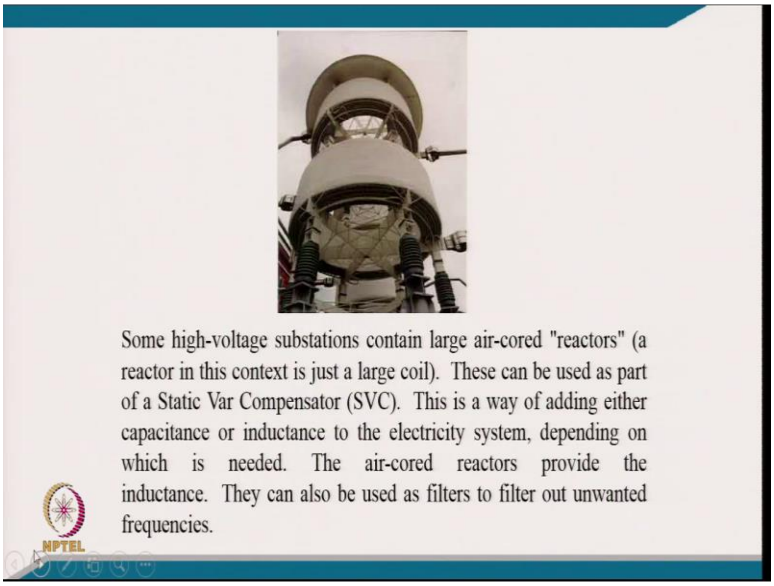

Some high-voltage substations contain large air-cored "reactors" (a reactor in this context is just a large coil). These can be used as part of a Static Var Compensator (SVC). This is a way of adding either capacitance or inductance to the electricity system, depending on which is needed. The air-cored reactors provide the inductance. They can also be used as filters to filter out unwanted frequencies.

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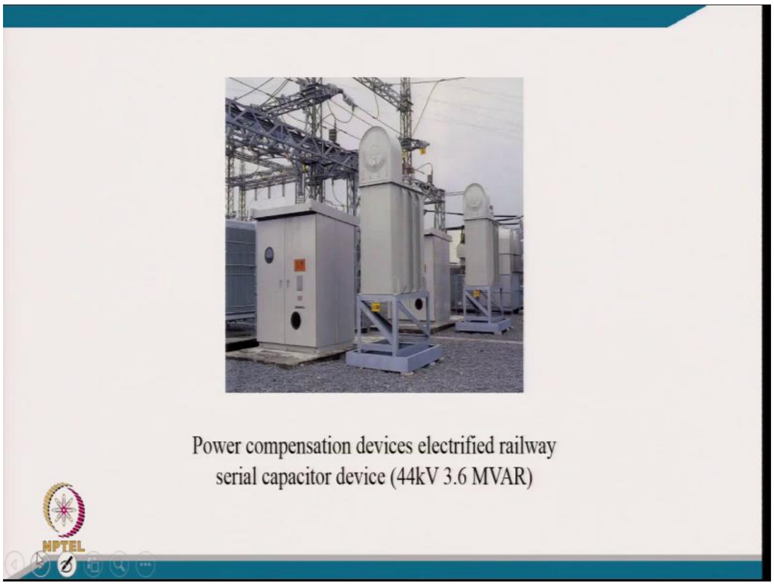

These are typically power compensation devices electrified on railways series capacitors device; at typically 44 kV and 3.6 MVAR.

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We talk about the state of the art on this passive shunt and series compensator.

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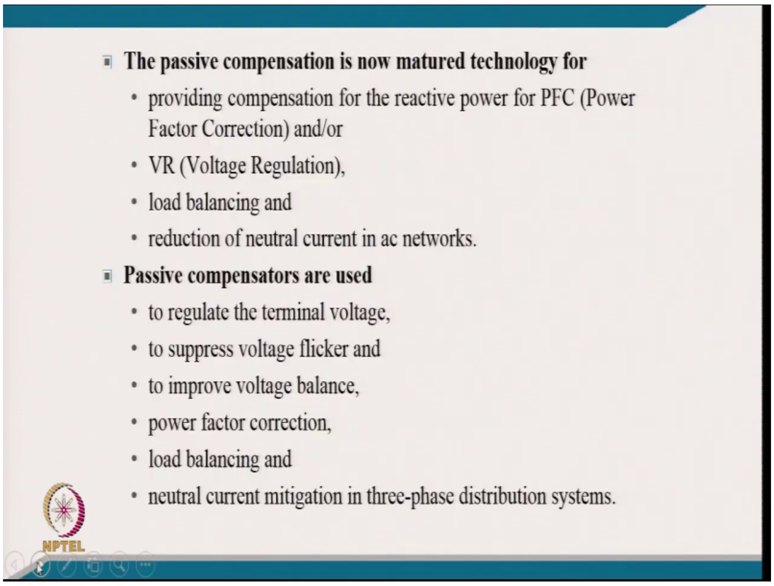

Passive compensation is now matured technology for providing compensation for the reactive power for power factor correction and or voltage regulation. But these two cannot go simultaneously; you might be using this shunt compensation for power factor correction or voltage regulation. Then, it can be used for load balancing and reduction of neutral current in the AC network. So, this is basically for a distribution system.

These passive compensators are also used to regulate the terminal voltage, suppress the voltage flicker, improve the voltage balance, and power factor correction and load balancing and neutral current mitigation in a three-phase distribution system.

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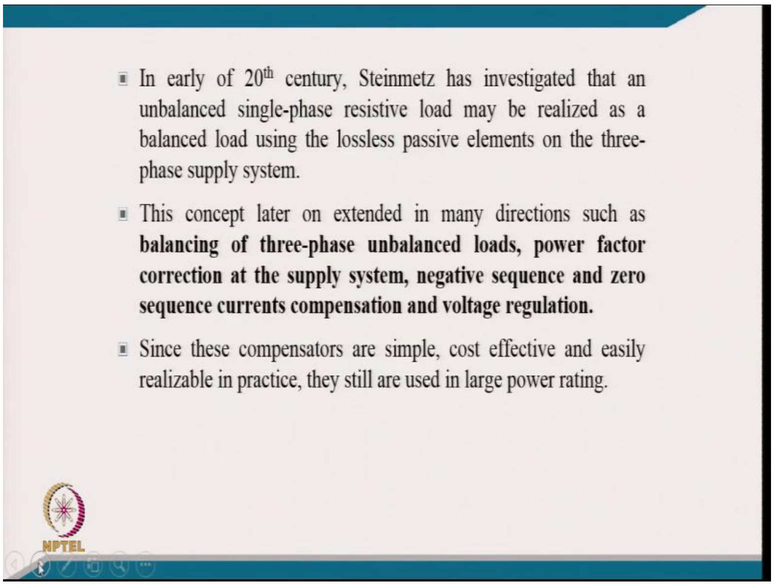

In the early 20th century, Steinmetz has investigated that an unbalanced single-phase resistive load may be realized as a balanced load using the lossless passive elements on three-phase supply system. And this concept later on extended in many directions, such as balancing of three-phase unbalanced loads, power factor correction at supply system, negative sequence and zero sequences current compensation, and voltage regulation.

Since these compensators are simple, cost-effective, and easily realizable in practice, they are still used in large power ratings.

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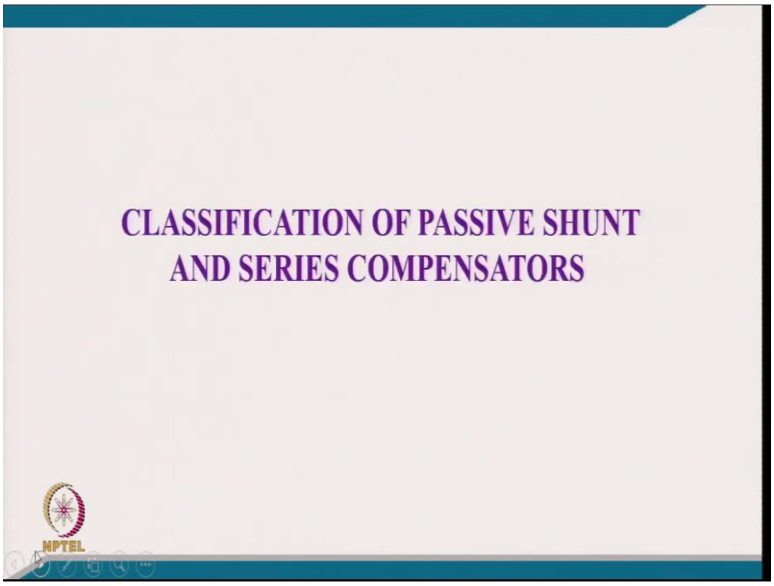

We would like to classify these passive shunt and series compensators.

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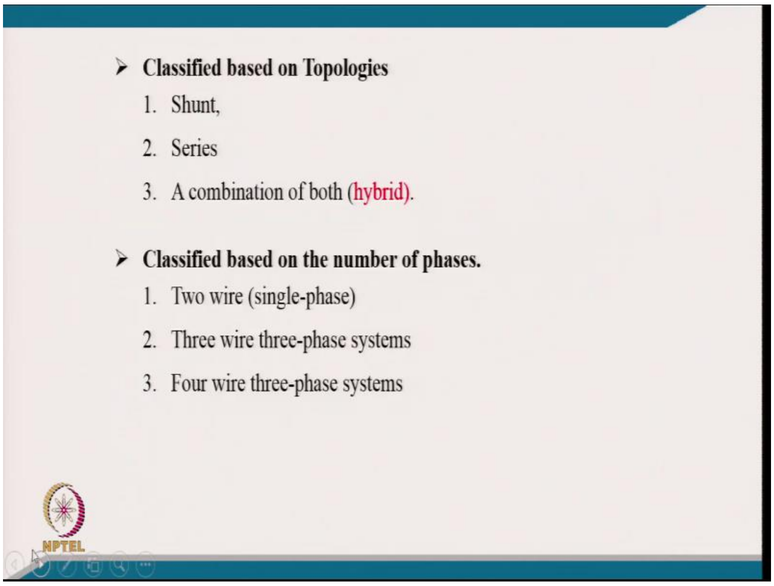

The classification is based on the topology. Either they are connected in shunt or series or a combination of both, like a hybrid, which means you have a series composition and shunt compensation. It can also be classified based on the number of phases; I mean you are using this compensator either in two wire system; like a single-phase system, or using this in a three-wire three-phase system or four-wire three-phase system.

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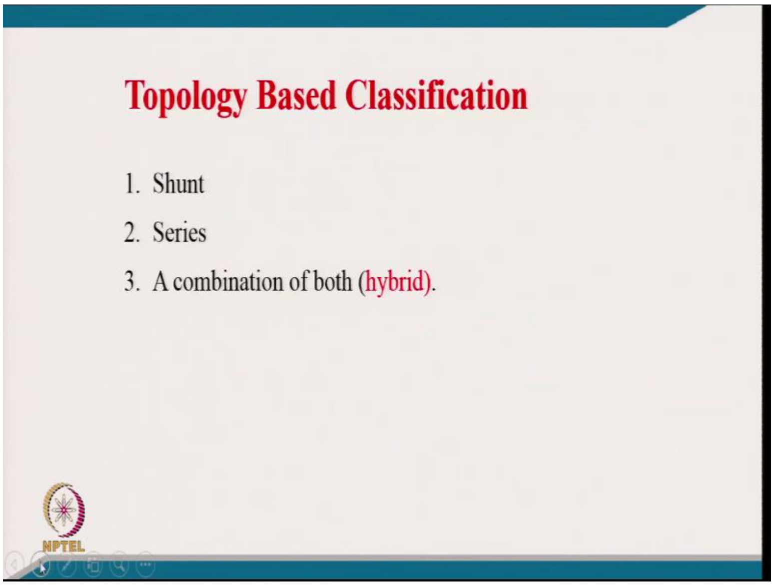

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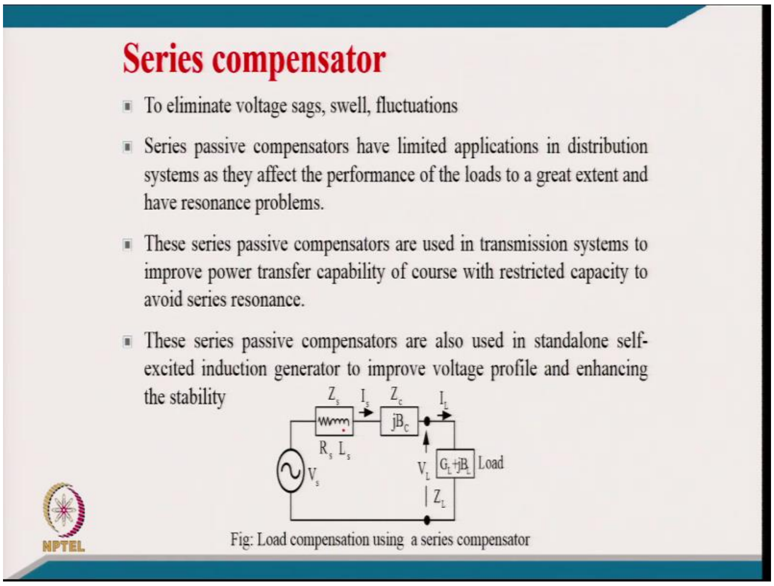

First, we talk about the series compensator, which is used to eliminate voltage sags, swell and fluctuations. The series passive compensator have a limited applications in distribution system as they affect the performance of the load to great extent and have resonance problem.

These series passive compensators are used in the transmission system to improve the power transfer capability with the restricted capacity to avoid series resonance. These series passive compensators are also used in standalone self-excited induction generator to improve the voltage profile and enhance stability.

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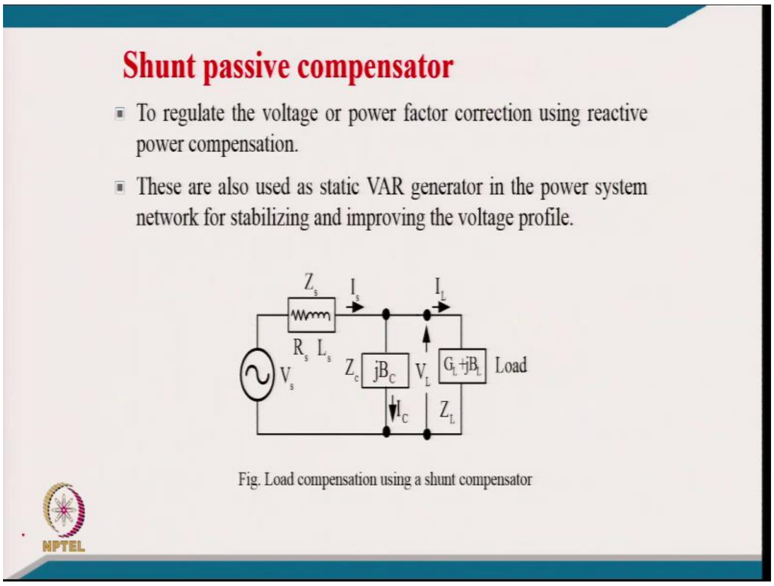

The passive shunt compensator is typically connected in shunt with the load at the closure to the load, so it is used to regulate the voltage across the load, or the power factor, using its reactive power. So, you can provide its reactive power to the load so that here at the supply side have a unity power factor. And these are also used as static VAR generators in the power system network for stabilizing and improving the voltage profile.

So, virtually, when they are not used to draw the reactive power, they can be used to improve the voltage profile. But as already mentioned earlier, either it can improve the voltage profile or the power factor correction, not both.

Slight improvement in voltage profile is always there with the unity power factor, but you cannot have both simultaneously; either you can regulate the voltage or typically correct the power factor.

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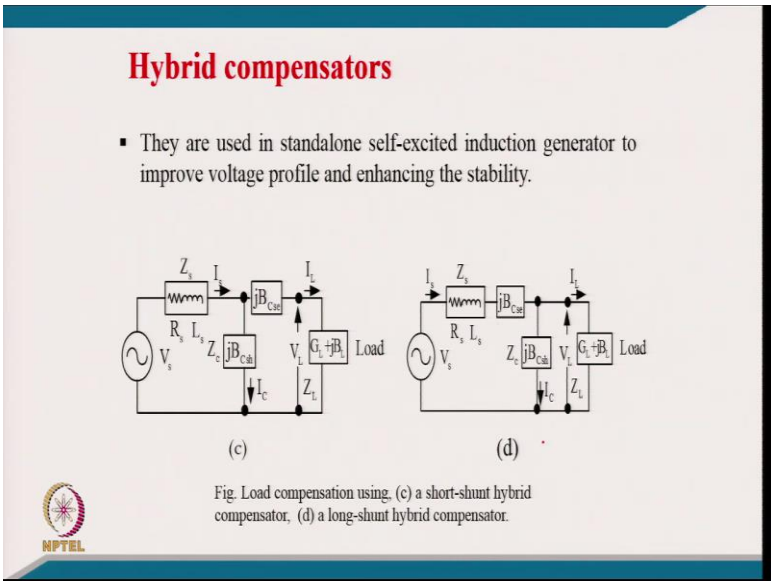

Well, this is the typical case of a hybrid compensator. They are used in standalone self-excited generators to improve the voltage profile enhancing typically. On the left side of the figure, you can see a type as a compensator in parallel and then in series. It is typically called a short shunt hybrid compensator. On the right side of the figure, you can see a type as a compensator in series and then in parallel. It is typically called a long shunt hybrid compensator

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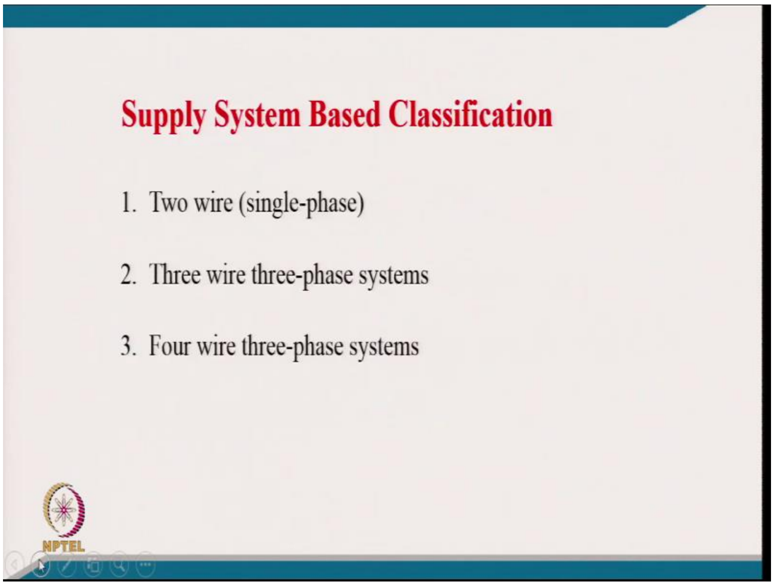

Based on the supply system, they can be classified into three categories; a two-wire single-phase system, a three-wire three-phase system, and four wires three-phase system.

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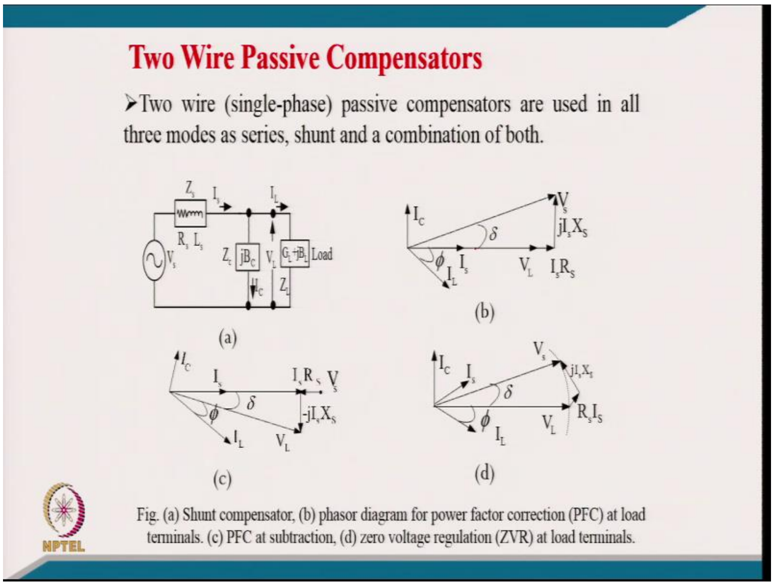

First, we discuss the case of a two-wire passive shunt compensator. The two-wire single-phase passive compensators are used in all three modes as series, shunt, or a combination of both.

If it is used for the power factor correction at load end, the supply current (I_S), should come in phase with load voltage (V_L). So, whatever the load's reactive power is required, you must compensate with the compensator.

Another compensation can be power factor correction at the substation, which means you can virtually correct the power factor at the substation point. In that case, the supply current should be in phase with the supply voltage.

In the first case, the supply current is in the phase with the load voltage; and in the second case the supply current is in phase with the supply voltage. It means you are correcting the power factor at the substation point; you will require a little higher value of the compensator to compensate even the series impedance of the line along with the load.

The third case is the zero voltage regulation, where the compensator is connected across the load to maintain the load voltage equal to the supply voltage. The load voltage will certainly deviate when the load is not connected, which depends upon its power factor. It may go down if the load has a lagging power factor, and it will go up with the leading power factor. So, you have to put a compensator parallel to the load so that the load voltage should be equal to the supply voltage.

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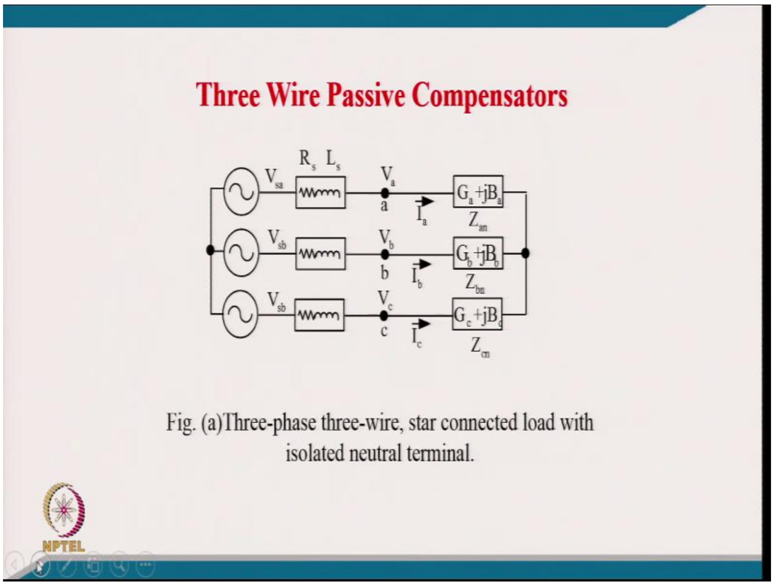

In a three phase system, a load can be star connected, or it can be like a delta connected. Here, we consider this load is equivalent to a star-connected load with isolated neutral; this neutral is not connected with the supplied neutral, and it is one of the cases. So, in a three phase system, different cases are possible.

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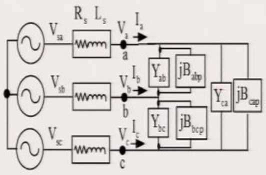

Fig. (b) Compensation for PFC of three-phase, three-wire, delta-connected load equivalent of Fig. (a) after star-delta transformation.

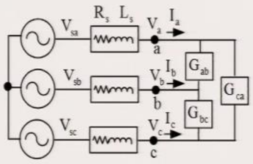

Fig. (c) Unbalanced delta connected unity power load after PFC at each phase load as an equivalent of Fig (b).

The star-connected load can be converted into an equivalent delta-connected load using the star-delta transformation. If it is already a delta-connected load, then no transformation is required. The load impedances are converted into load admittance, so at the load side, there are three load admittance between phase ab (Yab), phase bc (Ybc) and phase ca (Yca). These load admittance can be balanced (balanced load) or can be unbalanced (unbalanced load). The load can be resistive or have lagging pf or leading pf.

So across the load admittance, two sets of passive shunt compensators are connected. The first set of compensators provides reactive power compensation, and the load is realized as a resistive load. This set compensator admittance is denoted by Bxyp, where x-y is the phase terminal in the figure.

Now, the second set of compensators provides load unbalancing, and the resistive load is realized as a balanced resistive load on a three phase system. This set compensator admittance is denoted by Bxyb, where x-y is the phase terminal in the figure.

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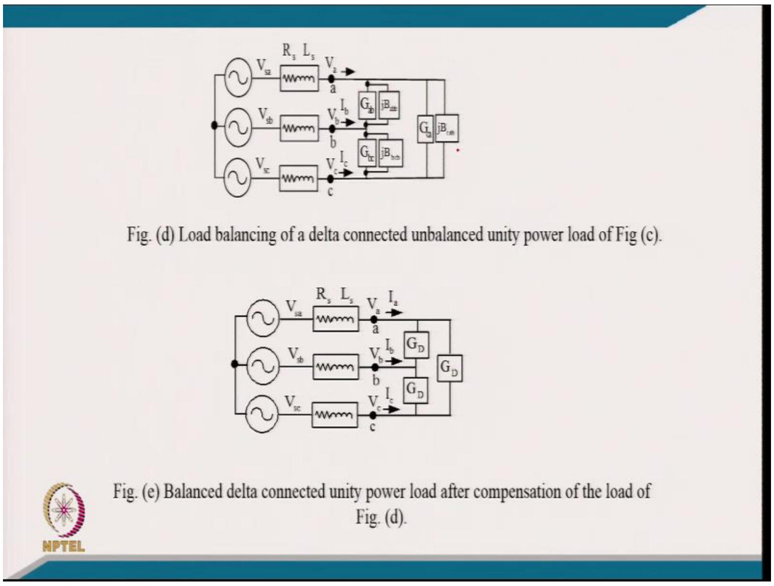

So, the load can be presented equivalent to a delta-connected resistive load with the conductance of G_D. So, the lossless compensator means the capacitor and reactor can provide power factor correction, making the load resistive and balancing the load. So, you will have a three-phase balance current flowing into the supply system at unity power factor because it is equivalent to a kind of resistive load.

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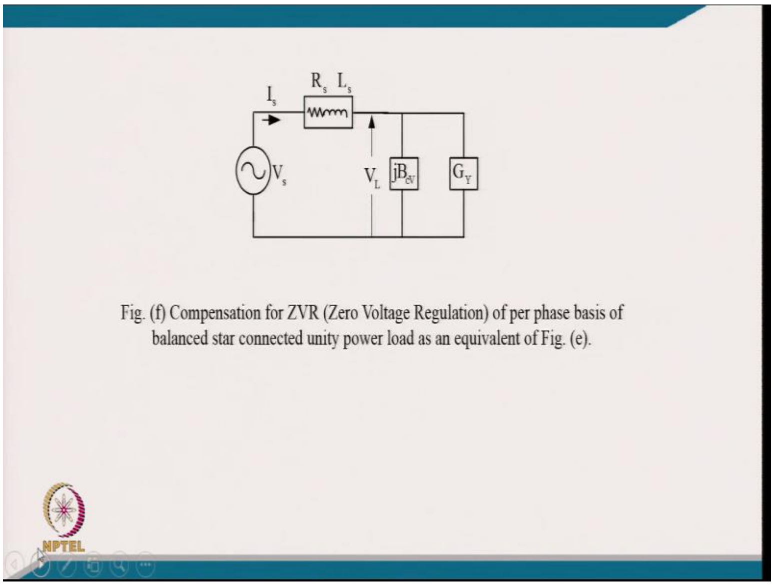

And now, balanced resistive delta connected load can be transformed into star connected load with Gy its admittance. Now, since load is a balanced load, the three phase system can be represented by the single line diagram (per phase basis) as shown in above Fig. with admittance Gy. Now, another compensator can be put which can provide voltage regulation.

So, we have three sets of compensators; one was for power factor correction for individual phases, another was for load balancing, typically by making an equivalent to a resistive load, and then for voltage regulation.

We have to convert equivalent to a star connection and put this another compensate for regulating the voltage load voltage equal to the phase voltage as we discussed in the case of single-phase compensation.

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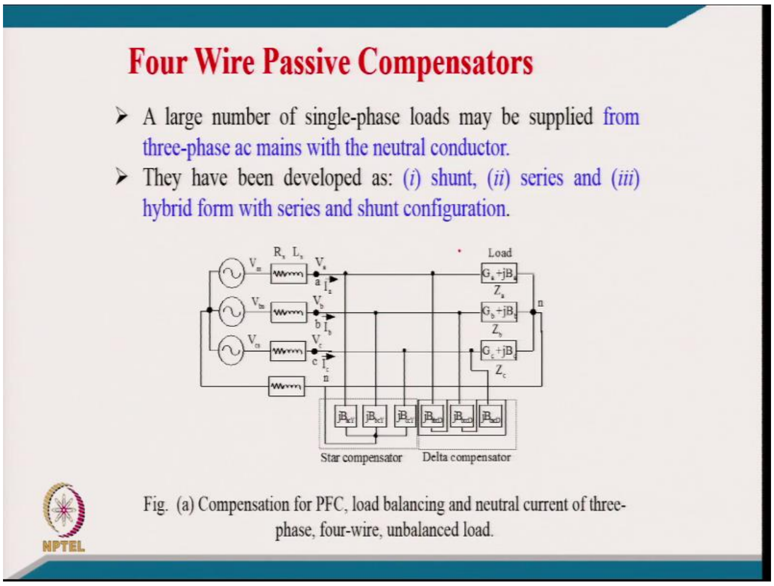

Well, that was the three-phase three-wire system. Now, coming to a three-phase four-wire system, where you have a neutral also, and you have a three-phase three unbalanced load with a neutral return, that is the original system you can call it A phase load, B phase load, C phase load and connected between neutral of supply and this.

And there is a possibility that these loads can be unequal and unbalanced. Even one can be even there may not be any load even one-phase or two-phase, only single-phase load may be there. So, a lot of conditions can be there, or it can be all three unbalanced loads.

So, now, a large number of single-phase load may be supplied from three-phase ac means with a neutral conductor because the neutral current conductor is connected here.

They have been developed as shunt series and hybrid with the series and shunt compensators. So, we need a six branch of the compensator for this purpose.

First, we can make this one compensator; here to make a kind of like a making a power factor correction of individually ok. Once you correct the power factor separately and compensate the neutral current also, then neutral current becomes 0. Then it is like a star equivalent with isolated neutral, which can be converted into delta equivalents, and you then we have a delta compensator to make a balancing of this network. So, here, you have a kind of 6 elements.

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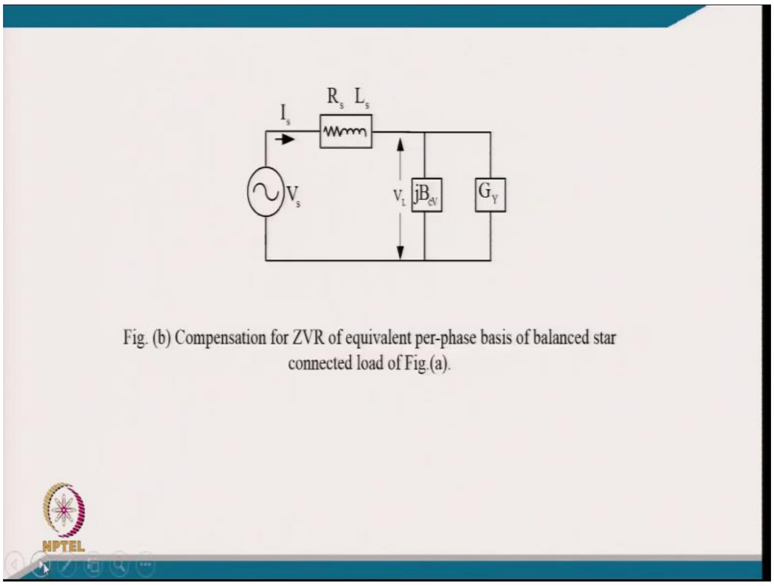

But you will find fascinating observations here, which will discuss in the next slide. So, the load can be converted equivalent to again star equivalent per phase, and then, for voltage regulation, you can put a compensator similar to as discussed in single-phase. So, you might have plenty of cases in a three-phase four-wire system.

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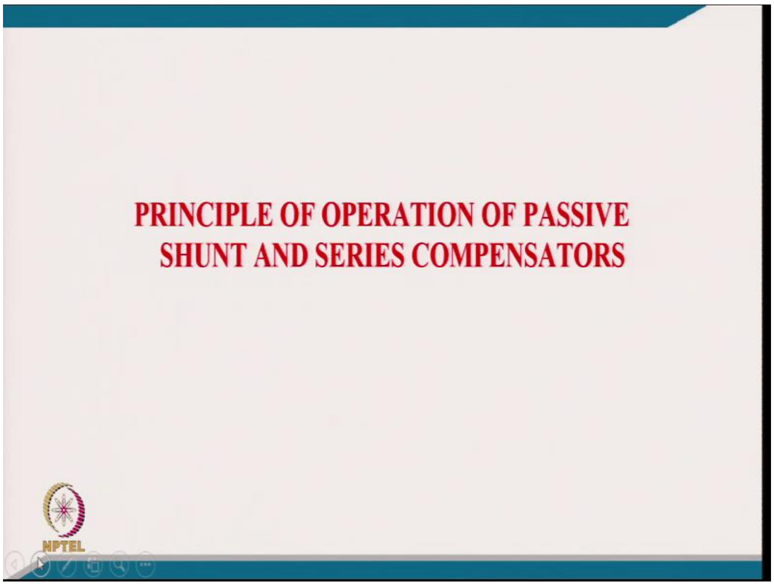

So, we will talk about the principle of operation of this passive shunt and series compensators.

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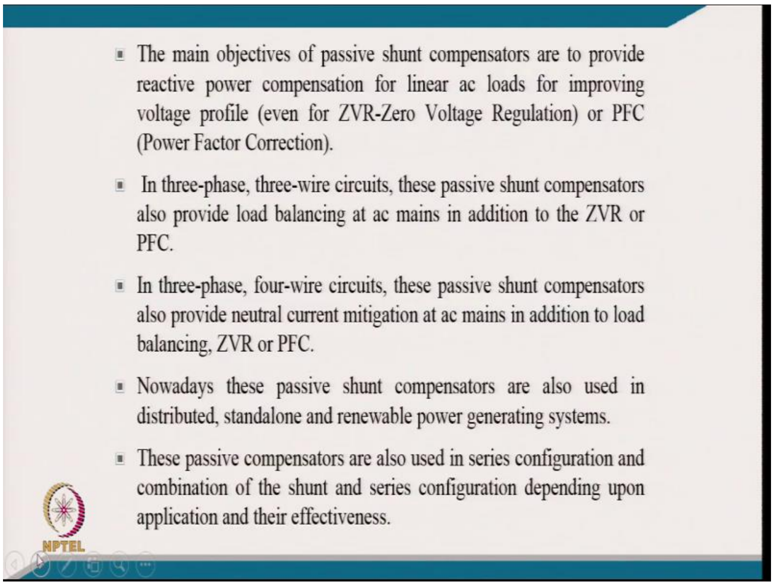

So, the main objective of a passive shunt compensator is to provide reactive power compensation for linear ac loads for improving the voltage profile; even for Zero Voltage Regulation or Power Factor Correction, both cannot go simultaneously. So, in a three-phase, three-wire circuit, the three passives shunt compensators also provide load balancing at ac mains and the Zero Voltage Regulation or Power Factor Correction.

So, in a three-phase, four-wire circuit, these passive shunt compensators also provide neutral current mitigation at ac mains and load balancing or Zero Voltage or Power Factor Correction. So, nowadays, these passive shunt compensators are also used in distributed, standalone or renewable power generating systems, so it requires the application of those because we would like to have a neutral current compensation as well as the reactive power compensation.

These passive compensators are also used in a series configuration and combination of the shunt and series configuration depending upon the application and their effectiveness.

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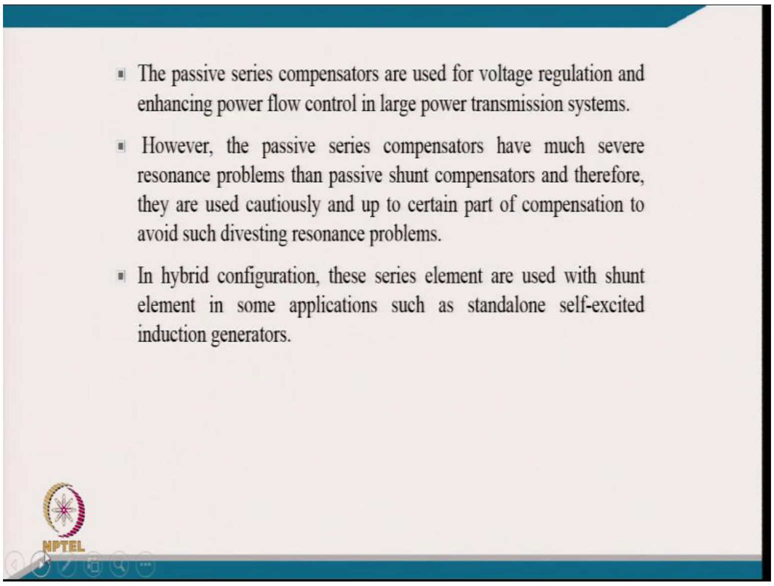

The passive series compensators are used for voltage regulation and enhancing power flow control in large power transmission systems. However, the passive series compensators have much more severe resonance problems than passive shunt compensators. Therefore, they are used cautiously and up to a specific part of the compensation to avoid such divesting resonance problems.

In a hybrid configuration, the series elements are used with shunt elements in some applications, such as standalone self-excited induction generators.

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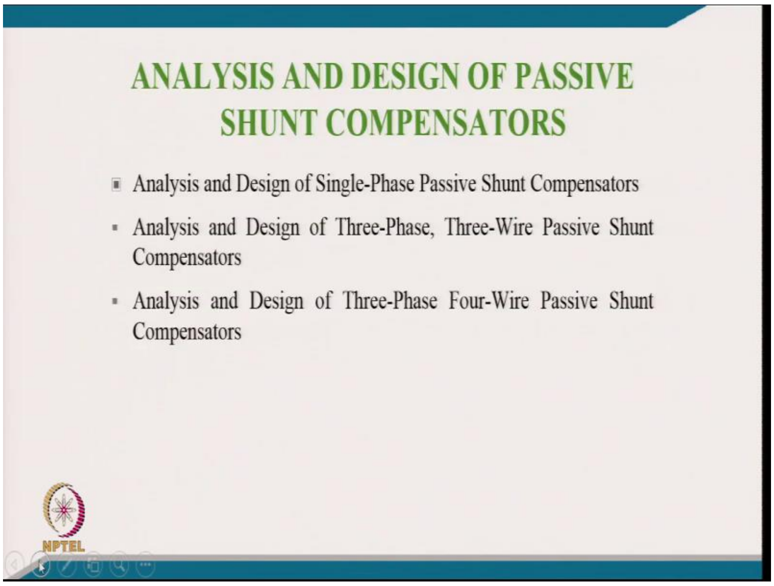

In recent years, there has been increased demand for the compensators to compensate large rating loads such as arc furnaces, traction, metros, commercial lighting, air conditioning etc. If these loads are not compensated, these loads create system unbalance and lead to fluctuations in the supply voltages. Therefore, such a supply system cannot be used to feed sensitive loads like computers, electronic equipment, etc. However, the importance of balanced load on the supply system has already been felt long back. The unbalanced loads cause reactive power burden and the presence of neutral current, resulting in low system efficiency, poor power factor, and disturbance to other consumers.

In single-phase systems, these passive shunt and series compensators are used for reactive power compensation for power factor correction or voltage regulation. In addition, these are used for load balancing in three-phase three-wire systems. In a three-four wire system, these passive compensators are also used for neutral current compensation, load balancing, and reactive power compensation for power factor correction or voltage regulation.

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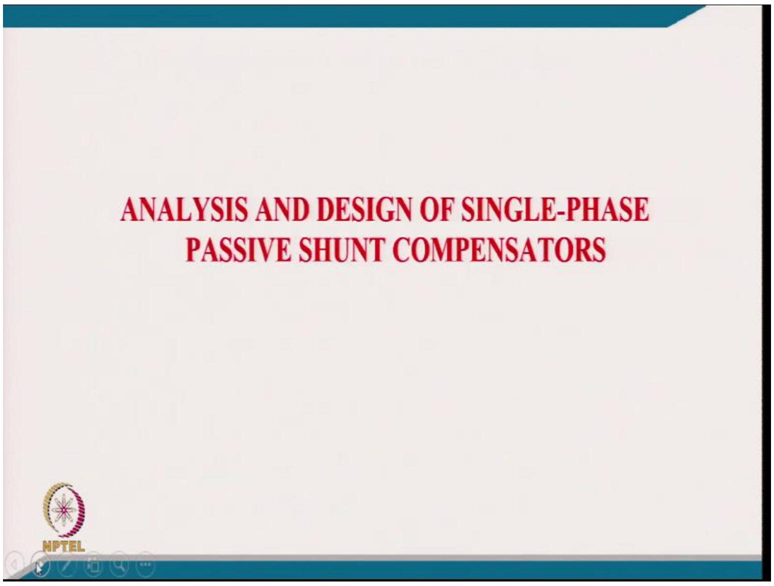
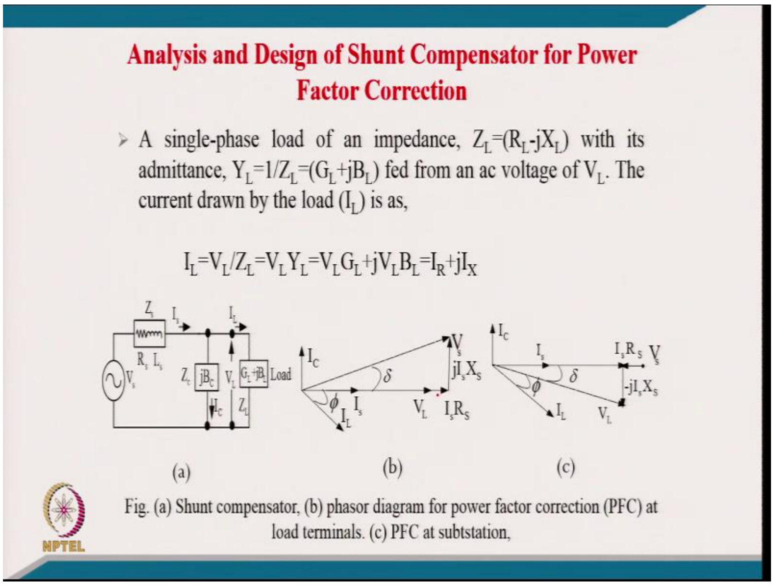


Single-phase passive shunt compensators are used for PFC (Power Factor Correction) or ZVR (Zero Voltage Regulation). The rating of the compensator may be estimated using the system data and given load data, for which compensation is to be made.



Normally, a passive shunt compensator is used as it is connected directly across the load to be compensated for the power factor correction of the load at ac mains.

This shunt compensator does not affect the voltage across the loads to the extent. The passive series compensator can also improve/correct the power factor, but it may affect the voltage across the load depending upon the load power factor and its current magnitude, therefore, they are not much preferred in the distribution system.

The above figure shows a single-phase load of an impedance, $Z_L=(R_L-jX_L)$ with its admittance, $Y_L=1/Z_L=(G_L+jB_L)$ fed from an ac voltage of V_L. All of these are RMS quantities. The current drawn by the load (I_L) is as,

The current drawn by the load is your I L equal to V L upon Z L or V L equal to Y L or V L G L plus j V L B L or that can be equivalent to like your resistive equivalent current active component current plus the reactive component of current like.

$I_L=V_L/Z_L=V_LY_L=V_LG_L+jV_LB_L=I_R+jI_X$

In this equation, I_R is active power component of the load current which is in phase with the load voltage V_L.

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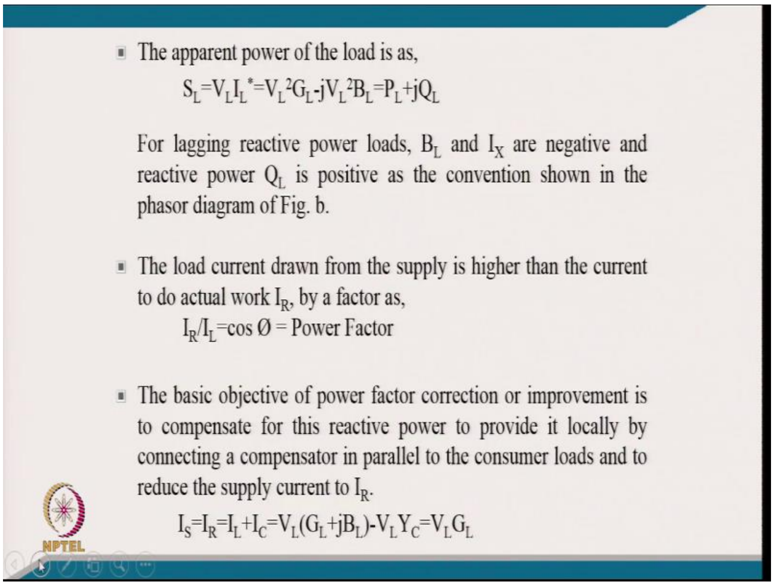

The other component is the load current's reactive power component, which is in phase quadrature with the load voltage V_L. In case I_X is negative, then I_L is lagging the load voltage V_L. The angle between V_L and I_L is Ø is known as power factor angle.

The apparent power of the load is as,

$S_L=V_LI_L^*=V_L^2G_L-jV_L^2B_L=P_L+jQ_L$

The apparent power S_L has active power component P_L (Real power responsible to do actual work) and a reactive power Q_L (Imaginary power which is not used to do any work but responsible for loading the system components). Typical examples of reactive powers are power corresponding to the magnetizing currents of an induction motor and the transformer. For lagging reactive power loads, B_L and I_X are negative and reactive power Q_L is positive as the convention shown in the phasor diagram of Fig. 3.2b.

The load current drawn from the supply is higher than the current to do actual work I_R, by a factor as,

$I_R/I_L=\cos Ø$

Here cos Ø is known as power factor and it can be expressed in terms of power triangle quantities as,

Power Factor=pf=cos Ø

This cos Ø is the fraction of the apparent power which is used to do actual work. Power loss in the feeder or cable is proportional to I_L^2, and is increased by a factor $1/(\cos^2 Ø)$. Therefore, feeder rating has to be increased from I_R to I_L and this loss has to burden on the consumers.

The basic objective of power factor correction or improvement is to compensate for this reactive power locally by connecting a compensator in parallel to the consumer loads and reducing the supply current to I_R.

$I_S=I_R=I_L+I_C=V_L(G_L+jB_L)-V_LY_C=V_LG_L$

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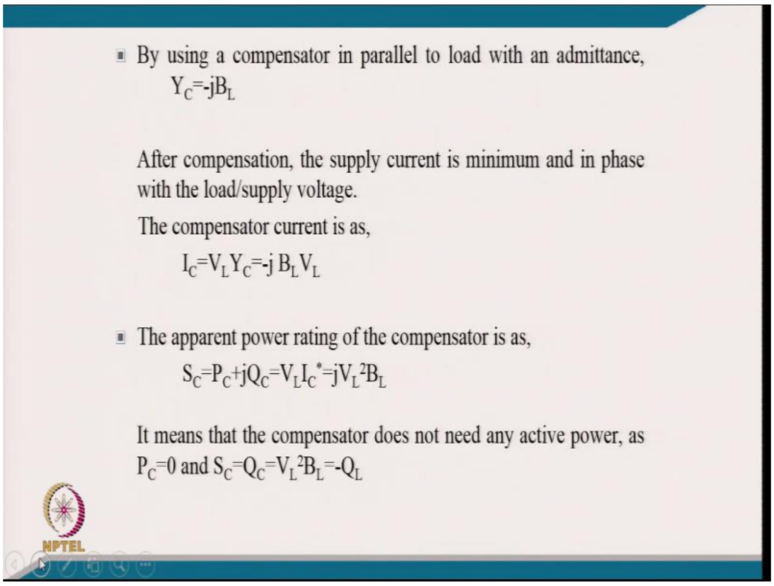

By using a compensator in parallel to load with an admittance,

$Y_C=-jB_L$

After compensation, the supply current is minimum and in phase with the load/supply voltage. It is correcting the power-factor of the supply to unity, however, power factor of the load remains same as cos Ø. The reactive power of the load is supplied locally by the compensator and the load is fully compensated. After this load compensation, the supply can feed additional load without exceeding the current limit of the feeder.
The compensator current is as,

$I_C=V_LY_C=-j\,B_LV_L$

The apparent power rating of the compensator is as,

$S_C=P_C+jQ_C=V_LI_C^*=jV_L^2B_L$

It means that the compensator does not need any active power, as $P_C=0$ and $S_C=Q_C=V_L^2B_L=-Q_L$. Majority of the loads are inductive in nature and thus the compensator has to supply capacitive current.

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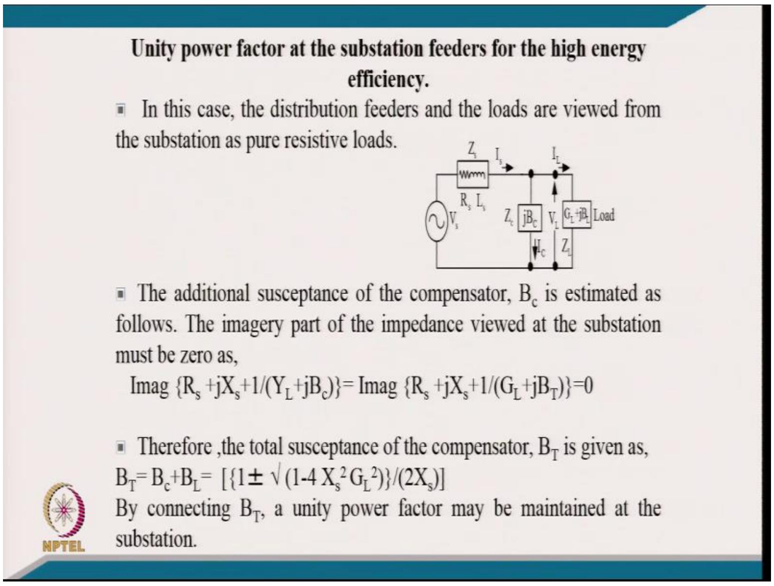

With this type of compensation, the power factor at the load bus is corrected to unity. However, sometimes it is required to maintain unity power factor at the substation feeders for the high energy efficiency. In that case, the distribution feeders and the loads are viewed from the substation as pure resistive loads. Fig. 3.2 shows a circuitry which consists of the impedance of distribution feeder, ($Z_s=R_s+jX_s$), an equivalent impedance of the load, ($Z_L=R_L+jX_L$), an impedance of the compensator, ($Z_c=jX_c=1/Y_c=-j/B_c$) connected at load end after the feeder, and ac mains voltage, V_s.

This additional susceptance of the compensator, B_c is estimated as follows. The imagery part of the impedance viewed at the substation must be zero as,

Imag $\{R_s+jX_s+1/(Y_L+jB_c)\}$= Imag $\{R_s+jX_s+1/(G_L+jB_T)\}=0$

Solving above equation, the total susceptance of the compensator, B_T is estimated as,

$B_T=B_c+B_L=-[\{1-\sqrt{(1-4X_s^2G_L^2)}\}/(2X_s)]$

By connecting this total susceptance of the compensator, B_T, a unity power factor may be maintained at the substation.

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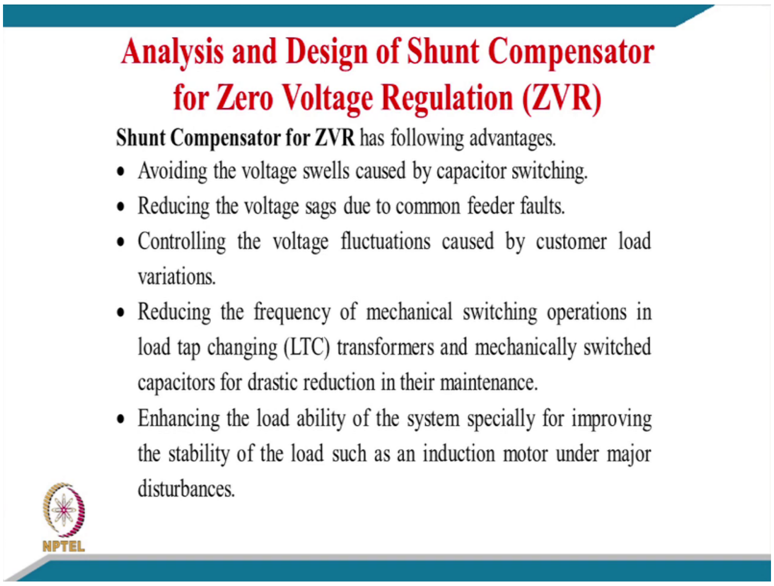

So, analysis and design of shunt compensator for zero voltage regulation is another condition. Shunt compensator for zero voltage regulation has the following advantage;

- Avoiding the voltage swell caused by the capacitor switching.
- Reducing the voltage sag due to the common feeder faults.
- Controlling the voltage fluctuations caused by customer load variation.
- Reducing the frequency of mechanical switching operations in tap changing, load tap changing transformers and mechanically switched capacitors for drastic reduction in their maintenanc.
- Enhancing the system's load ability, especially for improving the stability of the load such as induction motor under the major disturbances.

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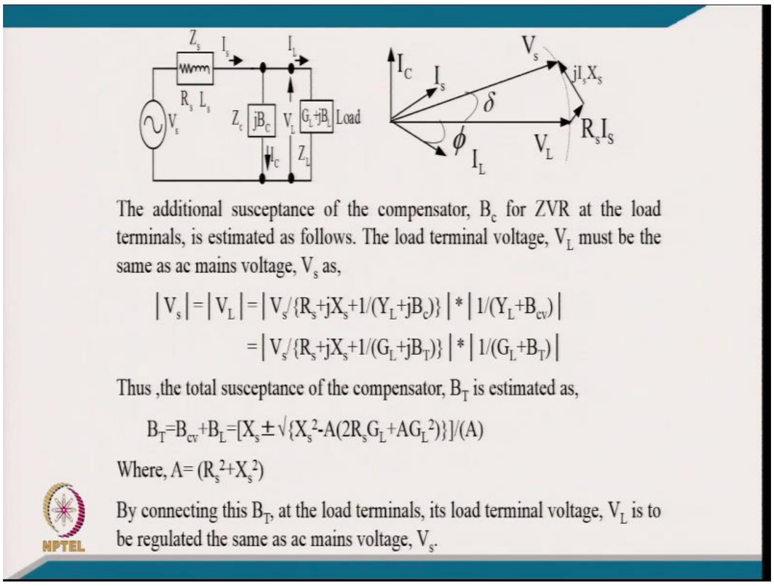

It is possible to make VL equal to Vs by putting a compensator in parallel to load. The circuit diagram and phasor diagram are shown above. For analysis, here, we consider that VL is equal to VS.

If a compensator with its additional susceptance, B_c is used across the load for ZVR, which consists of an impedance of distribution feeder, ($Z_s=R_s+jX_s$), an equivalent impedance of the loads, ($Z_L=R_L+jX_L$), an impedance of the compensator, ($Z_c=jX_c=1/Y_c=-j/B_c$) connected at load end after the feeder, and ac mains voltage, V_s.

This additional susceptance of the compensator, B_c for ZVR at the load terminals is estimated. The load terminal voltage, V_L must be the same as ac mains voltage, V_s as,

$|V_s|=|V_L|=|V_s/\{R_s+jX_s+1/(Y_L+jB_{cv})\}|*|1/(Y_L+jB_{cv})|=|V_s/\{R_s+jX_s+1/(G_L+jB_T)\}|*|1/(G_L+jB_T)|$

Solving the above equation, the total susceptance of the compensator, B_T is estimated as,

$B_T= B_{cv}+B_L= [X_s \pm\sqrt{\{X_s^2-A(2R_sG_L-AG_L^2)\}}]/(A)$

Where, $A= (R_s^2+X_s^2)$

By connecting this total susceptance of the compensator, B_T at the load terminals, its load terminal voltage, V_L is to be regulated the same as ac mains voltage, V_s.

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That is about voltage regulation power factor correction in the case of a single-phase system. Now, we will go into the analysis and design of three-phase three-wire compensators.

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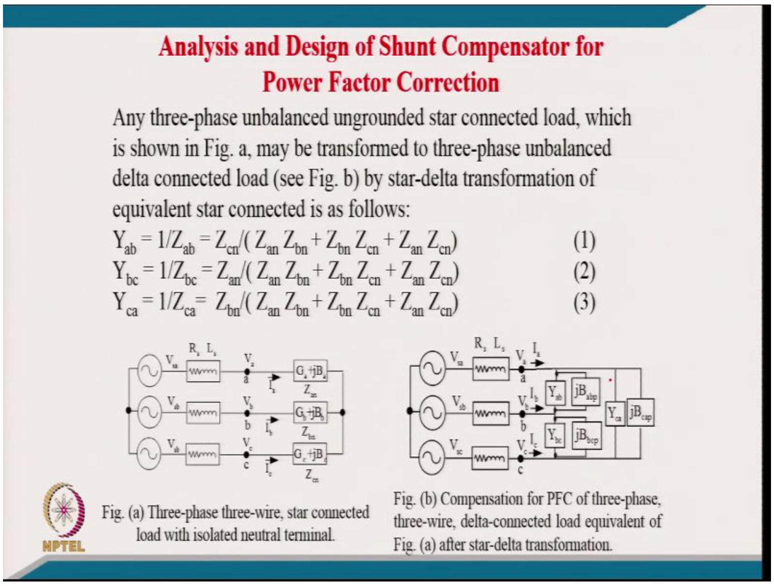

So, we talked about analyzing and designing a shunt compensator for power factor correction for a three phase system. First, any three-phase unbalanced ungrounded star-connected load, shown in the figure below, is transformed to a three-phase unbalanced delta-connected load by star-delta transformation.

The neutral is not connected here, so this is the isolated neutral. The unbalanced three-phase star-connected load can be converted equivalent to a delta connected, which can call it Yab, Yba, Yca.

Now, we can put the compensators for power factor correction parallel to this delta-connected load, as discussed earlier for a single phase system.

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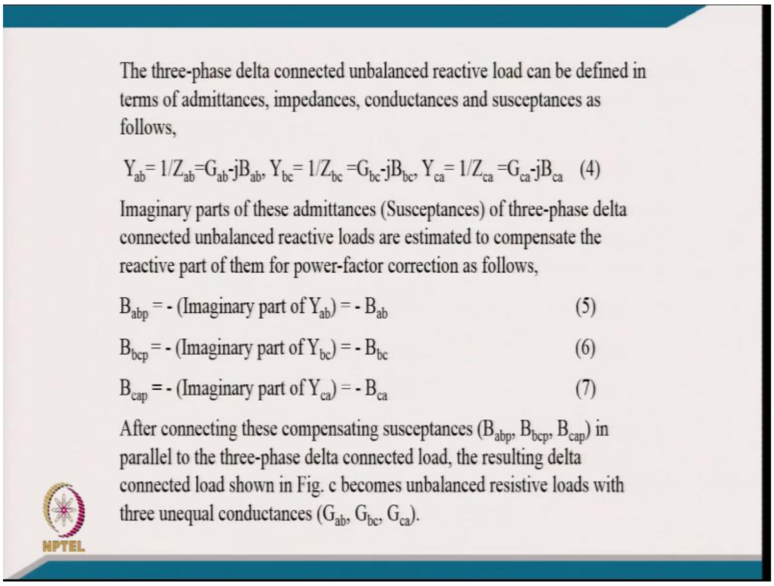

The three three-phase delta connector unbalanced reactive load can be defined in terms of admittance, impedance, conductance, and susceptances. We have the relation Bab, Yab upon Zab. The imaginary part of these admittances of three-phase delta connected unbalanced reactive load is to be estimated to compensate the reactive part for power factor correction.

After connecting these compensating susceptances (B_{abp}, B_{bcp}, B_{cap}) in parallel to the three-phase delta connected load, the resulting delta connected load shown in Fig. c becomes unbalanced resistive loads with three unequal conductances (G_{ab}, G_{bc}, G_{ca}).

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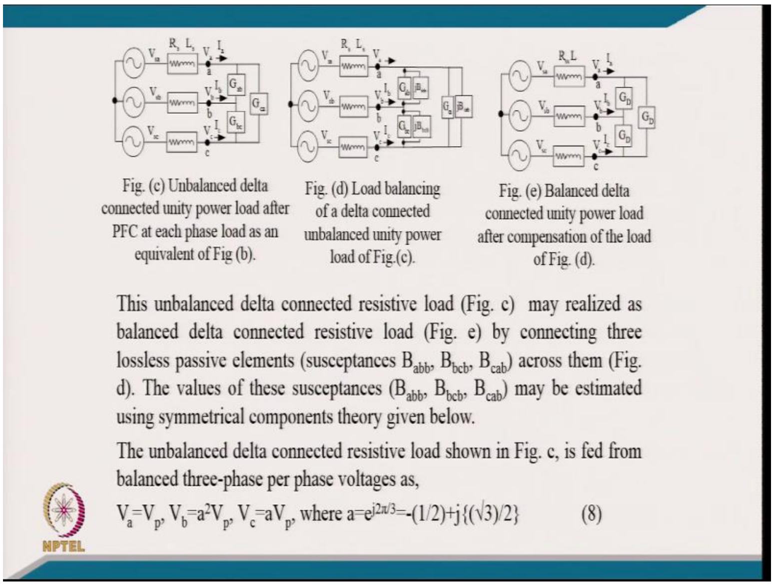

Now, the load becomes three phase unbalanced. This unbalanced delta-connected resistive load (Fig. c) may be realized as a balanced delta-connected resistive load (Fig. e) by connecting three lossless passive elements (susceptances B_{abb}, B_{bcb}, B_{cab}) across them (Fig. d). The values of these susceptances (B_{abb}, B_{bcb}, B_{cab}) may be estimated using the symmetrical components theory.

The unbalanced delta-connected resistive load shown in Fig. c, is fed from balanced three-phase per phase voltages.

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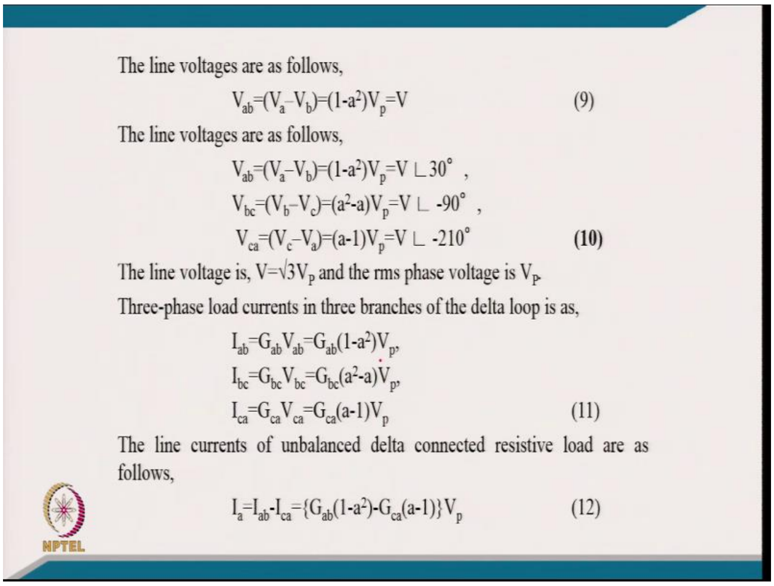

The line voltage can be found out from phase voltage as shown in equations (9)-(10). Similarly, the line currents can be found from the phase currents.

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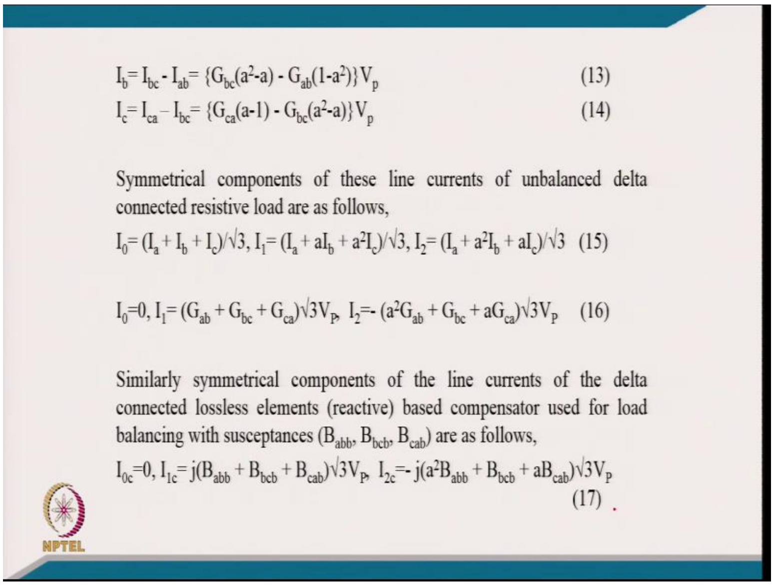

Now, the symmetrical components of these line currents of unbalanced delta-connected resistive load can be calcualted by using (15)-(16). Similarly, symmetrical components of the line currents of the delta-connected lossless elements (reactive) based compensator used for load balancing with susceptances (B_{abb}, B_{bcb}, B_{cab}) can be calculated.

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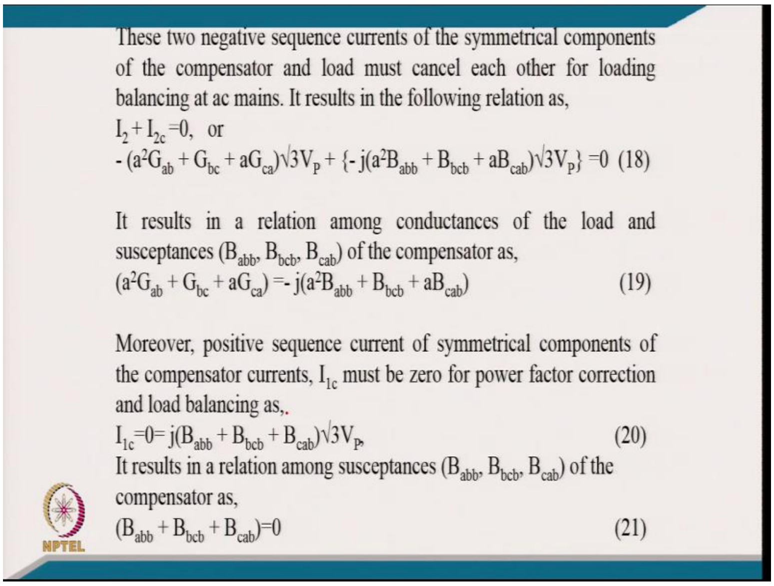

These two negative sequence currents of the symmetrical components of the compensator and load must cancel each other for loading balancing at ac mains. It gives the one relation between the compensator susceptances and the load conductances.

Moreover, positive sequence current of symmetrical components of the compensator currents, I_{1c} must be zero for power factor correction and load balancing, which gives another relation between the compensator susceptances.

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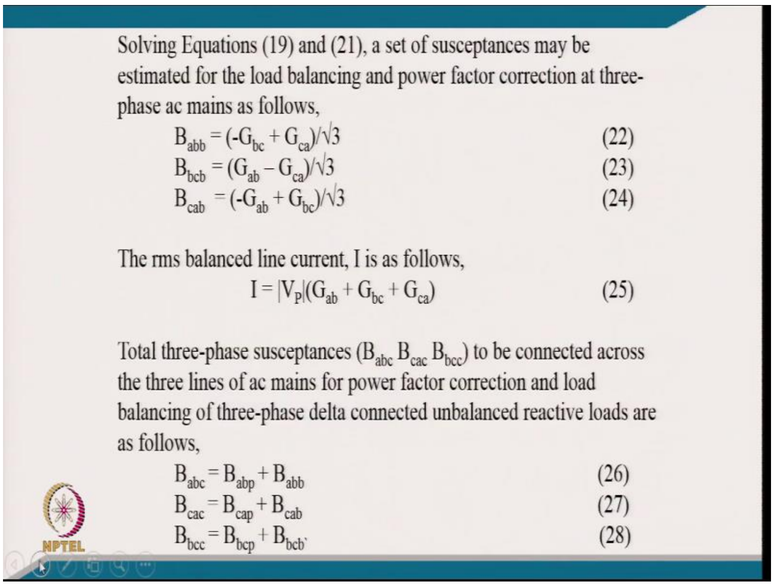

By solving these two relations, a set of susceptances may be estimated for the load balancing and power factor correction at three-phase ac mains.

So, you can find out the compensator for ab, bc, and ca in terms of these conductances and once their values are estimated, the network is balanced equivalent. You will get the balance line current.

So, three-phase total three-phase susceptances to be connected across the three lines of ac main for power factor correction and load balancing of three-phase delta connected unbalanced reactive load. And now total conductances of compensatord can be found which is for power factor correction of individual and this balancing for similarly for ca, similarly for bc for.

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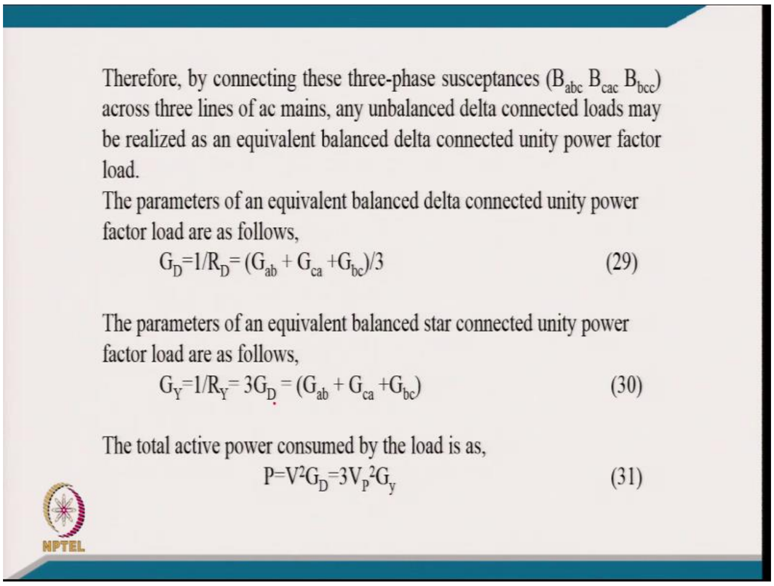

Therefore, by connecting these three-phase susceptances (B_{abc} B_{cac} B_{bcc}) across three lines of ac mains, any unbalanced delta connected loads may be realized as an equivalent balanced delta connected unity power factor load.

The parameters of an equivalent balanced delta connected unity power factor load are equal to GD equal to 1/RD, which is some of the average of three conductances: Gab, Gca, and Gbc.

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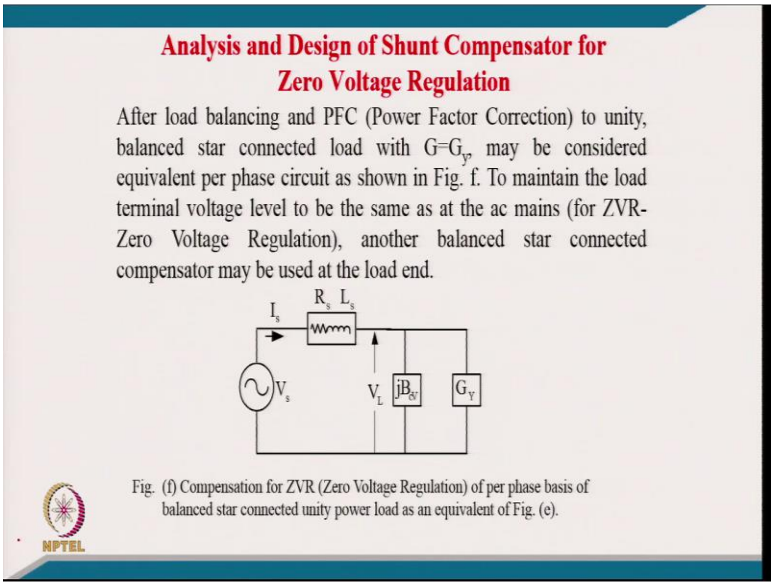

After load balancing and PFC (Power Factor Correction) to unity, balanced star connected load with $G=G_y$, may be considered equivalent per phase circuit as shown in Fig. f. To maintain the load terminal voltage level to be the same as at the ac mains (for ZVR- Zero Voltage Regulation), another balanced star connected compensator may be used at the load end.

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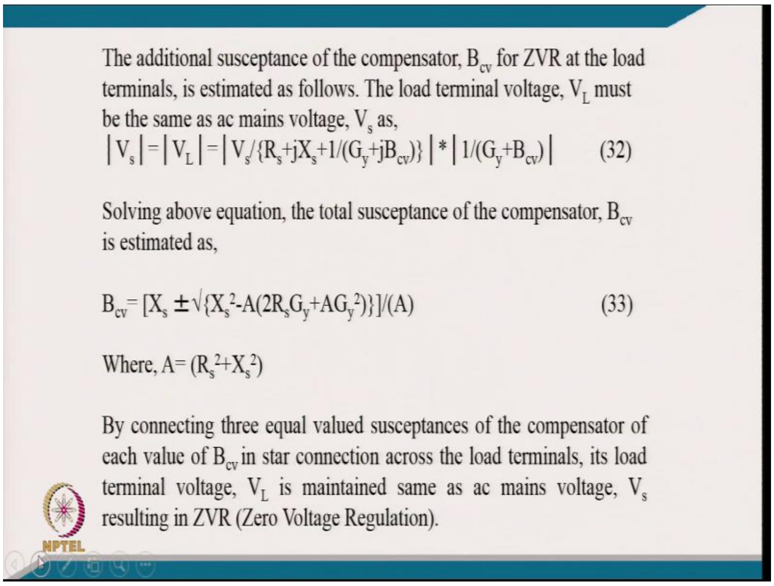

The additional susceptance of the compensator, B_{cv} for ZVR at the load terminals, is estimated as follows. The load terminal voltage, V_L must be the same as ac mains voltage, V_s as,

$$|V_s| = |V_L| = |V_s/\{R_s+jX_s+1/(G_y+jB_{cv})\}| * |1/(G_y+B_{cv})|$$

Solving above equation, the total susceptance of the compensator, B_{cv} is estimated as,

$$B_{cv}= [X_s \pm\sqrt{\{X_s^2-A(2R_sG_y+AG_y^2)\}}]/(A)$$

Where, $A= (R_s^2+X_s^2)$

By connecting three equal valued susceptances of the compensator of each value of B_{cv} in star connection across the load terminals, its load terminal voltage, V_L is maintained same as ac mains voltage, V_s resulting in ZVR (Zero Voltage Regulation).