Operation and Planning of Power Distribution Systems
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Module - 03
Various Power Quality Issues of Distribution Networks: An Introduction
Lecture - 18
Power quality problems in distribution systems

So, this lecture is a continuation of module 3, and in module 3 we have learned how to do the reliability analysis of a distribution network ok. And in this particular lecture that would be the last lecture or I kept it as a part 2 of module 3. We will learn in this lecture some of the Power quality problems or Power quality issues of distribution networks ok and a broad idea, how to mitigate or how to characterize those power quality issues ok.

So, this one lecture we will only focus on a broad categorization and characterization and also some mitigation approaches, for a various types of power quality issues, which are encountered in power distribution networks ok.

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So, first of all let me give you a basic idea that, what is power quality ok, what is the definition of power quality ok. So, as such, there is no standardized definition, but in many books you will get different different ways to define this term power quality. And in fact, this power quality is a such a big area nowadays, that people do research and it becomes a new paradigm of power system research ok.

So, this is how this one of the books which I refer in the reference that is authored by Professor Arindam Ghosh and Ledwich, they define this power quality. So, power quality is the ability of electrical grid on network to supply a clean and stable power to the customer. Again, there are two adjectives or terminologies, whatever you can call that is clean and stable power. Again, the question is what is clean and what do you mean by stable power ok.

So, in order to understand that you have to know that what sort of disturbances, what sort of distortion or what sort of issues that we have in supplying a clean power ok. Now, electric power quality mainly involves this voltage and frequency and its waveform variation. Ideally as a customer, that our goal or our need is to have a stable power supply, uninterruptible power supply as well as that whatever supply that we are getting that should have a proper magnitude, a proper RMS value.

That should have a proper frequency, and there is another thing that the waveform, voltage waveform that we are getting at our home, that should be a pure sinusoidal with a RMS value, if, since we are a single-phase customer. So, we used to have 230 volt single phase, 50 hertz pure sinusoidal voltage source that we are intending to have from the utility.

But, due to various problems, utility, no utilities in the world can ever give you the guarantee of having a pure sinusoidal voltage source which is having exactly of your desired frequency, in India it is 50 hertz and which is having the RMS value as your desirable value that is 230 volts. So, no utility can guarantee ok.

Now, then again coming back to the definition of this power quality, the good power quality can be defined as steady supply voltage within the prescribed range of RMS value. So, although we intend as a single-phase customer for a single-phase domestic customer, single phase domestic customer that we intend to have 230 volt RMS source having a 50 hertz frequency and pure sinusoidal voltage sinusoidal, sorry, pure sinusoidal voltage ok.

So, this is what our goal. This is our goal or this is what we intend to have from electric utility, but as I said it will never get. So, we know that voltage will never be constant at 230 volt RMS value. So, we know that if it is within some range let us say, some 5 percent variation then we can accept it ok.

Similarly, in steady AC frequency we will never get 50 hertz frequency constant, throughout the day, throughout the month, throughout the year; even it is it may so happen that in a particular day will never get 50 hertz at any instant of time. So, we know that frequency will slightly vary, but we know that it should be as close to the rated value and there is a band of variation of the frequency. if the frequency remains within the band, it is somewhat acceptable.

Similarly, there is a specific band of this RMS value of the supply voltage. If this voltage lies within its band, we can consider it as acceptable ok. Similarly, we are also concerned about this voltage waveform. So, we should, we know that we intend to have a pure sinusoidal voltage source, but eventually we will not get it ok.

So, this whatever the supply voltage we are getting, if you measure this voltage waveform and if you monitor it for some few hours, you will see it is far from this sinusoid ok. Although, it is not exactly means pure sinusoidal, but we intend to have as close as possible and also if we have some distortion in the sinusoidal. How do you characterize those distortion, how do we quantify those distortion those things, we will study, in this particular lecture ok.

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Now, as I said there are various power quality problems and at first, we need to understand what are those power quality problems. So, one is a poor load power factor. This is one thing that many of you know. Second is harmonic contents in the load. What do you mean by harmonic contents? Harmonics, I will discuss in one of my slides.

Harmonics is basically generated, because of distortion in your wave form of your supply voltage or load current, whichever we are getting or whichever is we are drawing. So, if they are pure sinusoid there will be no harmonic contents ok; but if they deviate from this pure sinusoid wave forms, then we will have some sort of harmonic into that. So, those things we will discuss.

Similarly, waveform notching is another sort of waveform distortion we will discuss. Similarly, having DC component in the sinusoidal supply voltage is another power quality problem. Unbalance or imbalance of this supply voltage which may be caused because of unbalancing of loads or there are many other reasons. So, those things also we will discuss.

Similarly, supply voltage waveform distortion and some of the short duration and long duration voltage quality problems and which we will discuss in this particular lecture. They are named as voltage sag, voltage swell, interruption and so on. So, those things we will discuss and finally, voltage flicker is another sort of voltage related disturbance we will discuss that.

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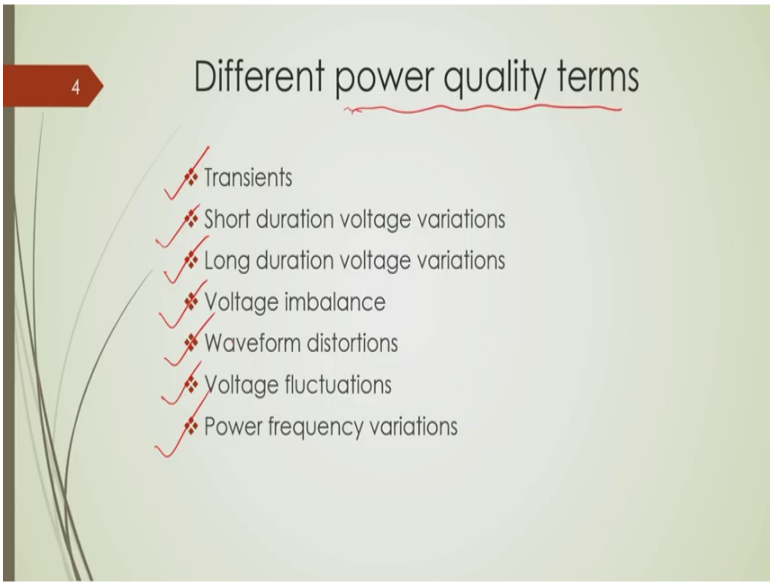

Now, we use different power quality terminologies to characterize or to classify this different voltage or current quality problems ok. Those terms are like transient problems, short duration voltage variations, long duration voltage variation, voltage imbalance or unbalance, waveform distortion, voltage fluctuations and power frequency variations.

So, these are the different power quality terminologies, which are used to classify different voltage or power quality aspects or power quality issues ok.

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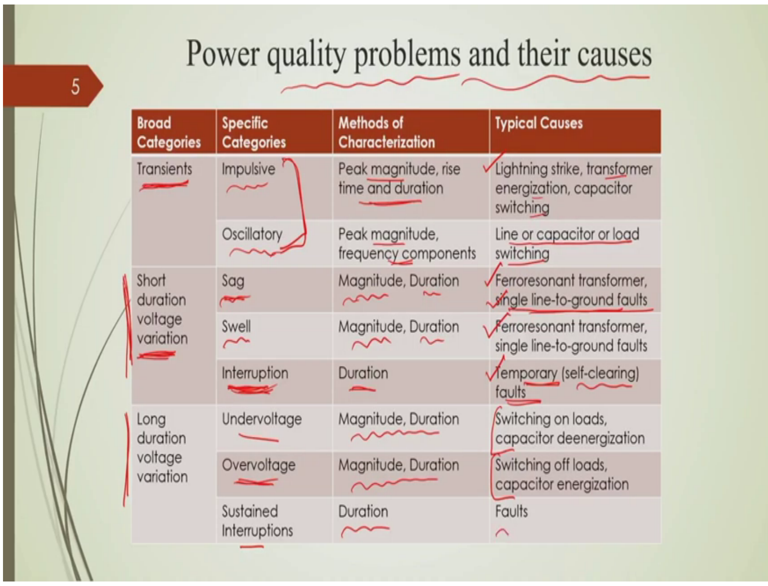

So, this table gives you some of the different types of power quality problems and they are possible and they are causes of encountering those power quality problems in power distribution networks. And also, this table will give you some more, how do we characterize those power quality problems ok.

So, the category 1 is transient type of power quality problem and there are 2 types of transients: one is called impulsive transient, another is called oscillatory transients ok. Now, what are those kinds of transients, I will discuss a little while after, but you need to know at this point that how do we characterize those transient power quality problems.

Basically, for impulsive type of transient, we classify them, we characterize them based up on this peak voltage magnitude, and rise time and duration ok. And the possible typical causes for these impulsive transients are lightning strike; lightning is one of the reason for having this type of power quality problems, transformer energization and capacitor energization or capacitor switching created is another sort of transient ok.

Similarly, this oscillatory type of transient, we also characterize them based upon this peak magnitude and frequency component. So, there is a difference between these two types of transients which I am going to discuss in one of my slides ok. And possible reason for this possible causes for this oscillatory transient are line or capacitor or load switching ok.

Now, next categories of power quality problems are short duration voltage variation ok, short duration voltage variation. So, for this short duration voltage variation the typical period of occurrence is very short, which lie within a few cycle up to 1 minute ok, from half cycle to one cycle to up to 1 minute ok. So, if so, this kind of problem sustains for a very short period of time ok;

But I will discuss in the impact of those kinds of short duration power quality problems which are not even short duration. So, impact will be long duration problem ok. So, that is why you know their mitigation at the time of the occurrence is very important ok. So, those things we will discuss.

So, voltage sag, as you know, is sudden if short duration voltage dip ok, which is characterized by its magnitude and duration and the possible causes for this kind of power quality problems are ferro-resonant transformer, single line to ground faults which are, you know, very frequent types of faults, the distribution networks they encounter ok.

So, single line to ground fault is very frequent fault for distribution networks ok; which may cause voltage sag ok. And this voltage sag is characterized by dip in the voltage magnitude and the duration ok. Similarly, voltage swell is just opposite of the voltage sag. It is basically a short duration rise of voltage, which is also characterized by voltage magnitude and the duration.

And it occurs due to the same reason as the voltage sag that is ferro-resonant transformer and single line to ground fault. Specifically, single line to ground fault, as I said, it is very very common in power distribution network. Also, we have a short duration voltage quality problem that is called short duration interruption ok.

So, it is characterized by the duration. Interruption means, I will discuss, the interruption means sudden if the supply voltage becomes 0 per unit; suddenly, for a very very short period of time less than 1 minute ok. So, this occurs due to some temporary or transient type of faults which are self clearing ok. As I said in distribution networks, you know, they encounter many faults due to non-technical reasons ok.

And one of the reasons is that weather related or these animal related issues. So, if at any instant of type, any branch of a tree which is located near to the distribution line is suddenly touched, the suddenly gets touched, with this one of the phases of the distribution line, which may cause a transient type of fault within a few second or within a microsecond of time they get this detached.

And thereby, they created transient fault which is self clearing ok. And this may sometimes cause voltage sag, voltage swell in other phases and also cause voltage interruption ok. But although they are short duration voltage variation they last for a few cycle up to 1 minute, but their impact is not much, impact is very heavy. So, those things we will discuss.

And we have different mitigation approaches because of those things, we will discuss. Similarly, we have long duration voltage quality problems which include under voltage, over voltage and sustained interruption ok. So, under voltage is similar to voltage sag, it is a dip of the voltage which occurs for a period of time which is more than 1 minute ok.

So, they are also characterized by magnitude and duration and the reason is switching on this load capacitor de energization etcetera. Similarly, over voltage is a sudden rise in voltage and if it sustains for more than 1 minute, it is categorized as overvoltage. It is also characterized by magnitude and duration of this magnitude of the over voltage and duration of this over voltage and it occurs due to switching of a very large load switching, of a very large load.

Similarly, sustained interruption is when supply voltage becomes 0 for more than 1 minute. It is categorized as sustained interruption and it occurs due to faults as we know ok.

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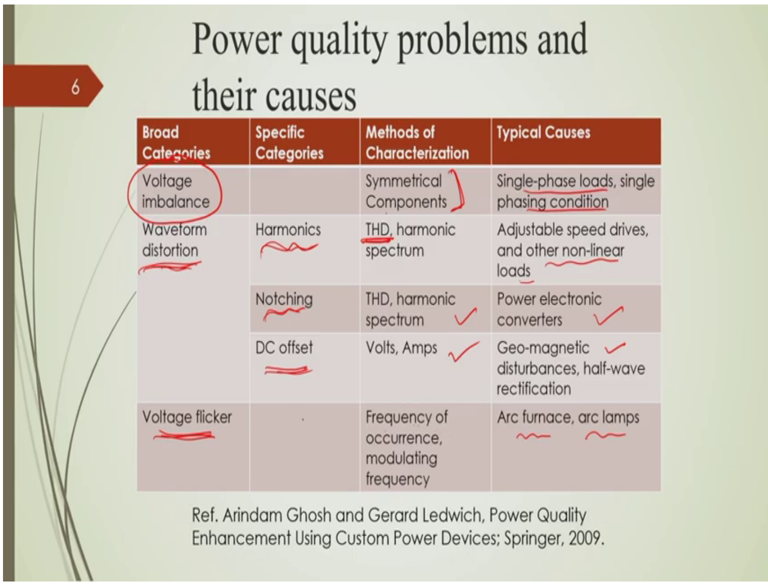

Similarly, voltage imbalance; it is another important power quality problems. What do you mean by voltage imbalance? Imbalance means since you know that our system is a three-phase, three-phase system and balanced three-phase system refers to a system having 3 same voltage or identical phase voltage of all the three phases as well as these voltages are exactly same spaced in the phasor; that means, they are 120 degree apart to each other.

So, if anything, if it appears any parameter meaning that if any of the phase voltage is much higher or lower than the other two phases, then it will cause a voltage unbalanced. Similarly, even though we have same voltage magnitudes, but they are, if they are phase spaced anything but not 120 degree apart to each other, then it will also cause voltage imbalance; I will discuss this.

And it is characterized by a well-known method called symmetrical component analysis and the reasons of this voltage imbalance are single phase loads, single phase conditions those things. Single phasing condition is another, is another type of faults ok. Similarly, wave form distortion is another category of power quality problems. There are some subcategories which are called as harmonics, harmonics means as I said we will discuss in one of our slides.

Harmonics are generated, because of some non-linear loads and these are characterized with an index called THD, THD is an index which is named as total harmonic distortion. So, it quantifies harmonics, how many harmonic components we have or how much harmonic components we have either in voltage or in current ok. Similarly, notching is another sort of waveform distortion.

So, harmonic is basically a periodic type of waveform distortion and notching is very short duration waveform distortion. Similarly, DC offset is another kind of waveform distortion. These are the way they are characterized and these are the reasons having this mostly, this waveform distortions occur due to the presence of powered electronic devices or power electronic converters.

Or in fact, many of the devices in industry or domestic applications, we use, are power converters. So, they create harmonics, they create waveform distortion, I will come to that. Similarly, voltage flicker is also sudden change of the supply voltage which causes sensation in our eyes. So, this is called as voltage flicker, if there is an arc type of load or arc lamps used in some locality.

So, this will cause this kind of voltage or power quality disturbance nearby the locality ok. So, they are, this is characterized by frequency of occurrence and modulating ok.

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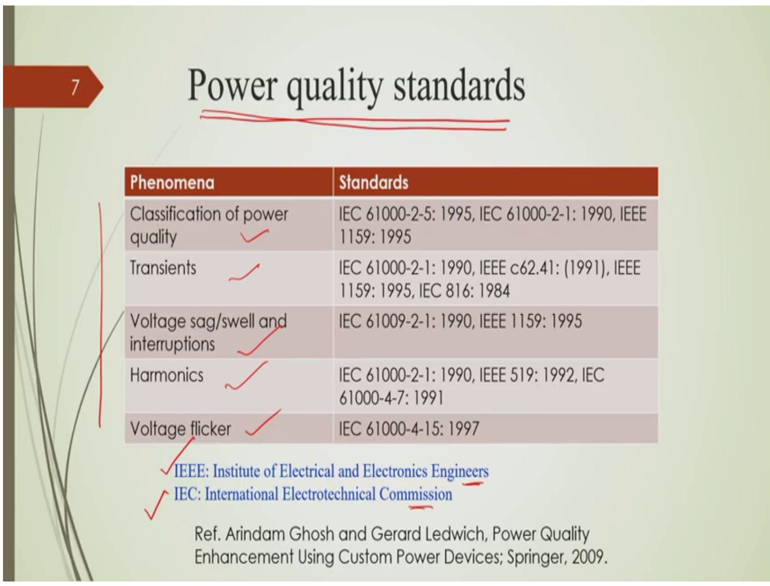

Now, in order to guide the electric utility, also in order to properly plan for the mitigation of these power quality issues; there are some standards which are developed primarily by IEEE, it is a world-famous body for electrical and electronics engineers which is full form is Institute of Electrical and Electronics Engineers.

Another is IEC which is International Electro Technical Commissions. So, they had some tasks to develop or to make these standards. So, that this power system planners or even power system customers, they will get to know that how much power quality problems are acceptable and from which point these power quality problems will start unacceptable. For example, as I said harmonics, we categorize we characterize it with an index called total harmonic distortion or THD.

Now, how much THD will be acceptable in our supply voltage and also how much is from which point it is not acceptable. So, those things you will get from these standards ok. So, classification of power quality, transients, voltage sag swells, harmonic, voltage flickers they have different standards. So, if you go through this standard you will get to know that how much distortion is or how much harmonics are acceptable and how much are not ok.

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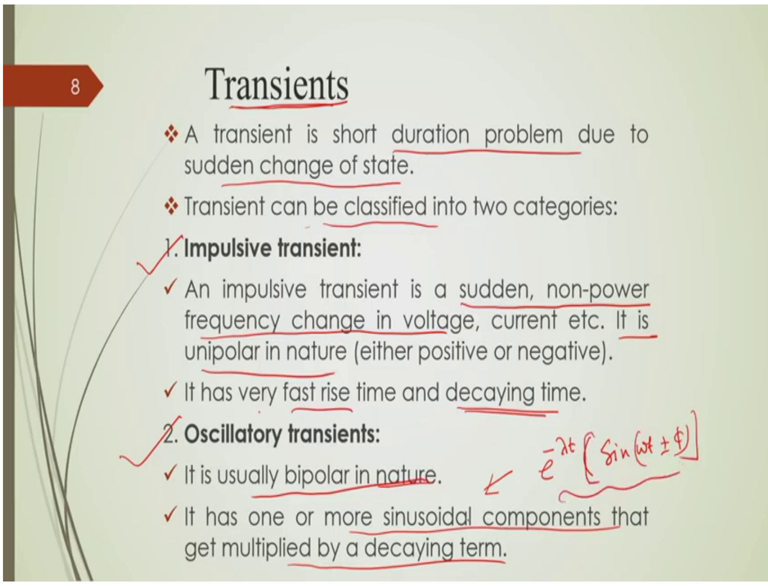

Now, let me discuss this power quality problems one by one ok. So, we will start with transients. So, transient type of power quality problem is a short duration problem due to sudden change of state ok. And as I said, transient types of power quality problems can be categorized as impulsive transient and oscillatory transients ok. And impulsive means, you know, it is type of transient which is associated with certain impulse. So, as you know impulse means, is a sudden, non-power frequency change in the supply voltage ok.

And it is most importantly, it is unipolar in nature. I will show you in my next slide how it looks like in a, how it creates a waveform distortion ok. So, these transients, they call, although they are very short, for short period of time, but they cause this waveform distortion ok, I will show you and it is this impulsive transient, that is categorized with a rise time and decaying time.

Similarly, oscillatory transients, unlike these impulsive transients, which are unipolar in nature; the oscillatory transients are bipolar in nature ok. So, it gives a sinusoidal component that gets multiplied with decaying term. So, they are characterized with some e to the power decaying term, lambda t multiplied by some sin omega t plus minus phi ok.

So, they are characterized by some decaying term along with the actual sinusoidal quantity ok.

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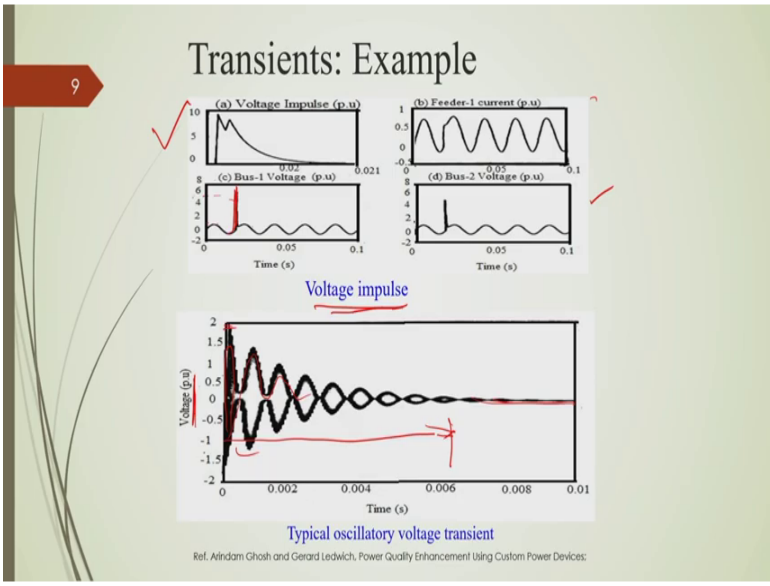

Now, this is the example of, you know, that voltage impulse, you can see. The impulse means sudden, increase in voltage which is of higher magnitude; where the nominal peak value of the voltage is 1 per unit. For a very short duration of time impulsive voltage magnitude may go as 6 to 8 per unit, that is, 6 to 8 times of the nominal peak voltage, which is pretty high, but it lasts for a very very short period of time on, in terms of microsecond or nanosecond ok.

So, in these examples, you will get voltage and current impulsive transients ok. Similarly, this is the example of oscillatory transients which causes some decaying term. So, they last for some period of time, then after that they go for steady state value ok. So, here it is voltage magnitude per unit is given, it is not this voltage waveform as such.

So, it has an oscillatory transient first few cycles of very high magnitude, but not as high as the impulse transients, but they may be up to twice of the nominal peak value of the supply voltage. But they take some considerable amount of time which is in the range of millisecond times for, to die down ok.

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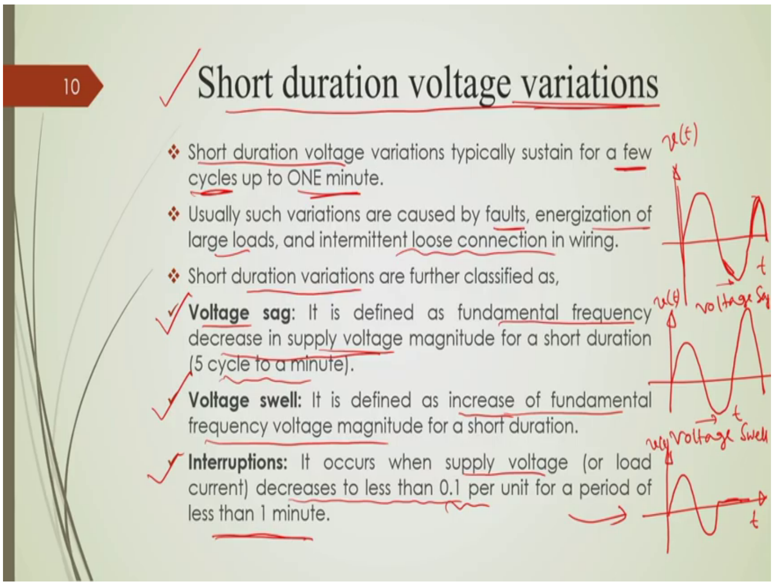

Now, we will come to short duration voltage quality problem or short duration voltage variation. As I said, this short duration stands for few cycles up to a half cycle to one minute. So, if there are voltage quality problems, which last maximum for one minute, we can, we will categorize it as short duration voltage variation ok.

So, this occurs due to faults, single line to ground fault is most common cause for this type of voltage quality problems or voltage variation and they are having some significant impact ok; and also, energization of large load and intermittent loose connection in the wiring ok. Now, there are 3 types of short duration voltage variation or short duration voltage quality problems: one is called voltage sag, one is called voltage swell, another is called interruptions, short duration interruption.

So, voltage sag is basically, it is fundamental frequency dip in supply voltage, fundamental frequency decrease in supply voltage which last for some few cycles even from half cycle to up to 1 minute. Similarly, voltage swell is, it is an increase of fundamental frequency voltage magnitude which also lasts up to 1 minute from few cycle up to 1 minute.

And interruption means when supply voltage becomes 0 or as less as, you know, 0.1 per unit, 0.1 per unit; that means, 10 percent of the nominal voltage for which last for less than 1 minute called as short duration interruption ok. So, basically it is, if I draw this problem, you know voltage sag, it is something like that suppose, this is your fundamental frequency voltage.

So, suppose this frequency remain same, but it dips the magnitude for some few cycles like this, then it will cause this voltage sag. Similarly, so, suppose the voltage waveform with respect to time ok. Now, in voltage swell means, suppose this is your fundamental voltage and for a certain cycle this voltage rises ok and it last for some few cycles then it is called voltage swell, it is called voltage swell. So, this is voltage swell, this is voltage sag.

And this interruption means suppose, this is your fundamental frequency voltage and it becomes almost 0 for, you know, very short period of time, then it is kind of voltage interruption. So, this is v t this is time. So, with this figure you can find out that how this, you know, voltage sag, swell, interruptions are; look like if you trace out this voltage waveform ok.

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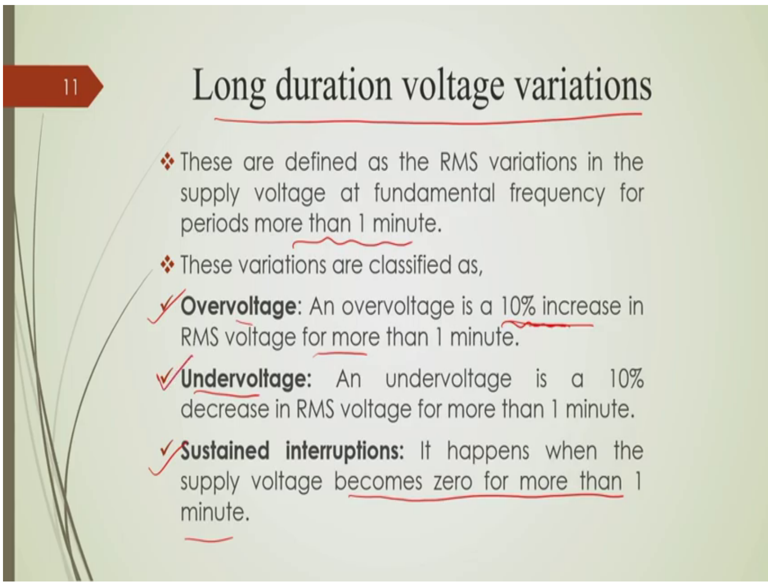

Similarly, this long duration voltage variations are their duration is more than of 1 minute ok. So, if the RMS value of the voltage reduced 10 percent or maybe 15-20 percent we will call it under voltage and if this RMS value rises to 10 percent or 15 percent we will call it over voltage ok.

And sustained interruption is again when supply voltage becomes 0 from more than 1 minute. It is similar to short duration interruption, but here, duration is more than 1 minute. So, under voltage is basically decreased of this RMS value of the supply voltage. It is the dip of the RMS value of the supply voltage for 5, more than 5 to 10 percent ok. 5 to 10 percent variation of voltage is acceptable.

Similarly, over voltage is increase of this RMS value of the supply voltage for at least more than 1 minute of time or higher than 1 minute of time for a more than 10 percent of, the increase of this 10 percent of the supply voltage.

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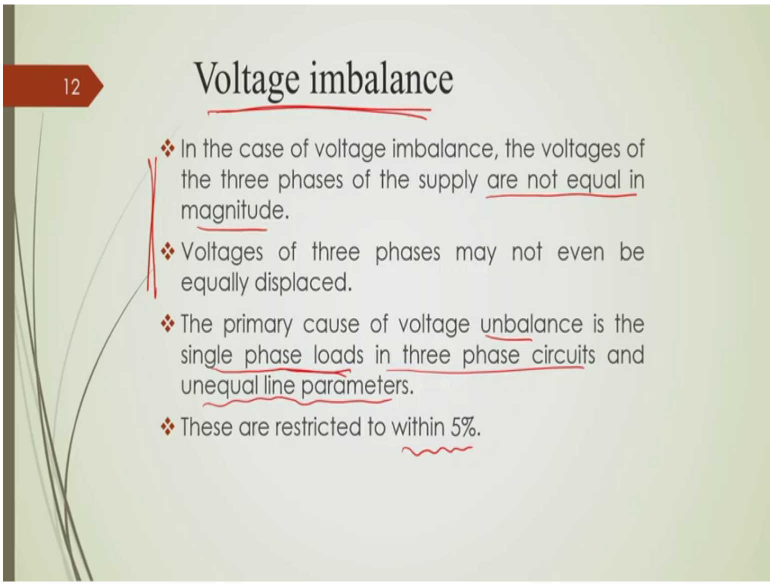

Similarly, voltage imbalance, it is another important aspect or it is another type of voltage quality problem. It occurs when these individual phase supply voltages are not equally in magnitude and not equally spaced by each other ok. So, these are the two reasons as we know that when we have a three-phase supply voltage and it, if it is a balance. So, individual phase voltage magnitudes are same as well as they are exactly displaced by 120 degrees apart to each other ok. So, if it does not satisfy that condition then we call it as a case of voltage imbalance ok or voltage unbalance.

And we will try to quantify this voltage unbalance and we will try to restrict it for a given value of this number ok. So, what are the causes of this voltage imbalance or voltage unbalance? So, this is, these are, due to the single-phase presence of the single-phase loads in the three-phase circuits.

Particularly, you know, secondary side of the distribution networks, where we have more domestic customers and they need a single-phase supply ok, but electric utility generally, they balance this loading of individual phases. But since different types of customers are connected in different phases, it is eventually not possible to have an identical loading in all the three phases ok.

So, at that time this unbalance or imbalance will occur. Similarly, when we have distribution lines with unequal line parameters, there is unequal voltage drop due to this unequal impedance of the line and which are caused by unequal spacing of the phases, primarily due to this unequal spacing of the phases, then we may have this type of problem.

In fact, this type of problem also occurs in transmission networks, but we have different ways to mitigate this, you know, unequal line parameters and that is called transposition ok, but in distribution lines they are not transposed at all. So, we have this kind of problems intact ok.

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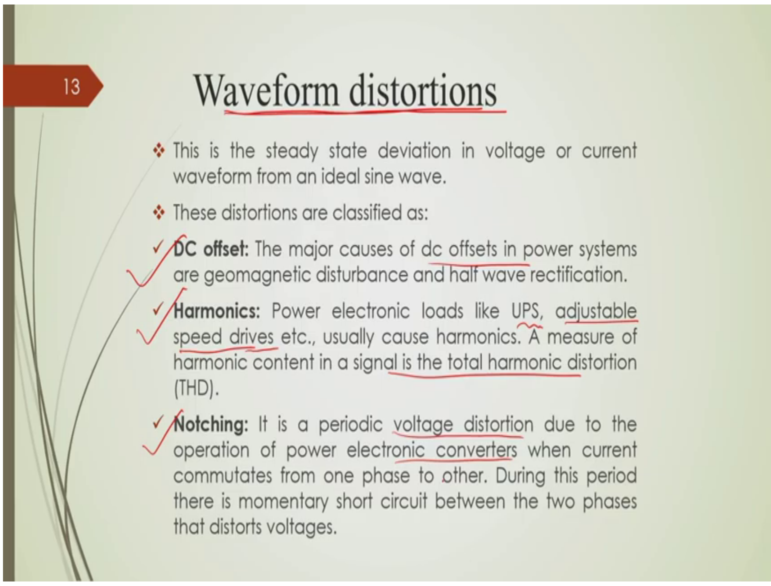

Now, we have also this some voltage quality problems which are called waveform distortions. So, what are the different types of waveform distortions we have? As we said DC offset, that means, presence of the DC voltage in the sinusoidal supply voltage is another reason for this waveform distortion, also known as harmonics. Harmonics are basically, they are a periodic type of voltage distortion ok, I will come to that.

And harmonics are generated because of UPS, because of UPS adjustable speed drives. All are basically power electronics-based loads, you can say, or power electronics-based equipment and they causes harmonic and they transmit harmonic to the system ok. If there is any harmonic present in the load, so, this will be transmitted to the whole network as well, which will cause distortion in the supply voltage ok.

So, similarly, notching is another periodic voltage distortion due to the operation of power electronic converters when current commutates from one phase to other ok.

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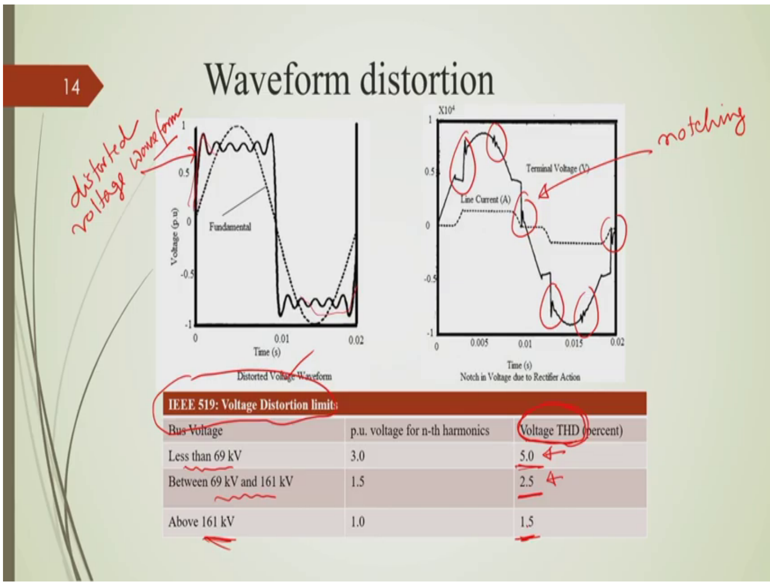

I will show you the typical type of this notching here. So, these are the notching. So, you can see they are very very short duration type of waveform distortion. So, these are notching and this is basically a distorted type of sinusoidal waveform.

So, this is a distorted voltage waveform and we know, we can translate a distorted periodic voltage waveform into a number of sinusoidal voltage waveform by using Fourier series analysis, which will have some fundamental along with some harmonic.

So, this is a typical distorted periodic voltage waveform which can be translated to a number of periodic waveforms which are called harmonics ok. And IEEE, they have some standards for a desirable harmonics and this harmonics, as I said, we categorized with a index called THD, that is total harmonic distortion.

I will come to that how, what is the mathematical function of this THD, I will come to that. But this THD is a measure, it is a numerically represent by this, you know, amount of harmonics that we have present in a particular system. And there are some limits of this acceptable THD. For example, when we have lower than 69 kV system, according to this standards voltage THD should be maximum 5 percent or lower than that.

Our acceptable voltage THD or voltage harmonic should be lower than 5 percent. Similarly, when we have a network with 69 kV to 161 kV, this THD should be 2.5 percent or lower. Similarly, above 161 V, this voltage, THD should be 1.5 percent or lower ok.

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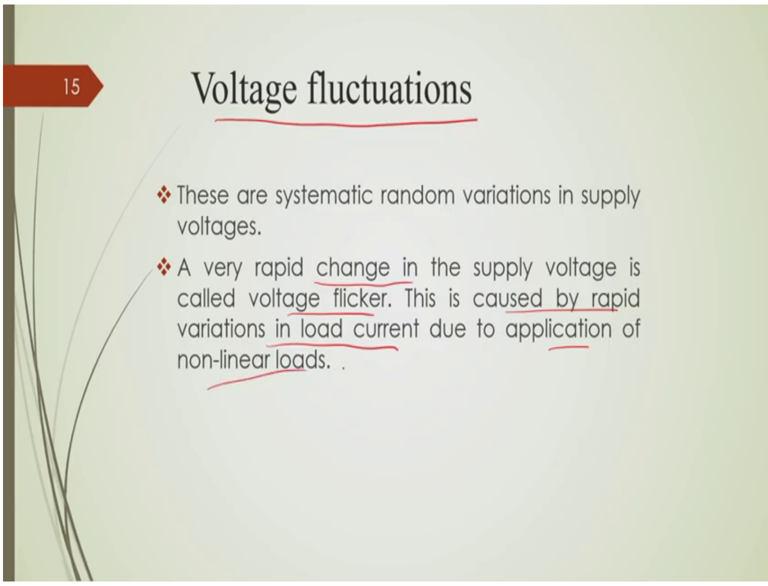

Now, there is another type of power quality problem which is called voltage fluctuations or we call this as a voltage flicker. It is a rapid change in the supply voltage, which is called as voltage flicker; which cause some eye sensation and this is basically caused by rapid variation in load current due to application of non-linear loads ok.

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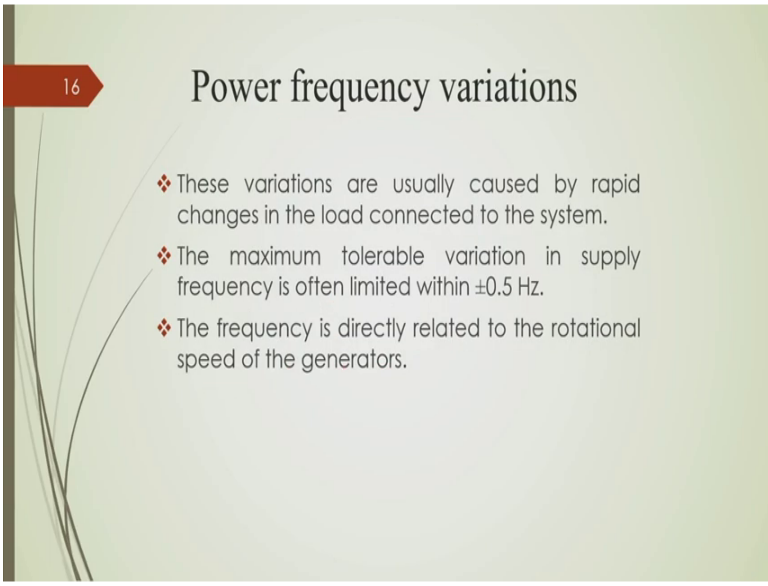

There is another kind of voltage quality problems, power quality problems which is called power frequency variation. We intend to have a constant frequency, as I said, that is 50 hertz, but we never get it. So, there is some tolerable variation of supply frequency, this varies from, you know, country to country, but anything plus minus 0.5 hertz is somewhat acceptable.

And it also depends upon different factors, but if we have a frequency lie within this acceptable band, so, we do not have any problem ok.

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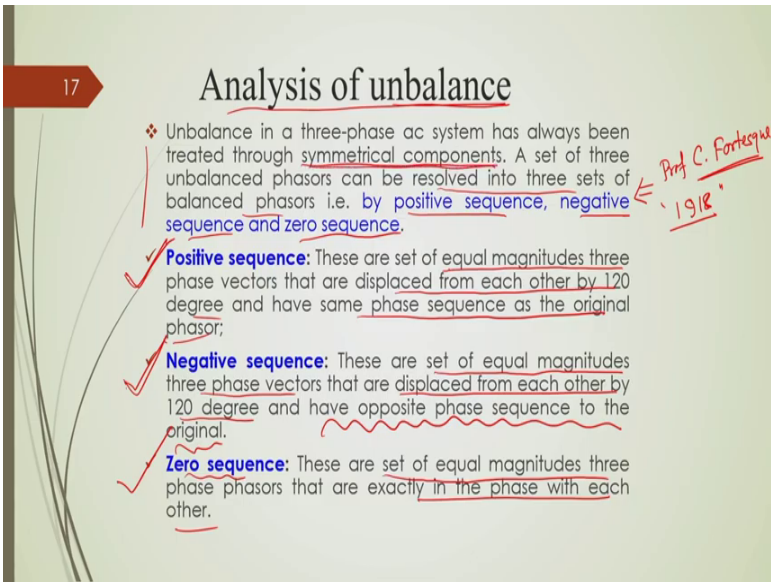

So, far we discuss different types of power quality problems and what are the possible causes for those power quality problems. At this point we will try and how do we characterize those problems, those things also we discuss. So, here at this point we will, I will also discuss how do we mathematically represent those problems so that we can develop some mitigation techniques on mitigation approaches for those problem ok.

So, let, I will start with this analysis of unbalance ok, analysis of unbalance or voltage imbalance which is a somewhat taught in your undergraduate power system course. So, any unbalanced three-phase voltage can be resolved into three sets of balanced phases; one is called positive sequence, another is called negative sequence, another is called zero sequence ok. So, this is basically a concept which is given to us by Professor Charles Fortescue ok in his landmark paper in 1918 ok.

So, he developed this concept that any unbalanced or any unbalanced three-phase supply voltage or three-phase supply current can be resolved into three balanced phasors ok. One is called positive sequence phasor, here we will represent this all these phase voltages equal in a magnitude and they are displaced exactly 120 degree by each other and they have same phase sequence as the original phasor. They have same phase sequence as the original phasor.

Now, negative sequence, they are also represented by a set of equal magnitudes of these three phasors and they are also displaced by 120 degree apart to each other, but they have some opposite phase sequence as the original phasor ok. So, positive sequence is a one component of this, you know, this transformed value of this unbalanced three phase voltage, negative sequence is another component.

And another component is third component that is called zero sequence, where we have three set of equal magnitudes of this voltage and they are exactly in same phase with each other. They are exactly same phase with each other ok. And this analysis is called symmetrical component analysis; this analysis is called, is called symmetrical component analysis.

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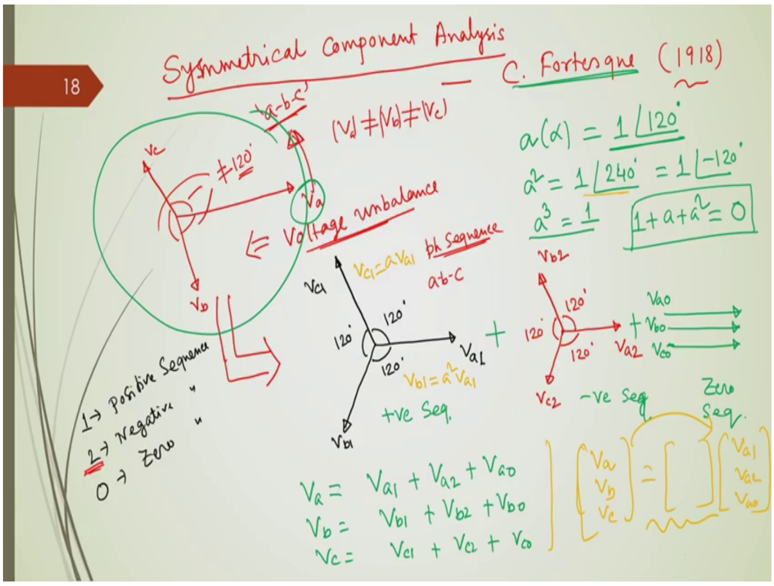

Let me discuss a brief idea of Fortescue symmetrical component analysis so that you can understand it in a better way. As I said it is provided by Charles Fortescue in his landmark paper of 1918, almost 100 years ago, but still we learn it, we use it for many applications. We also develop this mitigation concept based upon this symmetrical analysis approach ok.

Suppose, we have a three-phase system having unbalanced three phase voltages. Suppose, this is phase voltage V a, this is phase voltage V b and this is phase voltage V c ok. So, here you can see this V a magnitude is not equal to V b and V c, V b and also V c. And the angle they have, they are also not 120 degree apart, they are not equal to 120 degree each other.

So, this will cause a, this will cause a unbalance or imbalance. So, this will cause voltage unbalance. Now, this Fortescue says this type of three phase unbalanced voltage can be resolved into three components. Number 1 is positive sequence component, number 1 is positive sequence component and this positive sequence components are represented by this suffix 1 that is V a 1 ok.

So, this 1 stands for this positive sequence component. So, 1 stands for positive sequence component, 2 stands for negative sequence component and 0 stands for zero sequence component. So, this positive sequence components, in positive sequence components, all these phase voltages will be equal and they are exactly 120 degree apart to each other.

So, this is V a 1, suppose this is V b 1, and this is V c 1 ok and they are exactly 120 degree apart to each other. So, this is also 120 degree, this is 120 degree, this is 120 degree and magnitude wise also they are same, but they are also equal 120 degree apart to each other. So, this is a positive sequence ok.

Now, let us see how this negative sequence will look like. So, in negative sequence you can see, this phase sequence of this supply voltage is same as that of the original phasor, that is, here our phase sequence was a b c because we assume that they are rotating anti clock wise. So, after this phase a, phase b will come and then c will come. So, phase sequence is a b c.

Here also you can see that phase sequence is of a b c. So, phase sequence is same as the original voltage. Now, in negative phase sequence these voltage magnitudes they are equivalent, they are exactly 120 degree apart to each other, but their phase sequence is different, that means, they are rotating in opposite direction. So, negative phase sequence is represented by suppose this is V a 2, here 2 stands for negative phase sequence, then since the phase sequence is opposite. So, here we will have, V c 2 and here we will have V b 2.

So, they are 120 degree apart to each other. So, this is 120 degree, this is also 120 degree, this is also 120 degree ok. And there is another component which is zero sequence. In zero sequence all these three phase voltages they are having equal magnitudes. Suppose, this is V a 0 or V a 0, then this is V b 0 and this is V c 0, then and also, they are of same phase they are in same phase.

So, this is positive sequence, this is negative sequence, this is zero sequence sorry, this is zero sequence. Now, actual you know this unbalanced three phase system is represented by summation of this positive sequence, negative sequence and zero sequence phase voltage. And that is why you know this V a, which is you know actual phase voltage of this phase a is equal to V a 1 plus V b 1 plus V sorry, V a 1 plus V a 2 plus V a 0.

Similarly, V b is equal to V b 1 plus V b 2 plus V b 0. Similarly, V c is equal to V c 1 plus V c 2 plus V c 0 ok. So, this is what the symmetrical component, many of you might be aware on this. And also, this Fortescue gave an operator which is called operator a or in some books it is also called as operator alpha, which is equal to 1 at an angle 120 degree ok, which is 1 at an angle 120 degree.

So, what would be the value of a square which is equal to 1 at an angle; it is an unit vector; so, it will be 240 degree. So, which is also 1 at an angle minus 120 degree. Similarly, a cube which will be 1 at an angle 360 degree which is equal to 1 and also you know, 1 plus a plus a square would be equal to 0 ok, would be equal to 0 ok.

So, by using this a operator, they determine, they have made a relationship of a 1 b 1 in fact, b 1 and c 1 from a 1. For example, that here this V b 1 will be equal to a square V a 1, because it is minus under 120 degree with respect to this V a 1 or it is 1 at an angle 240 degree with respect to V a 1.

Similarly, V c 1 is equal to a V a 1. So, we can similarly, replace this b 1 and c 1 in terms of V a 1 V a 2 and V a 0 which will basically give you a kind of matrix where we will get V a V b V c in one hand and some transformation matrix and then we will be having this component V a 1 V a 2 V a 0 ok.

And this matrix is basically transforming these components to this symmetrical component and it is sometimes named as transformation matrix. So, this is how we will analyze or how this is how we will characterize, this symmetrical components.

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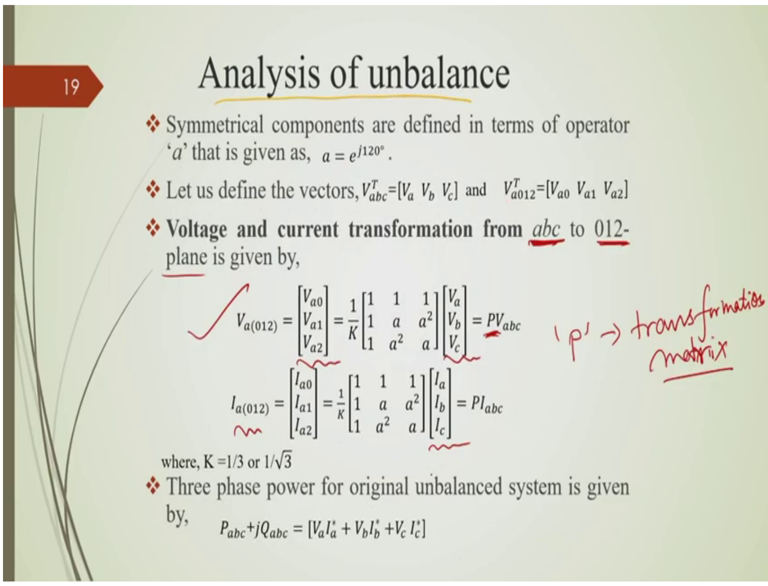

And in this part, we will get to know that symmetrical component analysis. So, this is how we transform this. In fact, this is a reverse transformation. We represent this symmetrical component in terms of actual magnitudes of the voltage ok. So, similarly current will also have similar kind of transformation and here we have this transformation matrix represented by p.

So, p is our transformation matrix, transformation matrix which transforms, you know, this a b c that is that is actual phase voltage to 012 plane which is basically zero sequence positive sequence and negative sequence or symmetrical component plane ok.

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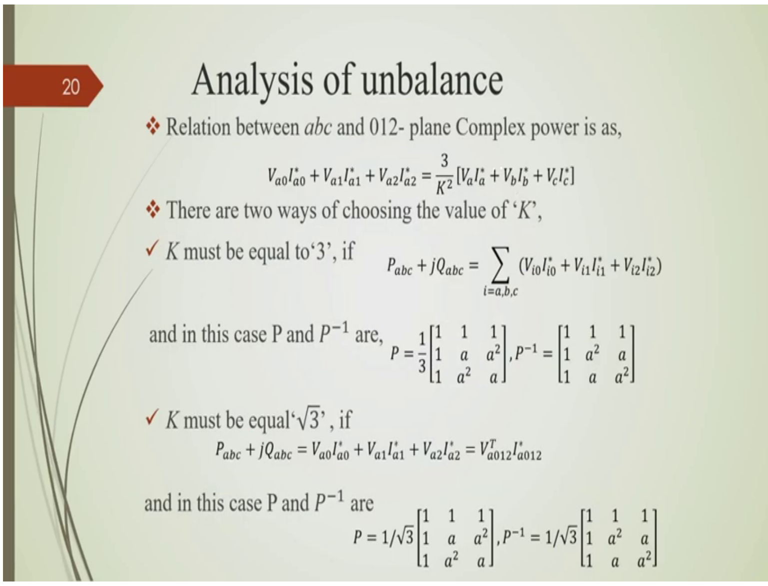

So, now in fact, this, here instead of finding out this transformation matrix; they find out this transformation matrix in different way having a factor k, and this k value, they are getting by making this power that is expression of a b c plane equal to the power expression in 012 that is symmetrical component plane ok. So, this is how we can do it.

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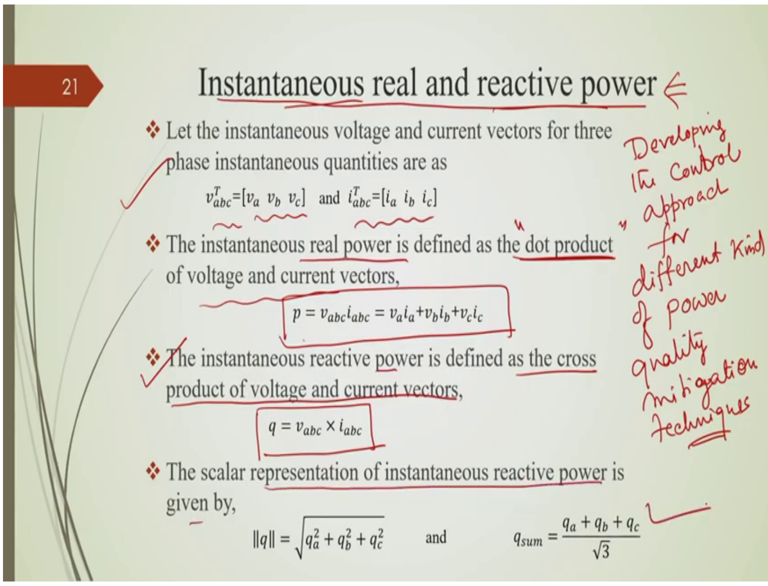

Now, there are another way of, you know, characterize of this sort of voltage imbalance or voltage unbalance or even voltage distortion which are called as instantaneous real and reactive power methods. These are basically used for developing this, developing the control approach for different kind of, different kind of power quality mitigation techniques power quality mitigation techniques.

So, which are very important and those who will work on this control of this power quality problems or power quality mitigation problem, they need to learn it. What is instantaneous real power, what is instantaneous reactive power. So, here you get the definition of instantaneous real and reactive power. Since they are instantaneous quantity, they are represented by small v.

Similarly, currents are also represented by small i. From this instantaneous real power is defined as the dot product which is very important to know; dot product of this voltage and current vector which is. So, now, what this equation and instantaneous reactive power is defined as the cross product of this voltage and current which is shown over here ok.

And the scalar representation of instantaneous power is given by this. All these equations are very important to develop the control approach of this different kind of power quality mitigation techniques.

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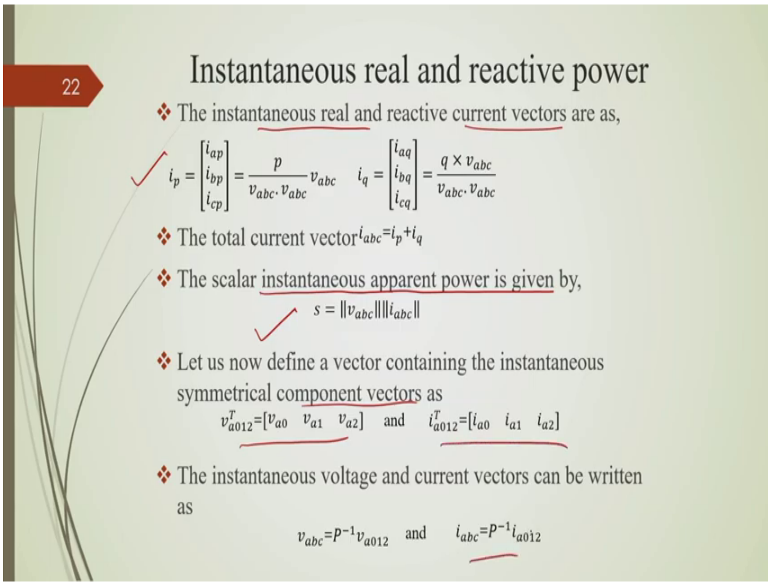

So, these are, you know, vectoral representation of real and reactive power currents, in terms of real and reactive power factors ok. And also, the scalar instantaneous apparent power is expression of this, and also we can represent this in terms of symmetrical component factors like this.

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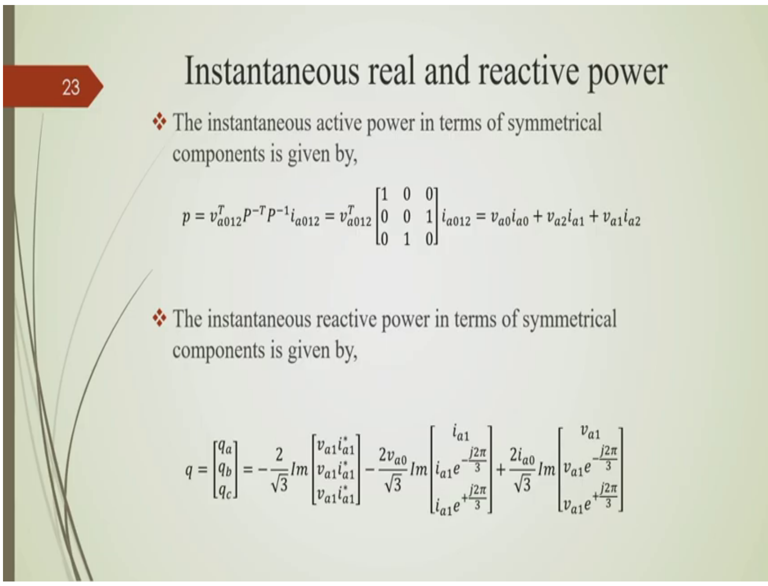

So, this is, this you need to take a look if you are interested in further working on this. So, this is how this instantaneous active power is made similar to the instantaneous power in the 012 plane that is zero sequence, positive sequence and negative sequence plane.

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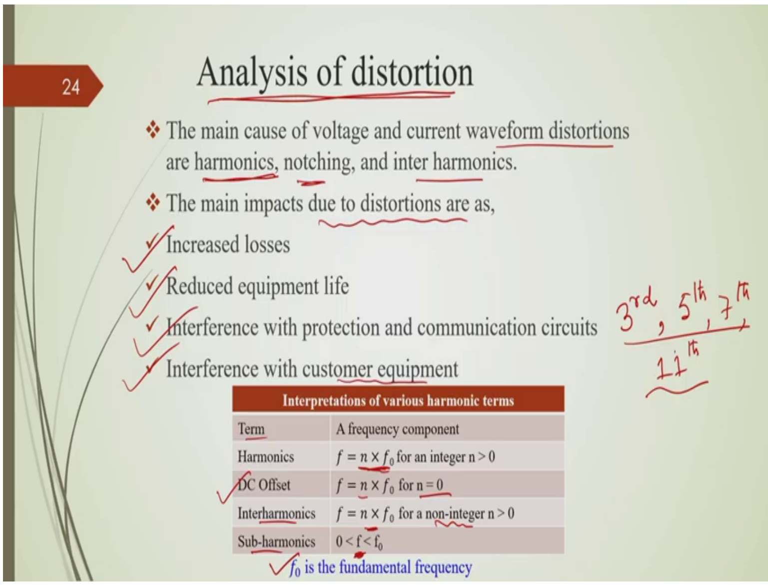

Now, we also go for different other analysis of distortions. As I said, here we are basically trying to understand how do we characterize this distortion ok. So, there are some periodic distortions and there are some non-periodic distortions. These periodic distortions are basically harmonics. In fact, notching as well and also inter harmonics ok.

And the impact of these distortions; they will create increased loss, because I will show you that any distorted periodic waveform can be resolved into a number of sinusoid with different frequency out of which fundamental frequency component is important for us, because that is what we are trying to provide to the customer as an electric utility.

But what will happen to this non-power frequency periodic distorted component? We call them as harmonic components. So, they will cause some extra losses that will reduce equipment life. They will interfere with protection and communication circuit. They will also interfere with the customer equipment, and many times, this customer, they generate harmonics and inject to the system ok.

Now, these harmonics are, as I said, integer multiple of this fundamental frequency component like n multiplied by f 0, where f 0 is your fundamental frequency component. Where n is an integer and you know since, we have an equal identical positive and negative half cycle, we do not have any even harmonics in power system, we mostly have odd harmonics. So, n is, n is of odd number.

So, we are concerned of some higher order odd harmonics like 3rd harmonics, 5th harmonics, 7th harmonics, 11th harmonics and up to that. So, those harmonics we need to study and we need to have some mitigation approach for those harmonics. So, that the total harmonic contents will be lowered and we will get supply voltage as sinusoid as it is possible. Similarly, DC offset means n is equal to 0. Inter harmonics means n is non-integer ok.

Any value in between 2 to 3 and so; and sub harmonic is f is lower than this frequency is lower than the fundamental frequency. So, if your fundamental frequency is 50 hertz, the sub harmonic frequency can be 25 hertz and so on.

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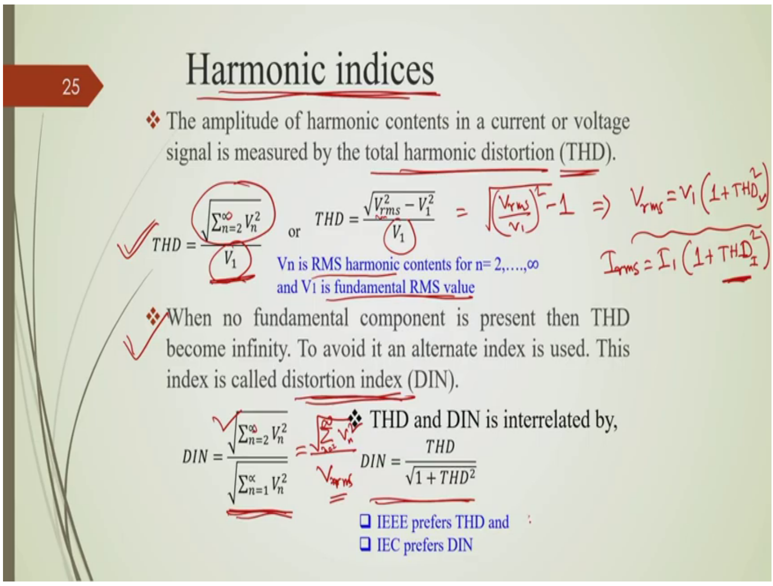

Now, we have some indices, as I said, to quantify these harmonic contents where one of them is total harmonic distortion that is THD ok. And THD is defined as the ratio of harmonic component to the fundamental component. So, here V 1 stands for fundamental component of this voltage and this V n starts from 2 to any value, is basically, if you take root mean root square then you will get this, you know that harmonic distorted component ok.

So, we can always represent this RMS value in terms of this THD and the fundamental quantity like here, you can see, this is equal to V rms by V 1 square minus 1. So, we can always write V rms is equal to V one multiplied by 1 plus THD square. So, this is also applicable for value of voltage as well as current. So, this is supposing the voltage harmonics which is represented by THD v.

Similarly, for current harmonics, we can write I rms is equal to I 1, where I 1 is the fundamental component of the current multiplied by 1 plus THD I square. So, here this THD I represent the harmonics in the load current or line current ok. So, there is another index which is called distortion index so that, we do this for same purpose, this is for the same purpose to quantify this distortion. So, that is called distortion index, here numerator is same as that of THD and the denominator is different; instead of this fundamental voltage it is basically RMS voltage that is V rms. So, this is, this one is similar to V rms.

So, its numerator is same as that of THD, THD that is summation of n is equal to 2 to infinity this is infinite in fact, this is also infinite in fact. This n square divided by V rms. So, the relationship of DIN and THD, you can also find out and this we IEEE, they prefer quantifying this harmonics by THD index, IEC they prefer this DIN index ok.

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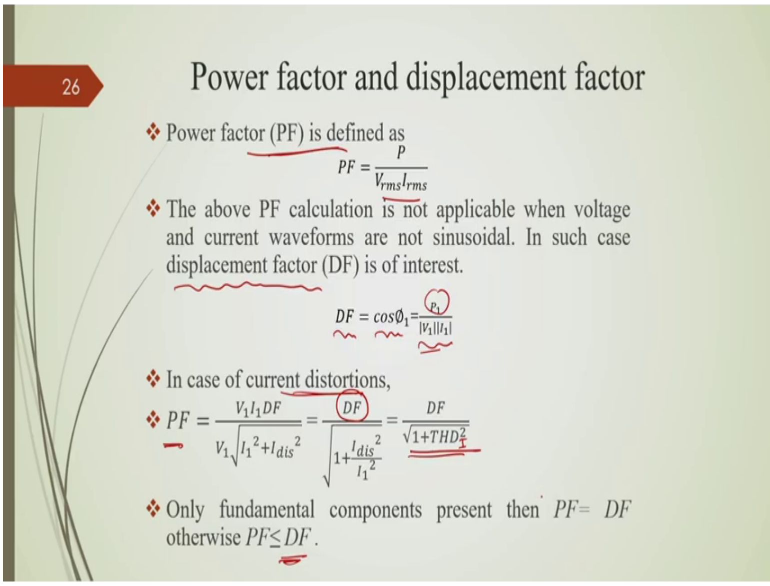

There is another concept here, quantifying this power factor. This power factor, as you know, this real power or actual power or useful power consumed divided by V rms I rms and if there is no distortion. So, this is coming out to be cos phi ok. But, if there is a distortion, this distortion for distorted sinusoidal this power factor is actually called as displacement factor, I had displacement factor is equal to cosine phi that is P 1 divided by V 1 multiplied by I 1.

So, this is basically actual part, this is what the apparent part. And when we have this distortion in the currents then the power factor is basically multiplication of distortion factor divided by 1 plus THD I. Similarly, if we have distorted, distortion in the supply voltage it be also function of THD V as well ok. And actual power factor is lower than this displacement factor that one should know.

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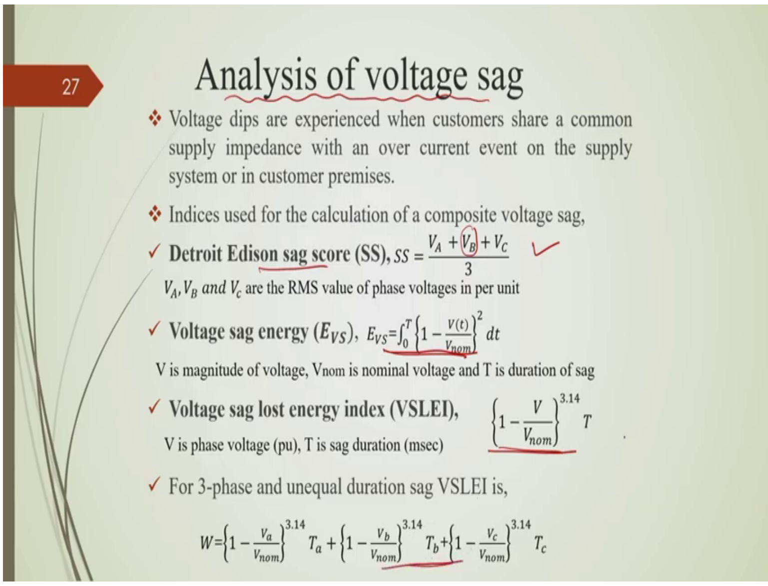

Now, these are the some of the ways we can categorize this voltage sag, many people did research on characterizing; this one is called Detroit Edison sag score where simply the magnitudes of three, or three phase voltage are summed, divided by 3.

So, if any of these voltage sag in any of the phase then magnitudes of any of the phase voltage would be lower than the nominal voltage. So, this code will be lesser than 1 and if there is no voltage sag it will be equal to 1. Similarly, some people they consider this voltage sag energy to quantify this voltage sag and people have used different indices to quantify this voltage sag.

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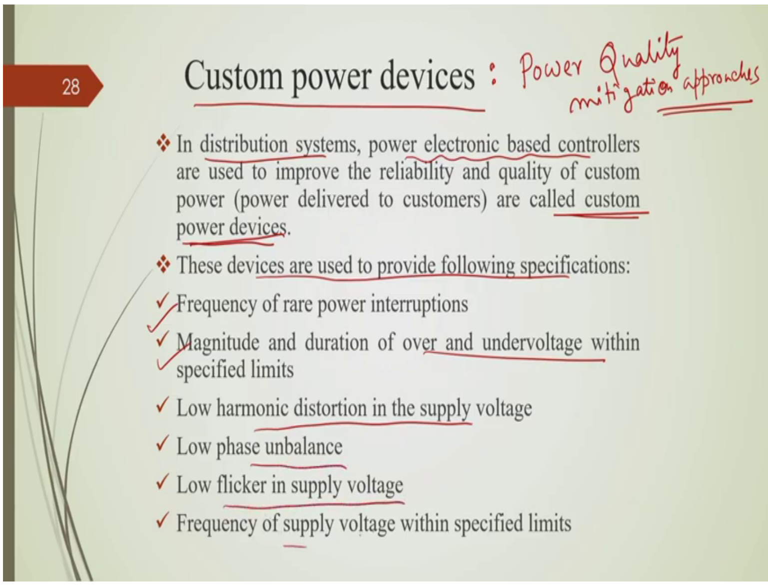

Now, mitigation approaches. So, this, these are basically power quality mitigation approaches, power quality mitigation approaches. So, this power quality mitigation approaches in power distribution systems are basically called they are also obviously, power electronic based controller, they are called custom power devices ok. They are called custom power devices.

So, they are similar to facts devices which are used in power transmission system, but they are having a difference with these facts devices. Facts devices are normally constructed for relatively balanced transmission lines whereas, custom power devices, they are constructed and controlled considering that relatively unbalanced power distribution networks ok.

And these devices are used to provide following specification frequency to the rated power magnitude and duration due to over voltage and under voltage; that means, if they use for over voltage under voltage mitigation. They used to have a frequency which will be similar to the supply frequency, they are used to mitigate this harmonic distortion, voltage unbalance or voltage imbalance to mitigate voltage flicker ok. So, for this purpose we use them.

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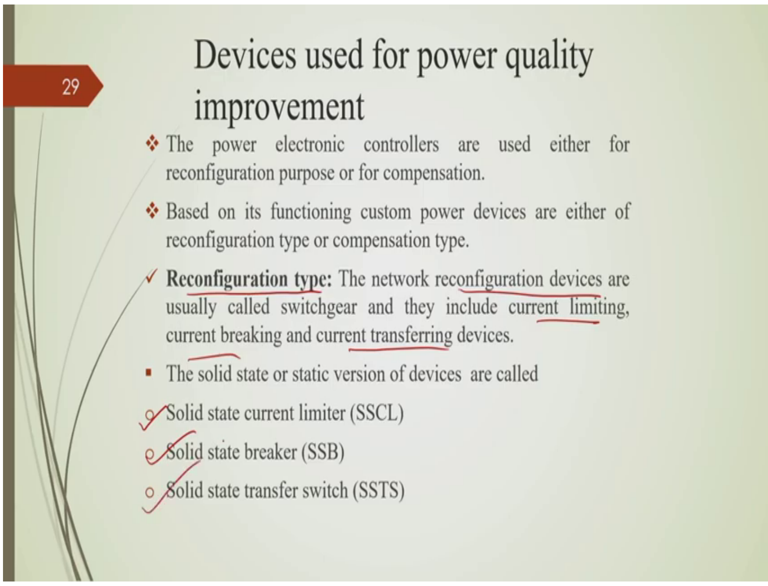

And there are two types of, you know, custom power devices. One is called reconfiguration type, which are used to reconfigure this network ok, for current limiting circuit breaking and current transforming devices. So, these are some reconfiguration type, custom power devices which are called solid state current limiter, solid state circuit breakers, solid state transfer switches.

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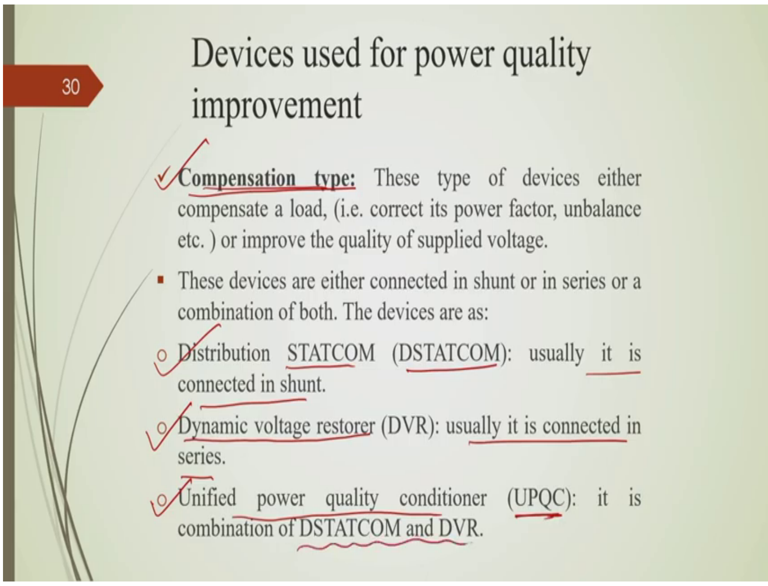

And we have some power electronic with compensation devices specifically constructed to mitigate these power quality problems. They are named as distribution STATCOM or

DSTATCOM: this is usually shunt connected devices and used for this mitigation for harmonics to provide reactive power compensation and there are multi functionalities.

Similarly, there is a custom power device which is called dynamic voltage restorer. It is usually a series connected power electronic device which is used to mitigate this voltage sag, voltage swell and many other power quality problems. And unified power quality conditioner which is also called as UPQC: it is a combination of DSTATCOM and DVR. So, they have dual functionalities.

They can mitigate current harmonics or load harmonics created in the customer premises, also, they can mitigate this voltage quality problems, like voltage sag, swell mitigation and voltage flicker mitigation ok.

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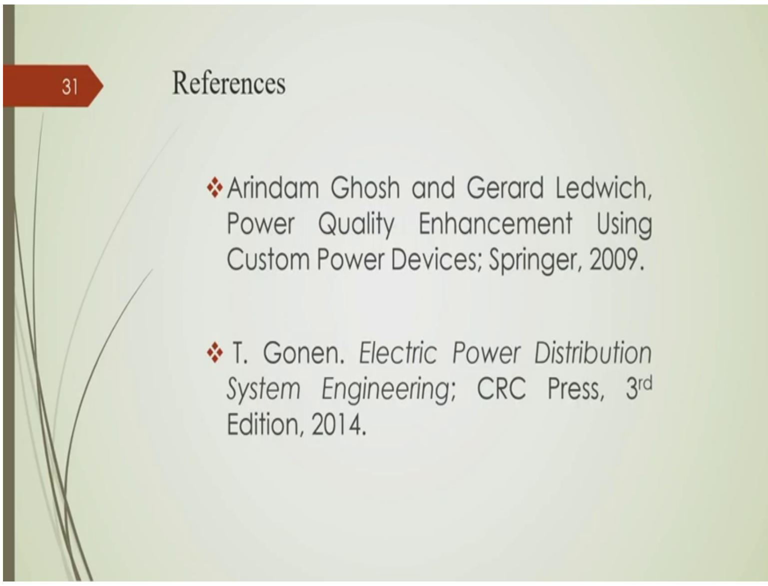

So, for this part of the lecture this is the main reference book that I took. In fact, this concept we will get in the Gonen's book as well ok.

So, finally, thank you for attending this part of the lecture. So, here we have completed this module 3.