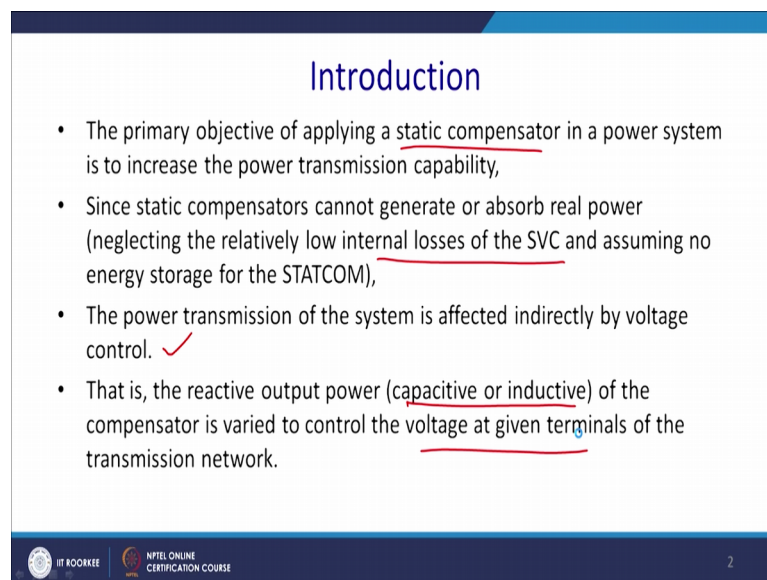


Flexible AC Transmission Systems (FACTS) Devices
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Lecture – 18
External Control Design of Static VAR Compensator

Welcome to our Flexibility AC Transmission Systems video lecture series. Today we are going to discuss, we have already discussed the actually the comparison between SVC and the STATCOM. We shall see detail today what are the controlled features of the STATCOM that is the title of this topic will be the External Control Design of the Static VAR compensator or SVC.

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Introduction

- The primary objective of applying a static compensator in a power system is to increase the power transmission capability,
- Since static compensators cannot generate or absorb real power (neglecting the relatively low internal losses of the SVC and assuming no energy storage for the STATCOM),
- The power transmission of the system is affected indirectly by voltage control. ✓
- That is, the reactive output power (capacitive or inductive) of the compensator is varied to control the voltage at given terminals of the transmission network.

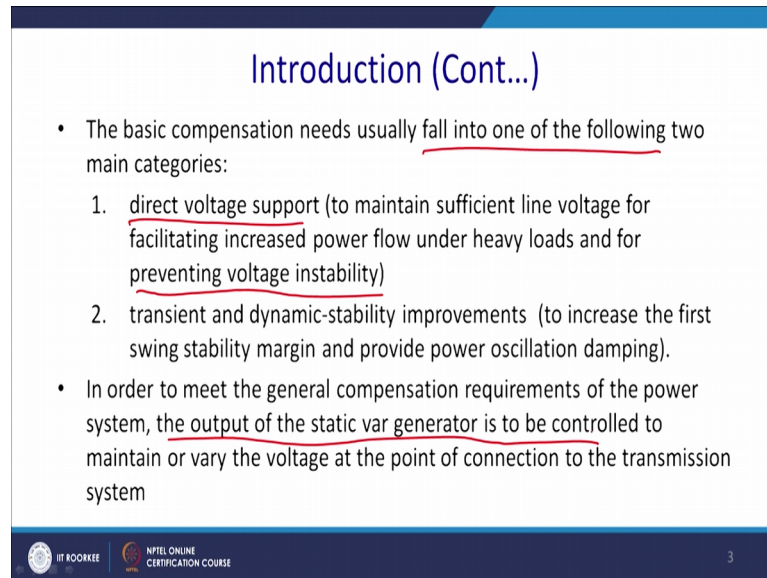
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Now, as we know that primary objective of applying the static compensator in a power system is to increase the power transmission capability. This is the basic principle of putting a FACTS devices. Since static compensator cannot generate or absorb real power we have to neglect the switching losses of the SVC, and we should now presently eliminate the idea of putting active component or the storage component with in a STATCOM.

Neglecting the relatively low internal losses of the SVC and assuming that no energy storage for the STATCOM; The power transmission of the system is affected indirectly by the voltage control, that is the reactive power the capacitive or inductive of the

compensator is varied to control the voltage at the given terminal of the transmission network.

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The slide is titled "Introduction (Cont...)" and contains a bulleted list of compensation needs. The text is as follows:

- The basic compensation needs usually fall into one of the following two main categories:
 1. direct voltage support (to maintain sufficient line voltage for facilitating increased power flow under heavy loads and for preventing voltage instability)
 2. transient and dynamic-stability improvements (to increase the first swing stability margin and provide power oscillation damping).
- In order to meet the general compensation requirements of the power system, the output of the static var generator is to be controlled to maintain or vary the voltage at the point of connection to the transmission system

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So, the basic compensation needs usually into the following two categories, one the voltage support, direct voltage support to maintain sufficient line voltage facilitating the increase in the power flow under heavy load and for preventing voltage instability. This is may be the purpose another is the transient stability the transient and dynamic stability improvement to increase the first swing stability margin and provide damping to the power oscillation.

So, in order to meet this two demand general compensation requirement of that of the power system, the output of the static var generator is to be is required to be controlled to maintain or vary the voltage at the point of the connections of the transmission line.

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General control scheme

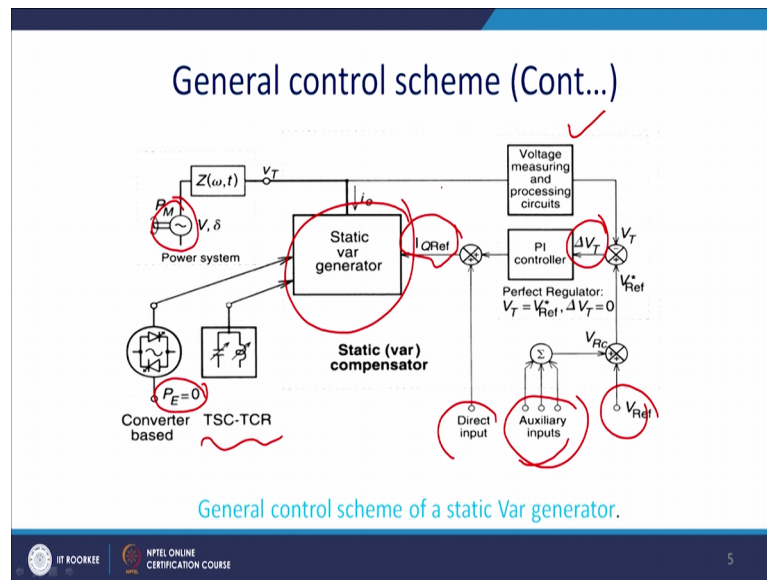
- A general control scheme, converting a static Var generator (either a controlled impedance type or a converter based type) into a transmission line compensator ✓
- The power system, at the terminal of the compensator, is represented by a generator with a generally varying rotor angle δ internal voltage V , and source impedance Z that is a function of the angular frequency ω and time t
- The terminal voltage V_T of the power system can be characterized by a generally varying amplitude V_T and angular frequency ω .

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So, this is the one of the desired feature of SVC in general the control scheme converting static var compensator, either to a controlled impedance or a converter type into a transmission line compensator. The power system at the terminal of the compensator is represented by the generator with a generally a varying angle varying rotor angle with the internal voltage V .

So, we know that actually P is given by $V_1 V_2 \sin \delta$. So, where δ is a rotor angle and the source impedance Z is the function of regular frequency and a time t . The terminal voltage that is V_T of the power system, can be characterized by generally varying the amplitude V_T with an angular frequency ω this is a way we model it.

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So, this is a general control scheme of SVC what happens you have a prime mover that generates a voltage. So, with an angle V and with voltage V amplitude V and the angle δ . So, this is the network and here you put a static var generator, essentially it does not have any power to compensate the real power. So, P is 0 this is the converter based and it may be actually TCSC or TCR. So, what do you how you will control it? So, essentially you will measure the voltage.

So, we will check that whether there is a sag in to the system or not. So, accordingly you will actually check the system capability. So, there is an auxiliary input there is a V reference from there will check that, whether there is a sag in input or not and also if it is not so, then you will put this value of the V_T as a V reference and thus actually ΔV becomes 0 and you also have auxiliary inputs. And from there you know actually you have the direct input and from there you essentially you compute what is your I_Q reference.

This I_Q reference you may get hybrid stat hybrid STATCOM or you may have this kind of controlled devices. So, that you required to inject the voltage i proportional to the I_Q ref.

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General control scheme (Cont...)

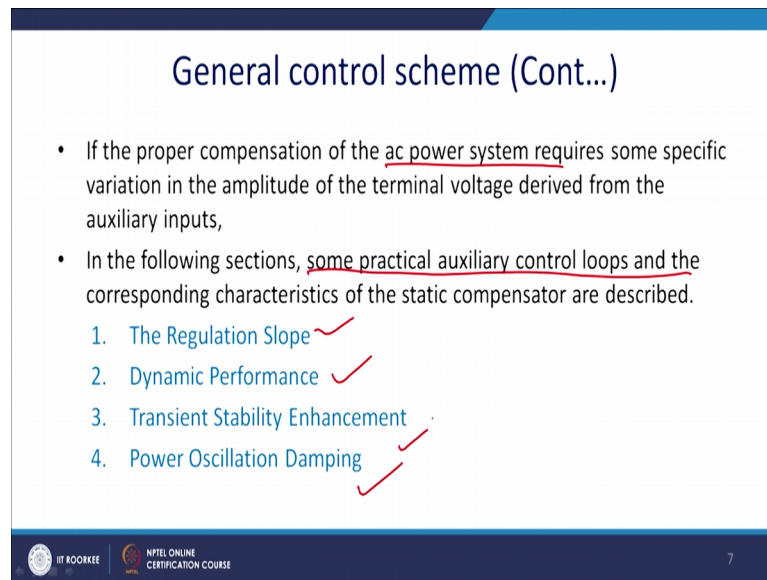
- The output of the static Var generator is controlled so that the amplitude I_o of the reactive current i_o drawn from the power system follows the current reference I_{Qref} .
- With the basic static compensator control, the Var generator is operated as a perfect terminal voltage regulator.
- The amplitude V_T of the terminal voltage is measured and compared with the voltage reference V_{ref} and produce an error.
- The error ΔV_T is processed and amplified by a PI (proportional integral) controller to provide the current reference I_{Qref} for the Var generator.

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The output of the static Var generator is controlled so, that the amplitude i_o of reactive current is drawn from the power system and system the reference current I_{Qref} with the basic compensator control the var generator is operated, at a perfect terminal voltage regulator.

So, that is something we have maintained the amplitude V_T of the terminal voltage is measured, and compared with the reference voltage V_{ref} and produce an error this error is fit to the pi controller. This V_T is processed and multiplied by a pi controller to provide the current reference I_{Qref} for the compensation of the var this is the principle operation of this SVC.

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The slide is titled "General control scheme (Cont...)" and contains the following content:

- If the proper compensation of the ac power system requires some specific variation in the amplitude of the terminal voltage derived from the auxiliary inputs,
- In the following sections, some practical auxiliary control loops and the corresponding characteristics of the static compensator are described.
 1. The Regulation Slope ✓
 2. Dynamic Performance ✓
 3. Transient Stability Enhancement ✓
 4. Power Oscillation Damping ✓

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If the proper compensation of the reactive power system require some specific variation of the amplitude of the terminal voltage and that is varied for the auxiliary inputs sometimes it may sac may occur or something. So, there may be the disturbance due to that then we actually work on the auxiliary input.

The following sections some practical auxiliary control loops are corresponding to these following item will be discussed, that is the slope regulation, dynamic performance, transient stability and the power damping. So, these are the four entities mostly will be actually we will see that what are the controlled technique will require to achieve those entities. Now, many applications the static compensation is not used as the perfect terminal voltage regulator.

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The Regulation Slope

- In many applications, the static compensator is not used as a perfect terminal voltage regulator, but rather the terminal voltage is allowed to vary in proportion with the compensating current

Why it is proportion with compensating current ?

- The linear operating range of a compensator with given maximum capacitive and inductive ratings can be extended if a regulation "droop" is allowed.

Regulation "droop" means that the terminal voltage is allowed to be smaller than the nominal no load value at full capacitive compensation and, conversely, it is allowed to be higher than the nominal value at full inductive compensation:

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But whether terminal voltage is allowed to vary proportional to the compensating current most of the cases why it is proportional to the compensating current? We know that actually reactive power handling capability varies with the q_s in case of the SVC. The linear operating in range of the compensator with the given maximum capacitor and the inducting current can be extended if the regulation droop is allowed.

So, then it will be linear otherwise it is quadratic. Regulation droop means the terminal voltage allowed to be smaller than the nominal no load value, at full capacitive compensation and conversely it is allowed to be the higher than the nominal value at full inductive compensation this is the droop regulation. So, thus what happen? The perfect regulation that mean the 0 droop or slope could results in poorly defined operating point and has a tendency to oscillate.

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The Regulation Slope (Cont...)

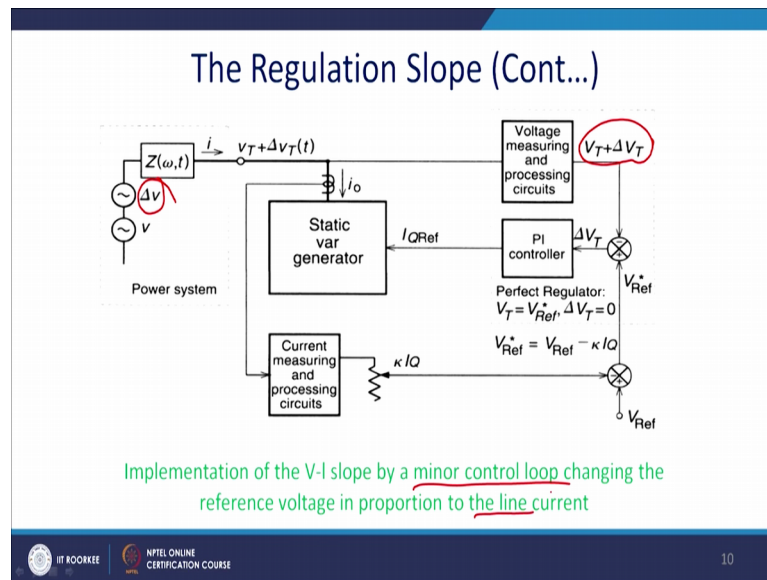
- 2. Perfect regulation (zero droop or slope) could result in poorly defined operating point, and a tendency of oscillation,
- 3. A regulation "droop" or slope tends to enforce automatic load sharing between static compensators as well as other voltage regulating devices normally employed to control transmission voltage.
- The desired terminal voltage versus output current characteristic of the compensator can be established by a minor control loop using the previously defined auxiliary input.

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So, that is something we require to prevent the regulation droop or the slope tend to ensure. Automatic load shading between static var compensator as well as the voltage regulating device normally employed to employed to control the transmission voltage. The desired terminal voltage verses the output current characteristics of the compensator can be established by a minor control loop using actually as you have shown a previously defined auxiliary input.

So, that will be used for loop control; loop control is very important feature, while the multiple entities working and how they will share the load ultimately let us assume that power system all of a sudden you have ΔV comes in to the picture.

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So, you have a soil in voltage and thus what happen this? V_T will be added up and this current will be sensed, current sensing and processing circuit and the measuring voltage also measured and will add up plus ΔV_T . So, the error ΔV_T will come and will give you the reference and perfect regulator, when V_T equal to V_{ref} and ΔV_T equal to 0 and V_{ref} equal to generally it is $V_{ref} - \kappa I_o$. Thus it will ensure the sharing of this reactive power between all the element implementation of the V-I slope by minor control loop, changing the reference voltage is proportional to the line current.

So, how this line current changes you actually inject some extra voltage and that is called the droop control feature. So, how you will calculate κ that is also a challenge we have written that i into κ into i .

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The Regulation Slope (Cont...)

- A signal proportional to the amplitude of the compensating current kI_Q with an ordered polarity (capacitive current is negative and inductive current is positive) is derived and
- summed to the reference V_{ref} then obtained effective reference (V_{ref}^*)
- k is regulation slope

$$k = \frac{\Delta V_{Cmax}}{I_{Cmax}} = \frac{\Delta V_{Lmax}}{I_{Lmax}}$$

- Where ΔV_{Cmax} is the deviation (decrease) of the terminal voltage from its nominal value at maximum capacitive output current

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The proportional a signal proportional to the amplitude of the compensating current kI_Q with an order of the polarity; capacitive current is negative and the inductive current is positive is derived. Summed to the reference V_{ref} then obtained effective V_{ref} reference then the V_{ref} will change dynamically as it will be required by the I .

So, avoid k is the regulating slope, but k is given by $\frac{\Delta V_{Cmax}}{I_{Cmax}}$ or $\frac{\Delta V_{Lmax}}{I_{Lmax}}$ depending on the capacitive or the inductive compensation. Where the ΔV_{Cmax} is the deviation or decrease in the terminal voltage from its nominal value at the maximum capacitive current, but by using this reference the amplitude of the terminal voltage V_T is regulated at a linear slope over the control range of the compensator.

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The Regulation Slope (Cont...)

- By using the reference the amplitude of the terminal voltage, V_T is regulated along a set linear slope over the control range of the compensator.
- For terminal voltage changes outside of the linear control range, the output current of the compensator is determined by the basic V-I characteristic of the Var generator used

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For terminal voltage range outside the linear control range the output current of the compensator is defined by the basic V I characteristic of the Var generator let us see this curve and that will explain the case.

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The Regulation Slope (Cont...)

- Load line 1 intersects the compensator V-I characteristic at the nominal (reference) voltage, thus the output current of the compensator is zero.
- Load line 2 is below load line 1 due to a decrease in the power system voltage (e.g., generator outage). Its intersection with the compensator and calls for the capacitive compensating current I_{c2}
- Load line 3 is above load line 1 due to an increase in the power system voltage (e.g., load rejection). Its intersection with the compensator and calls for inductive compensating current I_{L3}

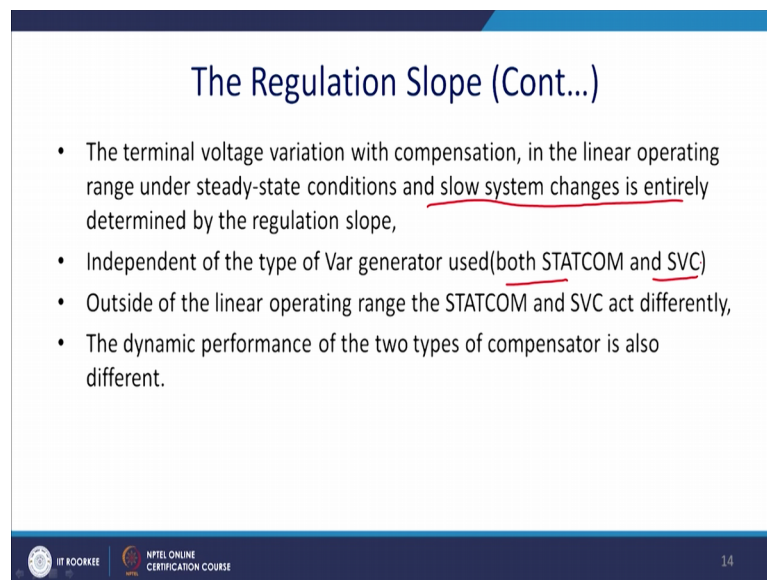
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Let us consider that the load line 1 intersects the V I curve. So, this is the load line 1 and this is the load line 1 and the characteristics of the nominal reference voltage and thus what happen? The output current of the compensator is 0 and this is the actually the load line 2. Load line 2 is a below the load line 1 due to decrease in the power system voltage

that mean the generator out h or something like that or sac it interacts interaction with the compensator and calls for the capacitive compensation of current I_c .

So, there will be some current it will be difference. Same way if there is voltages (Refer Time: 13:50) and the load line three is above the load line 1 due to the increase in the power system voltage, may be due to the load rejections. The intersection with the compensator and calls for the inducting compensation of current I_L ; so, there will be a some amount of extra current will come. So, you know if it is STATCOM then it will have a this kind of characteristics and if it is SVC you have linear characteristics and this is the actually without compensation.

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The Regulation Slope (Cont...)

- The terminal voltage variation with compensation, in the linear operating range under steady-state conditions and slow system changes is entirely determined by the regulation slope,
- Independent of the type of Var generator used (both STATCOM and SVC)
- Outside of the linear operating range the STATCOM and SVC act differently,
- The dynamic performance of the two types of compensator is also different.

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Now, the terminal voltage variation with the compensation in the linear operating range under steady state condition and slow system change is entirely determined by the regulation loop that is called loop control. Independent of the type of the var generator used both it can be SVC or STATCOM. Outside the linear operating range STATCOM and SVC act differently. So, that is the challenge; the ironic performance of the two types of compensator also will be different please note that. So, let us see that dynamic performance.

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Dynamic Performance

- The dynamic behavior of the compensator in the normal compensating range can be characterized by using the basic transfer function
- Therefore the terminal voltage

$$V_T = \frac{V}{1+G_1G_2HX} + \frac{V_{ref}G_1G_2X}{1+G_1G_2HX}$$

Where G₁ is regulator, G₂ Var generator, X system impedance and H is measurement

- the objective is to establish how well the terminal voltage is regulated against the (varying) system voltage

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The dynamic behavior of the compensator in a normal compensating range can be characterized by using a basic transfer function and therefore, the terminal voltage V_T is $V / (1 + G_1 G_2 H X) + V_{ref} G_1 G_2 X / (1 + G_1 G_2 H X)$ am coming to it. So, where G_1 is a regulator, G_2 is a var generator and X is a system impedance and H is the actually the transfer function of the measuring devices. The object is to establish how well terminal voltage is regulated against the varying system voltage.

So, that is something we require to put it let us assume that V_{ref} equal to 0 and consider the small variation only.

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Dynamic Performance(Cont...)

- Let $V_{ref} = 0$ and consider small variation only. ✓
- Then the amplitude variation of the terminal voltage ΔV_T against the amplitude variation of the power system voltage ΔV can be expressed as
$$\frac{\Delta V_T}{\Delta V} = \frac{1}{1 + G_1 G_2 H X}$$
 at steady state it become
$$\frac{\Delta V_T}{\Delta V} = \frac{1}{1 + \frac{X}{k}}$$
- It confirms that as the slope becomes smaller ($k \rightarrow 0$), the terminal voltage remains constant, independent of the system voltage variation
- Similarly, with increasing slope ($k \gg X$) the terminal voltage becomes unregulated ✓

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So, then amplitude of the variation of the terminal voltage V_T against the amplitude variation of the power system ΔV can be expressed in this term. At the steady state this becomes just 1 by 1 plus X by k . This confirms that the slope becomes smaller if k becomes large; the terminal voltage remains constant independent of the system variation. Similar with the increasing case slope the terminal voltage; becomes unregulated. So, we require to keep this terminal performance in to the mind the equation shows that a dynamic behavior of the compensator is the function of the power system impedance.

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Dynamic Performance(Cont...)

- The equation shows that the dynamic behavior of the compensator is a function of the power system impedance
- Therefore time response, and thus the stability of the control, is dependent on the system impedance

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So, SVC basically changes the power system impedance, therefore time response and thus the stability of the control is depend on the system impedance. So, this is something we require to keep in mind. Now transient stability with this SVC; this transient stability indicates the capability of the power system to recover from the major disturbance.

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Transient Stability Enhancement

- The transient stability indicates the capability of the power system to recover from a major disturbance
- Transient stability at a given power level and fault clearing time is primarily determined by the P versus δ characteristic of the post-fault system
- a static compensator, controlled to regulate the terminal voltage, can increase the transient stability by maintaining the transmission voltage in face of the increased power flow encountered immediately after fault clearing.

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Transient stability at a given power level or the fault clearing time is primarily determined by the power it is actually handling at the moment and the torque angle delta and the post fault system condition. The static compensator controlled to regulate the terminal voltage we have seen that can increase the transient stability by maintaining the transmission line voltage, in the phase of the increased power flow countered immediately after the faults shearing.

So, this is something that is specificant and thus increases the transient stability. This transient stability can be increased further by temporally increasing the voltage, above the regulating regulation reference for the duration of the first accelerating (Refer Time: 18:34) what it will do then, what will happen? Then the voltage increase above its nominal voltage value will increase the electric power transmitted.

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Transient Stability Enhancement(Cont...)

- The transient stability can be increased further by temporarily increasing the voltage above the regulation reference for the duration of the first acceleration period of the machine
- The voltage increased above its nominal value will increase the electric power transmitted and thus will increase also the deceleration of the machine. $V \propto P^2$
- The plot marked $V_m = V$ represents the P versus δ plot obtained with an ideal compensator holding the midpoint voltage constant

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Because you know you have $V \propto P^2$ if V is increasing. So, power handling capability increases and thus increases also the deceleration of the machine. The plot marked $V_m = V$, I shall come now represent the P versus delta power obtained with the ideal compensator holding midpoint voltage constant. So, see that this is the case. So, this is the area and this is the case with the STATCOM and this is the case with the SVC.

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Transient Stability Enhancement(Cont...)

- The plots marked STATCOM and SVC represent these compensators with a given rating insufficient to maintain constant midpoint voltage over the total range of δ

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So, this is the SVC and this is basically the STATCOM. So, the plot marks STATCOM and SVC, this compensator with the given rating insufficient to maintain the constant

midpoint voltage for the total angle delta because this is basically 0 to pi. So, thus it increases the transient stability.

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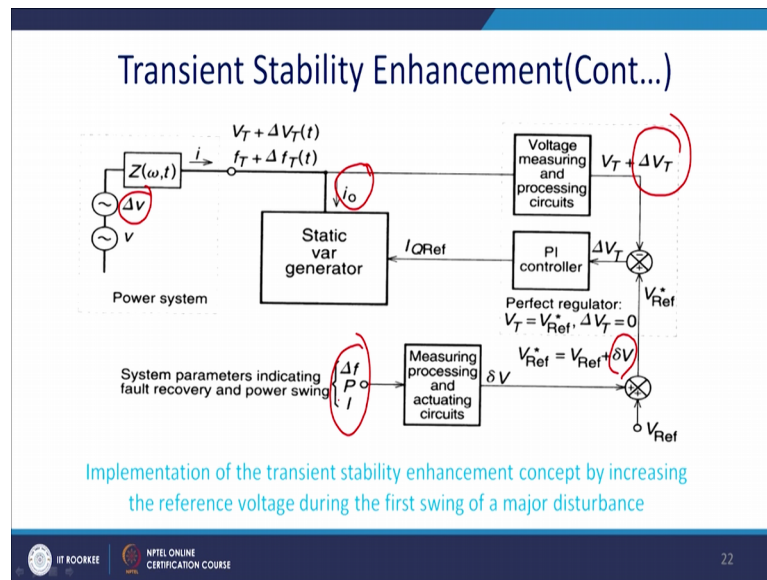
Transient Stability Enhancement(Cont...)

- The implementation of the transient stability enhancement in the basic control scheme, can be accomplished simply by summing a signal δV to the fixed voltage reference signal V_{ref} .
- The signal δV can be derived from the rate of change of transmitted power, line current or system frequency, indicating the angular change of the disturbed machines.

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The implementation of the transient stability enhances the basic control scheme and can be accomplished by simply by summing a signal δV to the fixed voltage reference V_{ref} . This signal δV can be derived from the rate of change of the transmitted power if you see that there is a change of transient part it can be changed. The line current or the system frequency indicating that the angular change of the disturbed machine, from there we can calculate what should be the δV change and thus we can incorporate it let us see that how does it work.

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So, power system with fault so, ΔV has been increased. So, this is basically the change of frequency change of voltage. So, ultimately it will be actually sinking the current i_0 and we have for this reason since it is a ΔV has been increased.

So, we will increase the actually the terminal voltage by Δv . So, ultimately you got a V_{ref} and V_{ref} will be added with the ΔV and thus you know this k will come and the system parameter indicates that you know if fault has recovered. So, from this parameter we can see that fault has recovered. So, a post fault session it can act and compensate first.

So, implementing the transient stability enhancement consent by increasing the reference voltage during the first thing or the major disturbance, will try to help us to establish stabilizes the system shown and ends SVC can or can or restore a system faster; Enlargement features of this actually SVC is definitely the power oscillation damping.

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Power Oscillation Damping

- Power oscillation damping generally requires the variation of the voltage at the terminal of the compensator in proportion to the rate of change of the effective rotor (or power transmission) angle.
- Rotor angle changes, result in frequency and real power variations.
- In practice, usually the variation of the transmitted real power or the system frequency is measured and used for controlling the Var output to produce the terminal voltage variation desired. ✓

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Power oscillation damping we have discussed several time, damping is generally requires the variation of the voltage and the terminal of the compensator in proportional to the rate of change of the effective rotor power angle.



The rotor angle changes and thus what happen results frequency and the real power variations. In practice usually the variation of the transmitted real power or the system frequency is measured and used for controlling the Var output to produce the terminal voltage variation desired.

So, how you will do that?

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Power Oscillation Damping(Cont...)

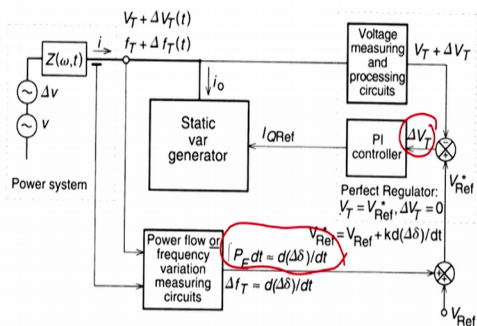
- The functional control scheme for damping power oscillations, in this same general idea of modifying the fixed voltage reference by an auxiliary control signal to derive the effective voltage reference
- Accordingly, a signal corresponding to the variation of the real power or that of the system frequency is summed to the fixed reference voltage signal V_{ref} .
- The added signal causes the output current of the compensator to vary (oscillate) around the fixed operating point to control the terminal voltage so as damp the oscillation



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Function of the control scheme definitely is to damping the power oscillation. In this general idea modifying the fixed voltage reference by auxiliary control signal, to derive the effective voltage reference is voltage reference will change accordingly a signal corresponds to the variation of the real power or that of the system frequency, is summed up with the fixed reference signal. The added signal causes the output current and the compensator to vary or change and on the fixed point to control the terminal voltage and thus it will damp out the oscillation. So, this is the case again you have this thing. So, del V.

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Power Oscillation Damping(Cont...)



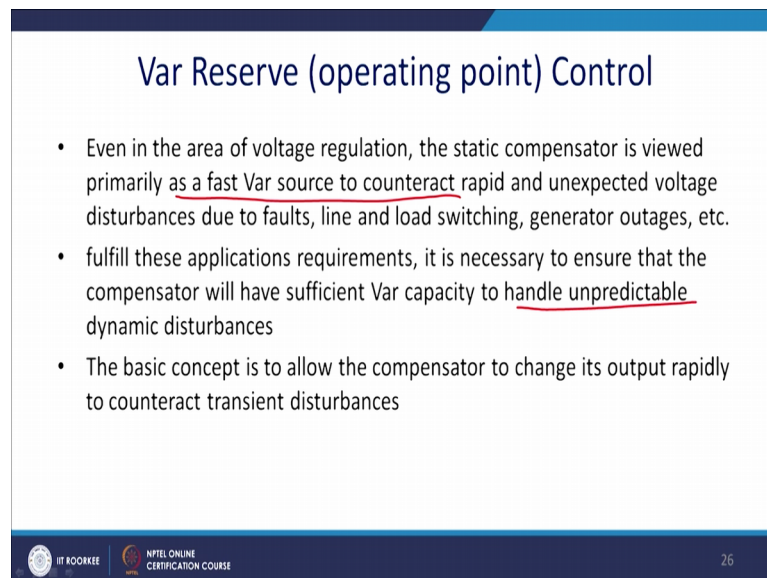
Implementation of power oscillation damping by modulating the reference voltage according to frequency or power flow variations.



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And in this case what will happen? You know actually you will you will add up. So, so basically $P dt$ will increase. So, that ultimately you will add up this. So, that power flow frequency variation circuit it can measure and accordingly. So, you will actually give you will feed the V reference.

So, this will give you a delta change and this delta will be need and varying according to the power oscillation and that value will give you a varying I_Q reference, and that will essentially damp out the oscillation. So, var reserve even in the area of the voltage regulation the static compensator is viewed as primarily as a fast source to counter, counteract the rapid or unexpected voltage disturbance due to fault line load switching etcetera.

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The slide is titled "Var Reserve (operating point) Control" and contains three bullet points. The first bullet point states that the static compensator is viewed as a fast Var source to counteract rapid and unexpected voltage disturbances. The second bullet point states that to fulfill these requirements, the compensator must have sufficient Var capacity to handle unpredictable dynamic disturbances. The third bullet point states that the basic concept is to allow the compensator to change its output rapidly to counteract transient disturbances. The slide footer includes the IIT Roorkee logo, the NPTEL Online Certification Course logo, and the number 26.

Var Reserve (operating point) Control

- Even in the area of voltage regulation, the static compensator is viewed primarily as a fast Var source to counteract rapid and unexpected voltage disturbances due to faults, line and load switching, generator outages, etc.
- fulfill these applications requirements, it is necessary to ensure that the compensator will have sufficient Var capacity to handle unpredictable dynamic disturbances
- The basic concept is to allow the compensator to change its output rapidly to counteract transient disturbances

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To fulfill this application requirement it is necessary, to ensure that the compensator will have sufficient var capability to handle the unpredictable dynamic disturbances. The basic conserve is to allow the compensator to change this output rapidly to encounter this transient disturbance.

So, we require to have a in built var handling capability. A possible scheme to implement the basic var control the magnitude of output current of the compensator is measured and compared against the reference I_Q .

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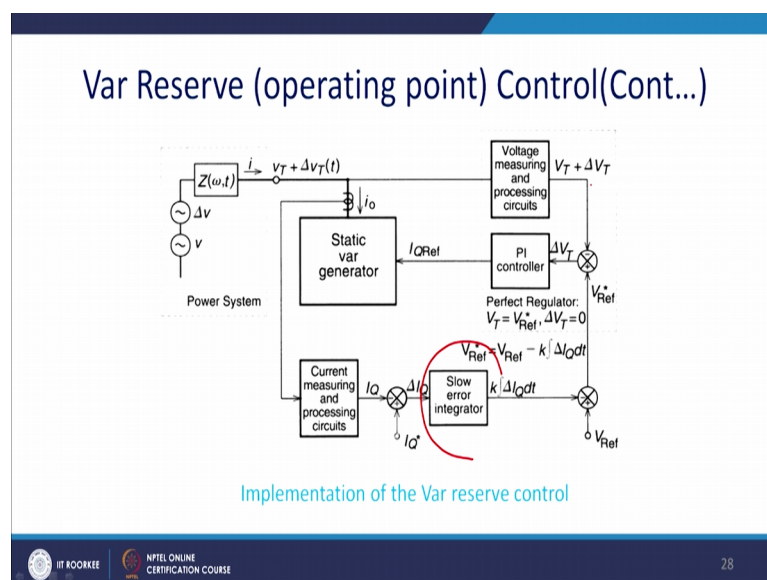
Var Reserve (operating point) Control(Cont...)

- A possible scheme to implement a basic var reserve control, the magnitude of the output current of the compensator is measured and compared against the reference I_Q^* .
- The error signal ΔI_Q is processed by an integrator of large time constant and added to the fixed voltage reference V_{ref} .
- This forces the input signal to the voltage regulator to change until the difference between the actual output current of the compensator and the steady-state output current reference I_Q^* become equal.



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The error signal V_Q is then processed by the integrator of the large time constant and added to the fixed value of the voltage reference what happen then? This forces the input signal of the voltage to regulate to change until the difference between the actual output current and the compensator, and the steady state output current reference become equal. So, this is a way to achieve it.

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So, this is the Var reserve capability and so, what happens is a slow integrator. So, it measures the current you have a I_Q reference. So, it will integrate and the ultimately this

will change the terminal voltage and in that way it will control the reference. Thank you for your attention this is the controlled technique of the SVC, we shall continue with the next class with some control technique of the SVC, thereafter we shall discuss about some entities and amplification of the STATCOM then we shall switch over to the series compensation.

Thank you so much for your attention.