

Flexible AC Transmission Systems (FACTS) Devices
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Lecture - 36
Control Structure of UPFC

Welcome to our lectures on Flexible AC Transmission System. Today we will session continue with a UPFC. So, we have we have started discussion on previous class on the control structure let us continue with it.

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Control Structure

- With suitable controls, the UPFC can cause the series-injected voltage vector to vary rapidly and continuously in magnitude and/or angle as desired.
- It is not only able to establish an operating point within a wide range of possible P, Q conditions on the line, but also has the inherent capability to transition rapidly from one such achievable operating point to any other.
- The control of the UPFC is based upon the vector-control approach
- The term Vector, instead of phasor, is used in this section to represent a set of three instantaneous phase variables, voltages, or currents that sum to zero

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And we have already told that with the suitable control, the UPFC can cause series injected voltage vector to vary rapidly and continuously in magnitude and angle as desired.

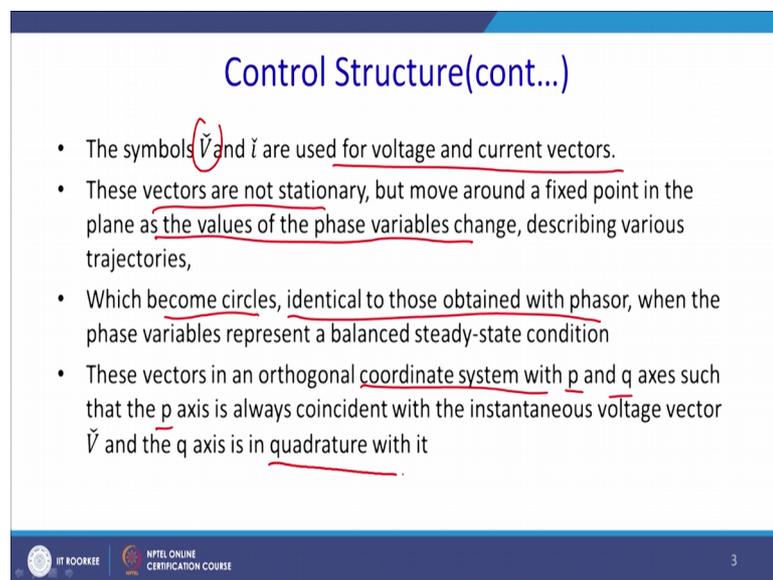
So, it can control by series injections and, voltage and angle it can manipulate by the voltage source converter and accordingly it can change magnitude as well as the phase as desired. So, due to this you know so it is so it can inject both in phase both in actually not only quadrature and phase, in any magnitude and the any angle and thus we have a considerable advantage of UPFC.

It is not only able to establish an operating point, within the wide range of possible P and Q condition on the line, but also it has the inherent capability of transition rapidly from one such achievable operating state to the another such operating state.

So, if you wish to change of power in the transmission line some from the point p 1 to p 2 this device can ensure that it reaches the point in a fastest possible way. So, you can have we have discuss the series different kind of series compensation, they are you know you will cannot independently control P and Q. Here there is a big advantage, you can shift operating point form one P and Q point to another P and Q point and the transmission can be very fast.

The control of the UPFC is based upon the vector control approach that is (Refer Time: 02:46) we since we have take the magnitude and the phase of the voltage, while injecting a particular voltage for this is we called it is a vector control approach. The term vector is used instead of the phasor, in this section to represent the set of instantaneous phase variable these are voltage current and whose sum total sum is actually zero for balanced three phase three wire system.

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Control Structure(cont...)

- The symbols \vec{V} and \vec{i} are used for voltage and current vectors.
- These vectors are not stationary, but move around a fixed point in the plane as the values of the phase variables change, describing various trajectories,
- Which become circles, identical to those obtained with phasor, when the phase variables represent a balanced steady-state condition
- These vectors in an orthogonal coordinate system with p and q axes such that the p axis is always coincident with the instantaneous voltage vector \vec{V} and the q axis is in quadrature with it.

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And the symbols is \vec{V} and \vec{i} used for the voltage and current vectors. You may actually say that it is a contradicting with the fundamental quantities because, you know potential essentially the voltage is a scalar quantity.

But it had advantage of using a vector quantity because, it will be represented by the phase and its magnitude so, you can treat them as a vector quantity per sake of understanding it. This vectors are not stationary and other rotating, but moves around the fixed point in the plane as the values of the phase variable changes, describing desired trajectories.

Which because actually circles if we shall plot the p and q and we will see that actually the locus of control of those UPFC and, thus trajectory can be any conic section ellipse circle and we will see that how it will be generated in few minutes identical to this obtained to the phasor.

When the phase variable is represented by a balance steady state condition, this phase this vectors are an orthogonal coordinate system with p and q axes such that the p axes always coincident with the instantaneous voltage vector V and the q axis with the quadrature with it.

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Control Structure(cont...)

- In this coordinate system the p-axis current component, i_p accounts for the instantaneous real power and the q-axis current component, i_q for the reactive power.
- Under balanced steady-state conditions, the p-axis and q-axis components of the voltage and current vector are constant quantities.
- This characteristic of the described vector representation makes it highly suitable for the control of the UPFC by facilitating the decoupled control of the real and reactive current components.
- The UPFC control system may, be divided functionally into internal (or converter) control and functional operation control.

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In this component in this case coordinate system the p axis current component is actually in phase component that is i_p , accounts for the instantaneous real power and q axis current component, i_q for this reactive power. Under balance steady state condition p axis and the q axis component of the voltage and current vectors are constant quantity.

So, that is thus actually the amount of the p and q , the reactive power in the real power required to be constant. This characteristics of the described vector representations makes it highly suitable for the control of UPFC by facilitating the decoupled control of real and the imaginary power.

So, we shall separate control on p q in real and the imaginary. Thus we are we shall establish the network, the UPFC control system may be divided functionally into internal, or the converter control and the functional operational control.

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Control Structure(cont...)

- The internal controls operate the two converters so as to produce the commanded series injected voltage and, simultaneously, draw the desired shunt reactive current.
- The internal controls provide gating signals to the converter valves so that the converter output voltages will properly respond to the internal reference variables, i_{pRef} , i_{qRef} and V_{pqref} .
- The series converter responds directly and independently to the demand for series voltage vector injection.
- The shunt converter operates under a closed-loop current control structure where by the shunt real and reactive power components are independently controlled.

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They internal control operates the two converters. So, as to produce the commanded series injected by the voltage, simultaneously draw the desired shunt current.

The internal control, providing gating signal to the inverter valve so, that the converter output voltage will be properly respond to the internal reference variable such as i_{pRef} , i_{qRef} and V_{pqref} . This series converter response directly and indirectly to the demand for the series voltage vector injection, shunt converter operates under a closed loop current control structure, where by the shunt real and reactive power components are independently controlled.

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Control Structure(Cont...)

- The shunt real power is dictated by another control loop that acts to maintain a preset voltage level on the dc link, thereby providing the real power supply or sink needed for the support of the series voltage injection.
- i.e the control loop for the shunt real power ensures the required real power balance between the two converters.
- As mentioned previously, the converters do not (and could not) exchange reactive power through the link.
- The external or functional operation control defines the functional operating mode of the UPFC and is responsible for generating the internal references.

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So, what else the shunt real power is dictated by another control loop that acts to maintains to preset the voltage level of the dc link, thereby providing the real power supply of the sink needed to support the series voltage injection. So, you have a another loop that mean the control loop for the shunt real power ensures the required real power balance between the two converters.

As mentioned in base of UPFC q c so, it is same for the UPFC previously the converter does not and exchange the reactive power through the link. The external or the operational functions of the control defines the functionally operating mode of the UPFC and is responsible for generating the internal references. So, this is the actually the control.

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Control Structure(Cont...)

- The functional operating modes and compensation demands, represented by external (or system) reference inputs, can be set manually by the operator or dictated by an automatic system optimization control to meet specific operating and contingency requirements.
- The capability of unrestricted series voltage injection together with independently controllable reactive power exchange offered by the circuit structure of two back-to-back converters, facilitate several operating and control modes for the UPFC.
- These include the option of reactive shunt compensation and the free control of series voltage injection according to a prescribed functional approach selected for power flow control.

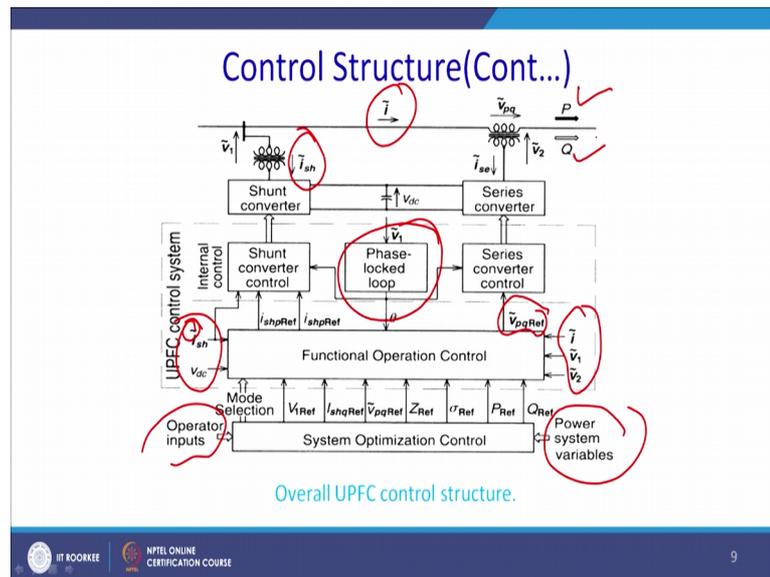
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The functional operating mode and the compensation demands represented by external reference input can be set manually, by the operator or dictated by the automatic system optimization control, either it will be sent by the users or a distinguishes power demand, or you required to optimize your network cost optimization, or the efficiency of optimizations, or loss optimizations.

Control made to specific operating and the contingency requirement. The capability of unrestricted series voltage injections through independently controllable reactive power exchange, offered by the circuit structure of two back to back converter, facilitate several operating and control mode for the UPFC.

This include the option of the reactive shunt compensation and the free control series voltage injection according to a prescribed functional approach selected for the power flow control. So, this is the overall structures of the UPFC that we have discussed already.

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Essentially this is a shunt compensations so, you have actually reference of i_{sh} that required to be injected and, you required to maintain the d c bus voltage and you have a operated inputs. And the power system variables and, you they will fit the data of v_1 reference i_{sh} reference that is p q that is injected voltage reference.

That is a impedance reference conductance reference, power reference, or the reactive power reference. And these are the actual values required to be sensed, you required senses to at least two current or three phase three wire system, mostly your transmission line such three phase three wire.

So, it will be i_{sh} and the V_{dc} and their after you will have to sense the current i at this point as well as the two voltages, v_1 and v_2 assuming that is a three phase three wire system. So, from their actually we have a phase lock loop that will generate the actually the theta and ultimately it will be converted to the actually a b c to d q frame so, that it can be totally decoupled.

And thus the control reference will generate the different kind of getting signals and that will affect to the shunt converter. So, that actually it sinks or provide the current i_{sh} at the constant voltage of v_1 . And similarly the p q reference which is has been calculated it will be injected here in series so, that you can transfer in desired level of p and q to the system.

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Functional Control of the Shunt Converter

- The shunt converter is operated so as to draw a controlled current, i_{sh} from the line.
- One component of this current, i_{shr} is automatically determined by the requirement to balance the real power of the series converter.
- The other current component, i_{shq} is reactive and can be set to any desired reference level (inductive or capacitive) within the capability of the converter.
- The reactive compensation control modes of the shunt converter are, very similar to those commonly employed for the STATCOM and conventional static var compensator.

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So, from this understanding we can say that shunt converter is operating so, as to draw a control i_{sh} from the line, it has a two component mainly, it is mainly makes a mainly actually the reactive power component of the current that is been provided.

The component of this current i_{sh} is automatically determined by the requirement of the balanced real power of the series converter. The other current i_{shq} is a reactive component of the load current, reactive component and can be set to any desired reference level, inductive or capacitive within the capability of the converter.

The reactive compensation control modes of the shunt converter are very similar to those commonly employed for the STATCOM and the conventional static var compensator. And let us see how it will control the P and Q. So, that is actually reactive this is basically Q control. Similarly we have P control in this mode the reference input is an inductive, or the capacitive var request mostly it is inductive.

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Functional Control of the Shunt Converter(Cont...)

Reactive power control mode 

- In this mode the reference input is an inductive or capacitive Var request.
- The shunt converter control translates the Var reference into a corresponding shunt current request and adjusts the gating of the converter to establish the desired current.
- The control in a closed-loop arrangement uses current feedback signals obtained from the output current of the shunt converter to enforce the current reference.
- A feedback signal representing the dc bus voltage, V_{dc} is also used to ensure the necessary dc link voltage.

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The shunt converter controls translate the var reference into a corresponding shunt current required requests and, adjust the gating converter to establish the desired current. The control in a closed loop arrangement uses current feedback, signals obtained from the output currents of the shunt converter to enforce the current reference.

The feedback signal representing the dc bus voltage V_{dc} is also used to ensure necessary dc link voltage.

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Functional Control of the Shunt Converter(Cont...)

Voltage control mode

- In voltage control mode (which is normally used in practical applications),
- The shunt converter reactive current is automatically regulated to maintain the transmission line voltage to a reference value at the point of connection, with a defined droop characteristic.
- The droop factor defines the per unit voltage error per unit of converter reactive current within the current range of the converter.
- The voltage control uses voltage feedback signals, usually representing the magnitude of the positive sequence component of bus voltage \vec{V}_1 .

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Now, we have a voltage mode control, we generally current is the shunt in case of the voltage mode control let us see, the voltage mode control which is normally used, in all practical applications. Shunt converter reactive current is automatically regulated to maintain the transmission line voltage reference.

So, it will inject the reactive power value at a point of the connections or point of common coupling generally we say, with a definite droop characteristics. The droop factor defines the per unit voltage error per unit voltage per unit voltage error per unit of the converter reactive current, within the current range of the converter. Voltage control uses voltage feedback signals, usually representing the magnitude of the positive sequence component of the bus voltage v_1 .

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Functional Control of the Series Converter

- The series converter controls the magnitude and angle of the voltage vector \vec{v}_{pq} injected in series with the line.
- This voltage injection is directly or indirectly, always intended to influence the flow of power on the line.
- \vec{v}_{pq} is dependent on the operating mode selected for the UPFC to control power flow.

Direct voltage control mode

- The series converter simply generates the voltage vector, \vec{v}_{pq} , with the magnitude and phase angle requested by the reference input.

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This series converter controls the magnitude and the angle vector v_{pq} injected in series with the line. The voltage injection is directly or indirectly always intended to influence the flow of the power on the line, v_{pq} is dependent on the operating mode selected for the UPFC control flow.

The direct voltage control mode there is a one case that is called direct voltage control mode, series converter simply generate the voltage factor that is $p q$ with the magnitude and the phase angle requested by the reference input.

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Functional Control of the Series Converter(Cont...)

- This operating mode may be advantageous when a separate system optimization control coordinates the operation of the UPFC and other FACTS controllers employed in the transmission system.
- Special functional cases of direct voltage injection include those having dedicated control objectives,
- E.g when the injected voltage vector, v_{pq} is kept in phase with the system voltage for voltage magnitude control, or
- In quadrature with it for controlled "quadrature boosting," or
- In quadrature with the line current vector, to provide controllable reactive series compensation.

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The operating mode may be advantageous, when the separate system optimization control coordinates with operations with the UPFC and, other FACTS controllers employed in the transmission system. Special functional cases of direct voltage injections include those having dedicated control objectives.

When the injected voltage factor v_{pq} is kept in phase with a system voltage for the voltage magnitude control; or in quadrature with the controlled "quadrature boosting"; Or the quadrature with the line current vector to provide controllable reactive power compensation.

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Functional Control of the Series Converter(Cont...)

Bus voltage regulation and control mode

- The injected voltage vector, \tilde{v}_{pq} , is kept in phase with the "input" bus voltage vector \tilde{v}_1 and its magnitude is controlled to maintain the magnitude "output" bus voltage vector \tilde{v}_2 at the given reference value.

Line impedance compensation mode

- The magnitude of the injected voltage vector \tilde{v}_{pq} , is controlled in proportion to the magnitude of the line current, i ,
- So that the series insertion emulates an impedance when viewed from the line

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Bus voltage regulation control mode the injected voltage vector p q is kept in phase with the input bus voltage vector v 1 and, it is magnitude is controlled to maintain the magnitude output.

But voltage vector v 2 at the given reference value, line impedance compensation mode the magnitude of the injected voltage vector v q is controlled in proportional to the magnitude of the line current i. So, that the series insertion emulates and impedance when viewed from a line.

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Functional Control of the Series Converter(Cont...)

- The desired impedance is specified by reference input and in general, it may be a complex impedance with resistive and reactive components of either polarity.
- A special case of impedance compensation occurs when the injected voltage is kept in quadrature with respect to the line current to emulate purely reactive (capacitive or inductive) compensation.
- This operating mode may be selected to match existing series capacitive line compensation in the system.

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The desired impedance is specified by the input in general, it may be a complex impedance with resistive and the capacity resistive and, the reactive component of either polarity. The special case of the impedance compensation occurs, when injected voltage is kept in quadrature, with respect to the line current to emulate purely reactive that is capacitive or the inductive compensation.

This operating mode may be selected to match the existing series capacitive and, the line composition of the system mode. So, both can be coupled together, another is actually the phase angle regulation mode you can this UPFC can acts as a p r.

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Functional Control of the Series Converter(Cont...)

Phase angle regulation mode

- The injected voltage vector \vec{v}_{pq} is controlled with respect to the input bus voltage vector \vec{v}_1 ,
- so that the output bus voltage vector \vec{v}_2 , is phase shifted, without any magnitude change, relative to \vec{v}_1 , by an angle specified by the reference input.
- One special case of phase shifting occurs when \vec{v}_{pq} is kept in quadrature with \vec{v}_1 , to emulate the "quadrature booster."

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So, injected voltage the p q is controlled with respect to the input bus vector v 1 so, that the bus voltage v 1 is phase shifted without any change in magnitude, relative to v 1 by an angle specified by the reference input. One special case of the phase shifting occurs, when p q is kept in quadrature with v 1 to emulate the quadrature booster, that we have already discussed in case of the series compensation.

Now, this is the power flow control, we want that actually amount of the power flows to the line can be controlled by the UPFC. Thus it is automatic power flow control mode.

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Functional Control of the Series Converter(Cont...)

Automatic power flow control mode ✓

- The magnitude and angle of the injected voltage vector, \vec{v}_{pq} is controlled so as to force such a line current vector i , that results in the desired real and reactive power flow in the line.
- In automatic power flow control mode, the series injected voltage is determined automatically and continuously by a closed-loop control system to ensure that the desired P and Q are maintained despite power system changes ✓
- This operating mode, which is not achievable with conventional line compensating equipment, has far reaching possibilities for power flow scheduling and management
- It can also be applied effectively to handle dynamic system disturbances (e.g., to damp power oscillations)

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The magnitude and the angle injected by the voltage vector p q is controlled so, control as to force that the line current vector i , result in the desired real and the reactive power flow through the UPFC. In automatic power flow control mode, the series injected voltage is determined automatically and, continuously by a closed loop control system to ensure that the desired p q are maintained despite power system changes.

That is something we required to too. The operating mode which is not achievable with conventional, line compensating equipments has power reaching possibilities, for power flow scheduling and management because, it can dynamically control the flow of the power into the system. It can be applied effectively to handle dynamic system disturbances and, dynamically tamp out the oscillations and a transient stability. So, these are the cases it is found to be very suitable.

Now, so let us discuss the basic control systems for the p q control how you do it, we shall first discuss it there after will show you the control technique.

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Basic Control System for P and Q Control

- The UPFC has many possible operating modes.
- But only the automatic power flow control mode, providing independent control for real and reactive power flow in the line.
- This control mode utilizes most of the unique capabilities of the UPFC and it is expected to be used as the basic mode in the majority of practical applications, just as the shunt compensation is used normally for automatic voltage control. ✓
- Accordingly, block diagrams giving greater details of the control schemes are shown for the series converter and for the shunt converter.
- The control scheme shown assumes that the series converter can generate output voltage with controllable magnitude and angle at a given dc bus voltage

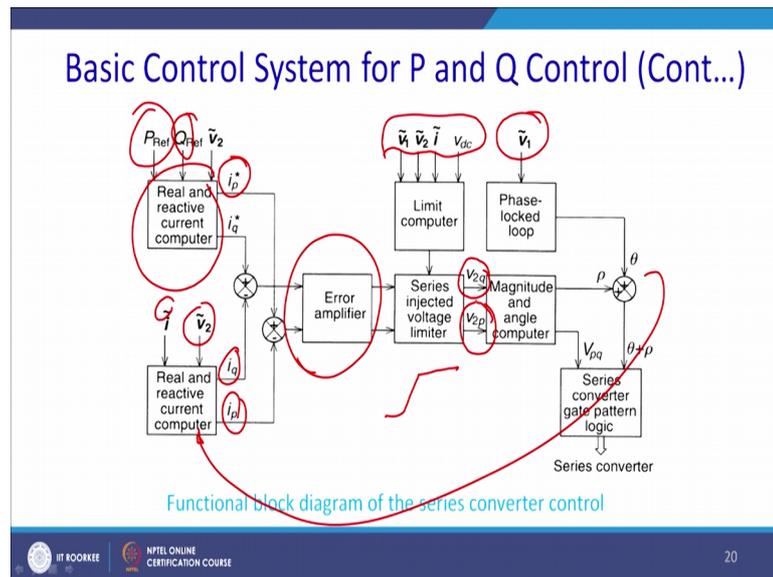
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The UPFC has many operating mode that we have already mentioned so, but only automatic power flow mode of control providing independently control of real and the reactive power flow in the line. So, independently you can control P and Q.

This is control mode utilizes the most of the unique capabilities of the UPFC. And it is expected to be used as a basic mode of the majority of the practical applications, such that shunt compensation is used normally for the automatic voltage control. Accordingly we shall show the block diagram having a greater details of the control schemes, as shown in the series converter and the shunt converter.

The control scheme shown assume that the series converter can generate the output voltage, with controllable magnitude and phase angle given by the d c bus voltage. So, this is the control P Q control.

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So, you have either you have a automatic control, or the customers or the administrator will actually set this things, these are v_1 P reference and the Q reference. And thus you will you will sends that actually the sending and voltage v_1 .

And so, there is a block will be will be calculating i_p^* that is i_p reference and the i_q reference and, you have actual values of i_n v_2 from there you can calculate the actual value of P and P Q. So, you will be mostly it is generally done by the p l l and make it a dc quantity thus actually p become d and q generally written as a q as a nomenclature.

So, now it will be fitted to the error amplifier, error amplifier is essentially and PI controller PID controller in most of the applications. So, there will be a voltage limiter because error can go very high and low. So, you have to truncate the error and, it will take these input also from the senses there is a sending end voltage, actual receiving end voltage and i.

So, these are the based on that these two calculations will be made and, will compare and from there actually it will estimate, that value of the V_p and V_q of required to be injected by the series injector.

And you will have a phase lock loop, you can have a phase lock loop to be fitted here also and, then it will become all is operating in a d q mode otherwise, it can go like this. Magnitude and the phase angle of the computer basically it will check the magnitude V_q

and the V_p and angle and $\tan \phi$ will be basically, $\tan \phi$ will be will basically P_q by V_p .

And you will add the phase with it, or then you have to convert it into the and thus you get a p_q with an angle to be injected that is $\theta + \phi$ so, this voltage will be injected by the your series regulator, this the control of your automatic power flow control.

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Basic Control System for P and Q Control(Cont...)

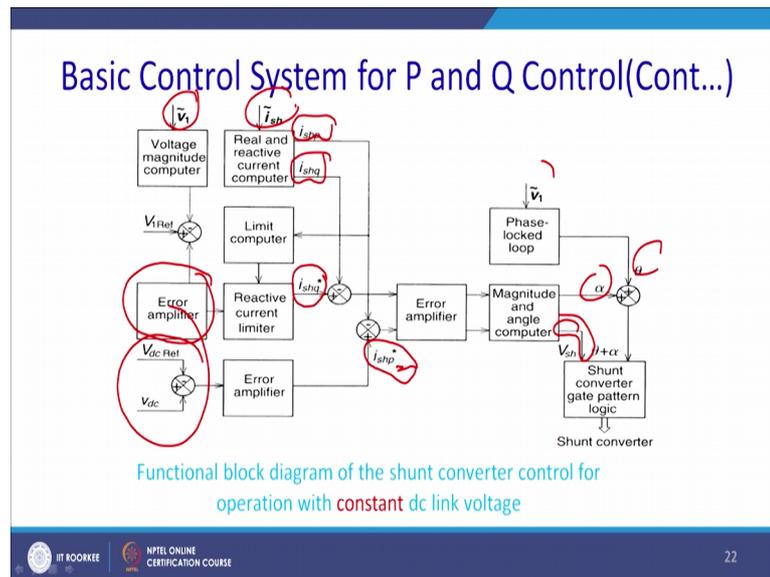
- The control scheme for the shunt converter also assumes that the converter can generate output voltage with controllable magnitude and angle. ✓
- However, this may not always be the case, since the converter losses and harmonics can be reduced by allowing the dc voltage to vary according to the prevailing shunt compensation demand. ✓
- Although the variation of the dc voltage inevitably reduces the attainable magnitude of the injected series voltage when the shunt converter is operated with high reactive power absorption, in many applications this may be an acceptable trade-off ✓

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So, the control schemes for the shunt active power filter assume, that the converter can generate output voltage with controllable magnitude and angle however, this is not always the case. Since the converter losses and the harmonic can reduce the allowing the dc level voltage, dc link voltage to vary according to the prevailing the shunt compensation demand. So, we have to actively compensate the d c link voltage.

Although the variations of the dc link voltage inevitably reduce, the attainable magnitude of the injected series voltage, when the shunt converter is operated with high reactive power absorption, in many application this may be acceptable trade off. So, we have to set a limit on it. So, this is the actually the basic control of the P Q.

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And this is the sense voltage v_1 of the sending end voltage and the voltage magnitude and, you will have a V_{ref} so, for their you got a error of the PI controller and you have to maintain the dc link voltage. So, this $V_{dc,ref}$ minus V_{dc} minus so, you got an error amplifier and, this is for to meet the losses due to harmonics and the switches.

And this will be the reactive power and, ultimately this value will be the i_{shq} this is a shunt part of the system. And thus you compute the i_{sh} the reactive power component of the computer assuming that we have predominantly reactive power.

So, you have i_{shp} and i_{shq} so, this i_{shp} in phase component will be added to the loss component of it. So, ultimately it will give i_{shp} and both will be fitted to the error amplifier and, from there we will compute the magnitude of it.

And you have a phase lock loop from phase lock loop will compute θ and, this α then this θ and α will be added, to give the desired the phase shift and, ultimately this current will be converted to the V_q balance voltage of v_{sh} 's and you will be fit that logics into the converter to compensate for the shunt compensation.

Thank you for your attention I will continue to next lecture with UPFC.