

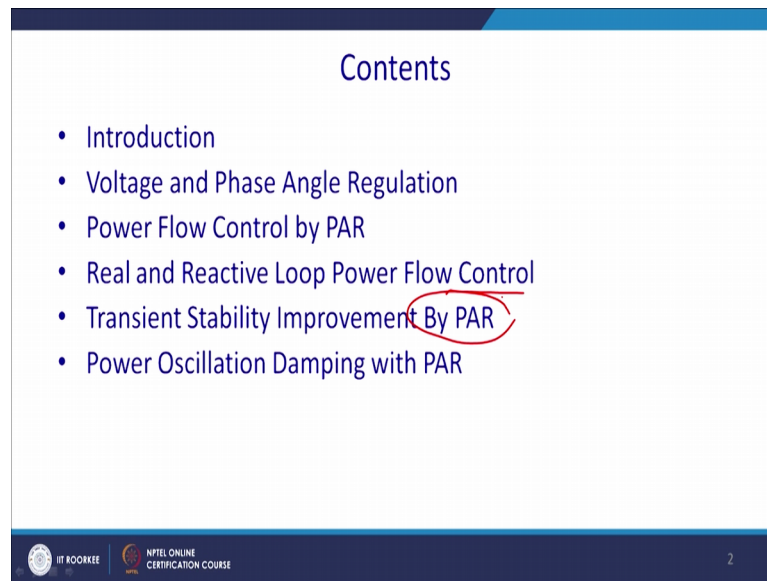
Flexible AC Transmission Systems (FACTS) Devices
Dr. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Roorkee

Lecture – 28
Voltage and Phase Angle Regulation

Welcome to our lecture of the Flexible AC Transmission System. Today, we are going to discuss a new topic, that is Voltage Phase Angle Regulation or the in abbreviation we shall use the term phase angle V P R or P A R.

So, our discussion will be based on the understanding of the P A R, that is the introduction followed by the voltage and the phase angle regulation functioning and the power flow of phase angle regulator that is P A R reactive and the real power loop of and the power flow.

(Refer Slide Time: 01:09)



Contents

- Introduction
- Voltage and Phase Angle Regulation
- Power Flow Control by PAR
- Real and Reactive Loop Power Flow Control
- Transient Stability Improvement By PAR
- Power Oscillation Damping with PAR

IIT ROORKEE NPTEL ONLINE CERTIFICATION COURSE 2

And, the reactive power flow control then the transient stability improvement by P A R that is same we have discussed for the series and shunt and we are continue with the also with this P A R, and the power angle oscillation also with the phase angle regulator.

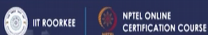
So, why we choose phase angle regulator?

(Refer Slide Time: 01:42)

Introduction

$\frac{V_1 V_2}{X} \sin \delta = P$

- The transmitted real power, P , and reactive line power, Q , are a function of the transmission line impedance, the magnitude of the sending- and receiving- end voltages, and the phase angle between these voltages.
- All ready discussed series reactive compensation which can be a highly effective means to control power flow in the line as well as improving the dynamic behavior of the power system
- Series reactive compensation is generally highly effective for power flow control, but it can be impractical or economically not viable for some application

 3

Essentially you know that sending an voltage receiving in voltage by X into $\sin \delta$ is the power sent through the transmission line. So, instead of you have advantage and disadvantage of both of course, you can increase the sending n power by changing the actually the voltage V_1 or V_2 or X that we have seen in case of the series compensation real power, but we can also do the same thing by changing the delay angle α , delay angle δ , and thus power can be enhanced or decreased as you wish by not touching other parameters line V_1 V_2 and X .

The transmitted so, the transmitted real power P and the reactive power line Q , are the function of the transmission line impedance, the magnitude of the sending and then the receiving end voltage and the phase angle between these voltages.

So, now we shall deal with this part that is phase angle, already we have discussed the series compensation which will which can be highly effective by means of the power flow in the line as well as the improving the dynamic behavior of the transmission line of the power system. And, this series reactive compensation is generally highly effective for the power flow control, but it is impractical or you know you know or economically non-viable on non-economical for some applications.

So, where you actually you have to increase the power rating of the devices and you require to have a different devices with a high power rating problem involves, control of the real and reactive power flow in a meshed network.

(Refer Slide Time: 03:54)

Introduction (Cont...)

- Problems involve the control of real and reactive loop flows in a meshed network.
- The solution to these types of problems usually requires the control of the effective angle.
- Apart from steady-state voltage and power flow control, the role of modern voltage and phase angle regulators with fast electronic control can also be extended to handle dynamic system events
- As compared to reactive compensators, voltage and phase angle regulators bring a new element to the control of dynamic events, the capability to exchange real power

IIT ROORKEE NPTL ONLINE CERTIFICATION COURSE 4

So, there actually you have to find it out where the maximum sag occurs and have to compensate that, solution of this type problem requires the control of the effective angle delta it is not that V and X you have to control the delta. Apart from the steady state voltage and the power control the role of the modern role of this phase angle regulator with a fast electric control can also be extended to handle the dynamic system events like oscillation falls, sub synchronous reactance all those.

As compared with the reactive compensator, voltage and the phase angle regulators, brings a new element to the control dynamics event and the capability of this power lines and with this enhance. So, it is a one of the new member and it has shows a huge potential to increase the or effectively control the power handling capability of the transmission line.

(Refer Slide Time: 05:22)

Voltage and Phase Angle Regulation

$\delta \rightarrow (\delta \pm \sigma)$

- The basic concept of voltage and phase angle regulation is the addition of an appropriate in-phase or a quadrature component to the prevailing terminal voltage in order to change (increase or decrease) its magnitude or angle to the value specified (or desired).
- Thus, voltage regulation could, theoretically, be achieved by a synchronous, in-phase voltage source with controllable amplitude, $\pm \Delta V$ in series with the ac system
- An adjustable voltage is provided by means of a tap changer from a three-phase (auto) transformer for the primary of a series insertion transformer

IIT ROORKEE | NPTEL ONLINE CERTIFICATION COURSE | 5

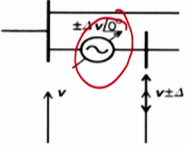
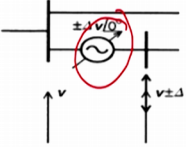
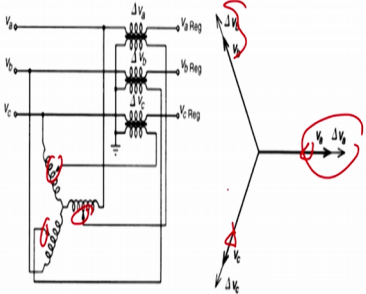
Now, what is the concept the basic concept of the voltage angle regulator is addition of the appropriate phase angle. So, you got a delta; delta will be modified by delta plus sigma or minus sigma that is that is what you wanted to do, appropriate in phase or adequate quadrature component to the prevailing terminal voltage in order to in order to change increase or decrease the magnitude or the angle of the value is specified or desired. Thus the voltage regulation could theoretically be achieved by a synchronous in phase voltage source with controlled amplitude plus minus delta V in the series with a c system.

An, adjustable voltage is provided by means of the tap changing 3 phase auto transformer for the primary series injections or insertion of the transformer, we shall see this circuit here.

(Refer Slide Time: 06:30)

Voltage and Phase Angle Regulation (Cont...)

- From the arrangement it is evident that injected voltages $\pm \Delta V_a, \pm \Delta V_b, \pm \Delta V_c$, are in phase with the line to neutral voltages V_a, V_b, V_c , respectively



The diagram illustrates a three-phase voltage regulator. It shows three transformer windings connected to the three phases (A, B, C). The injected voltages $\Delta V_a, \Delta V_b, \Delta V_c$ are shown to be in phase with the line-to-neutral voltages V_a, V_b, V_c . A phasor diagram shows the line-to-neutral voltages V_a, V_b, V_c and the injected voltages $\Delta V_a, \Delta V_b, \Delta V_c$ all in phase. A simplified circuit diagram shows a line-to-neutral voltage V and an injected voltage $\pm \Delta V$ in phase.

IIT ROORKEE | NPTEL ONLINE CERTIFICATION COURSE | 6

So, this is the in phase voltage regulator. So, what happens you have the actually step changing or auto transformer. So, from there you will tap this thing and ultimately you will add up a voltage in phase.

So, what happens the transmission capability increases and same way you can actually reduce the phase? So, you can add up $\Delta V_a, \Delta V_b, \Delta V_c$ for this arrangement it is evident that, injected voltage $\Delta V_a, \Delta V_b$ and ΔV_c are in phase with the line to the neutral voltage V_a, V_b, V_c . So, you can actually have a voltage regulator, which can inject the voltage or take out the voltage in the same phase.

So, it will be add up or decrease it will add up or decrease the same amount. And, you can have a quadrature voltage regulator; let us understand how can you make a quadrature it is very simple you know, actually all are wanted in phase shift it is V_a this is V_b and this is V_c .

(Refer Slide Time: 07:44)

Voltage and Phase Angle Regulation (Cont...)

- similar manner, the arrangement can be used for phase angle control simply, i.e the injected voltage ΔV , to have a phase of $\pm 90^\circ$ relative to the system voltage V

7

If, I want to make this voltage which is actually perpendicular to the V so, ultimately you just these is minus V_c and take the resultant of it and scale it. So, you know actually V_c if you inject V_c in phase a that will be leads to the 90 degree phase shift same way for the other phase, that is what it is been done here? You know actually this is the V_a and this is the ΔV_a and what happen you will you can add this phase here and here you can add this phase here and here. And so, that you can have this 3 voltages, ultimately you have to see that you know when you are it is in a star combination it is in a delta combinations.

So, ultimately it will have a 30 degree phase shift. So, this will lead to the 60 degree phase shift or the voltages and ultimately you get a voltages at quadratures of the current. So, ultimately A B C so, this is point is A. Similar manner the arrangement can be made used for the phase angle control that mean the injected voltage ΔV to have a phase of 90 degree relative to the system voltage. And, this is the combination with the line you will have a 90 degree phase.

(Refer Slide Time: 09:45)

Voltage and Phase Angle Regulation (Cont...)

- For relatively small angular adjustments, the resultant angular change is approximately proportional to the injected voltage, while the voltage magnitude remains almost constant.
- for large angular adjustments, the magnitude of the system voltage will appreciably increase and, for this reason, is often referred to as a quadrature booster transformer (QBT)
- QBT arrangement has typically been used in conventional phase shifting applications.

AS e ind

IIT ROORKEE NPTEL ONLINE CERTIFICATION COURSE 8

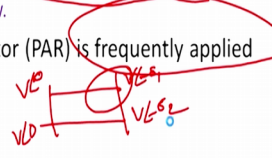
For relatively small angle adjustment the resultant angle angular change is approximately proportional. So, in when δ and $\sin \delta$ is almost same or that the, this value change rather. So, then the result the angular change is proportional to the injected voltage while the voltage magnitude remains almost constant.

So, this value will change. For large angle adjustment then voltage will change the magnitude of the system voltage will appreciably increase or decrease for this reason this often referred to as a quadrature boost transformer, generally it is enhanced. So, we shall use this term very frequently Q B T and it is may this typically has been used in conventional phase shifting application power flow control by Phase Angle Regulator or PAR.

(Refer Slide Time: 10:59)

Power Flow Control by PAR

- The optimal loading of transmission lines in practical power systems cannot always be achieved at the prevailing transmission angle.
- Example
 1. when power between two buses is transmitted over parallel lines of different electrical length
 2. when two buses are inserted whose prevailing angle difference is insufficient to establish the desired power flow.
- In these cases a Phase Angle Regulator (PAR) is frequently applied



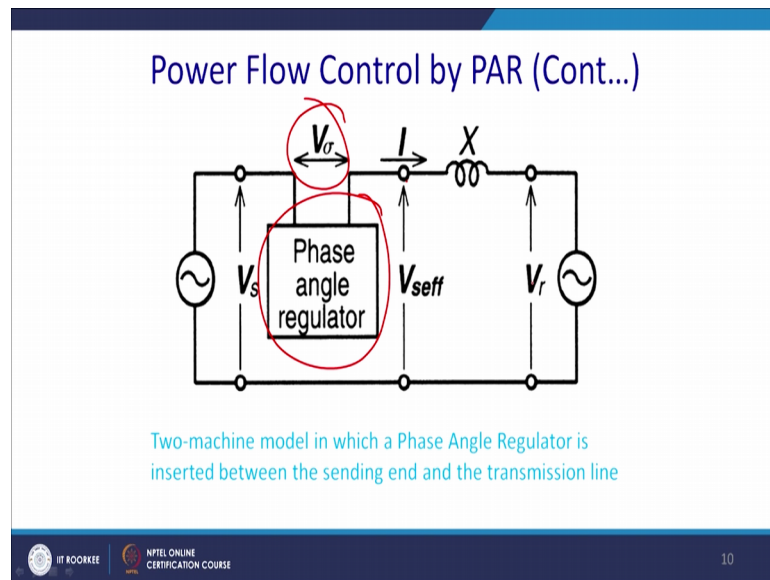
IIT ROORKEE NPTEL ONLINE CERTIFICATION COURSE 9

So, the optimal loading of the transmission line in practical power system cannot be achieved due to the following reason mostly the delta we have a limitation on the delta, achieve at the prevailing transmission line. For example, when power between the 2 buses is transmitted over the power lines of different electrical length, it is sometime difficult to have the same electrical even though they are coming from the 2 points.

Then, 2 buses are inserted whose prevailing phase difference is insufficient to establish the desired power flow. So, one will supply power angle delta minus 1 assume that it is 0 that this is reversed and if it is V_0 it will be minus delta 2. So, there you require to have a phase correction.

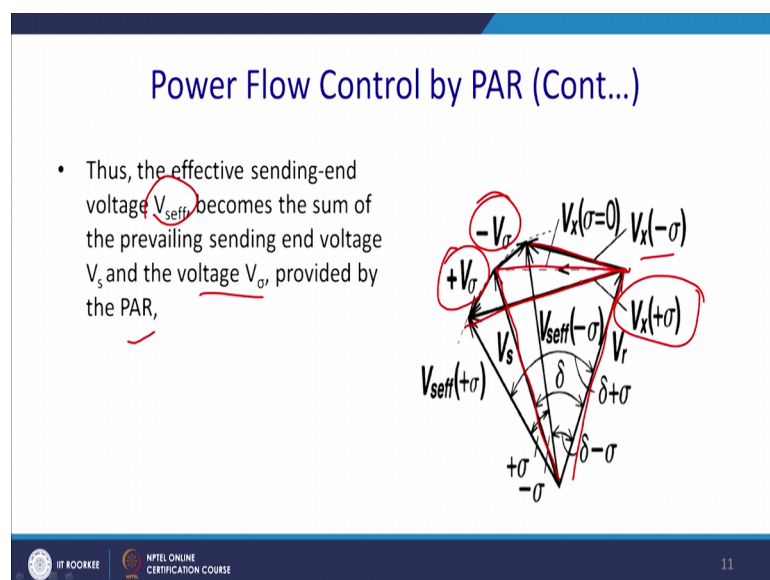
And the 2 buses inserted prevailing the angle difference of insufficient to establish a desired power flow, because someone will carry more current and someone will carry the less current. In this cases phase angle regulator or par is frequently applied to actually make this there phase voltage this angle sign.

(Refer Slide Time: 12:40)



So, thus this is the 1 line diagram of P A R in the from the 2 machine model this is the supply voltage in between you have a phase angle regulator and that will actually change the phase angle by sigma. So, ultimately it will inject the sigma and thus this is the sending an effective voltage after the phase sigma, and you got a X and you got a r. So, this is the way of representation of P A R.

(Refer Slide Time: 13:11)



Now, how does it work let us understand the phasor, phasor of P A R, the effective sending an voltage V s effective becomes sum of the prevailing sending end and the V s voltage and that is sigma is provided by the P A R.

So, what happened let us assume that this was your initial V s and this was your initial V r, and you can add or subtract V sigma with that supply voltage and thus effectively you can make it minus sigma or plus sigma.



And, ultimately V X is a k s where it is sigma is added and V X is the case where sigma is subtracted and V X is the case, where actually you have the when actually it is uncompensated V sigma equal to 0.

(Refer Slide Time: 14:36)

Power Flow Control by PAR (Cont...)

- The basic idea behind the independent angle regulation is to keep the transmitted power at the desired level, independent of the prevailing transmission angle δ .
- In this the power can be kept at its peak value after angle δ exceeds $\pi/2$,
- By controlling the amplitude of quadrature voltage V, so that the effective phase angle $(\delta - \sigma)$ between the sending and receiving-end voltages stays at $\pi/2$
- In PAR the transmitted power P and the reactive power demands at the ends of the line

$$P = \frac{V^2}{X} \sin(\delta - \sigma) \text{ and } Q = \frac{V^2}{X} (1 - \cos(\delta - \sigma))$$

 IIT KHARAGPUR
  NIPTEL ONLINE CERTIFICATION COURSE
 12

So, from this understanding of the phasor the basic idea behind the independent angle regulation is to keep the transmitted power at desired level, independent of the prevailing transmission angle delta. In this power can be kept at the peak value after the angle delta decreases by pi by 2 by controlling the amplitude of quadrature voltage V. So that, the effective phase angle sigma minus delta between the sending and the receiving end voltage stage as pi by 2. The P A R the transmitted power P and the reactive power demands at the receiving line will change in this fashion.

So, you had P that is V square by X sin delta in this case it becomes delta minus sigma and the reactive power also changes V square by X 1 minus cos delta minus sigma.

(Refer Slide Time: 15:57)

Power Flow Control by PAR (Cont...)

- The Phase Angle Regulator does not increase the transmittable power of the uncompensated line.
- It makes to keep the power at its maximum value at any angle δ in the range $-\pi/2 < \delta < \pi/2 + \sigma$
- Results, shifting of P versus δ curve to the right.
- The P versus δ curve can also be shifted to the left by inserting the voltage of the angle regulator with an **opposite polarity**

Relationships between real power P, angles δ and σ

13

The phase angle regulator does not increase the transmittable power of the uncompensated line please understand that angle does not increase the value of the P_{max} , but it can shift the P_{max} . So, it was uncompensated line. So, that here it is $\pi/2$, but you have added σ . Now new power will come at this point, and within the region you know there are it can change the maximum power. The, it makes or keep the power at a maximum value at any δ that is the advantage. So, you can make the power maximum and even 30 degree even at 45 degree even some other values.

So, these ranges to actually σ should be less than $-\pi/2$ to $+\pi/2$, and that is actually the range for σ the result shifting P versus δ curve to the right will what will happen. So, you can increase the delay angle the P versus δ curve can also be shifted to the left side by inserting voltage to the angle regulating in a opposite polarity. So, you can shift to plus σ voltage this way you can get this voltage by injecting minus V_c .

(Refer Slide Time: 17:43)

Power Flow Control by PAR (Cont...)

- If the angle of phasor V_s relative to phasor V_σ , is stipulated to be fixed at $\pm 90^\circ$, the Phase Angle Regulator becomes a Quadrature Booster (QB),

$$V_{seff} = \sqrt{V^2 + V_\sigma^2}$$

- For a Quadrature Booster type angle regulator the transmitted power P

$$P = \frac{V^2}{X} \left(\sin\delta + \frac{V_\sigma}{V} \cos(\delta) \right)$$

The graph shows the power P on the y-axis versus the phase angle δ on the x-axis. The x-axis is marked at 0 , $\pi/2$, and π . Several curves are plotted for different values of V_σ : $V_\sigma = 1.0$, $V_\sigma = 0.66$, $V_\sigma = 0.33$, $V_\sigma = 0$, $V_\sigma = -0.33$, $V_\sigma = -0.66$, and $V_\sigma = -1.0$. The curves for positive V_σ are shifted to the left, and the curves for negative V_σ are shifted to the right. Handwritten red circles and arrows indicate these shifts. The equation $P = \frac{V^2}{X} \left(\sin\delta + \frac{V_\sigma}{V} \cos(\delta) \right)$ is written above the graph and circled in red.

Now, let us see the characteristics of the P A R if the angle of the phasor V_s relative to the V_σ is stipulated to be fixed at plus 1 90 degree. So, you have a 90 degree injection.

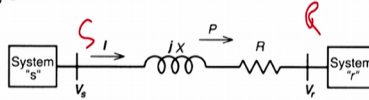
The phase angle regulator becomes quadrature boost so, QB. So, effective voltage becomes $V^2 + V_\sigma^2$ or quadrature boost type angle the regulator of the transmitted power have this logic $V^2 \sin\delta + V_\sigma V \cos\delta$. And, thus this will be the power curve real power curve and this is for $V_\sigma = 1$, this is for $V_\sigma = 0.66$ for this $V_\sigma = 0.66$, in this case voltage also increases because it increases the sending in voltage.

So, this is the case and this is the case for $V_\sigma = 0$. Similarly, this is the case for $V_\sigma = -1$ and this is the case of the $V_\sigma = 1$, if you make it minus if it make it V_σ plus this curve will shift in left hand side and if you make it V_σ minus curve will shift to the right hand side.

(Refer Slide Time: 19:18)

Real and Reactive Loop Power Flow Control

- In contrast to the previously investigated reactive shunt and series compensation schemes, the phase angle regulators generally have to handle both real and reactive powers
- Consider two power systems "s" and "r" connected by a single transmission with reactance X and resistance R.
- The transmission of power P from "s" to "r" results in a difference in magnitude between the terminal voltages V_s and V_r and also a shift in phase angle

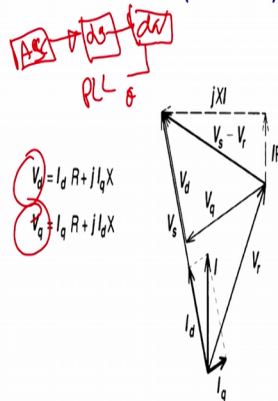


So, the contrast in contrast to the previously investigated shunt and the series compensation scheme, it has a major advantage the phase angle regulator generally have to handle both real and the reactive power in same manner. So, it has a property that it can handle the active as well as real power consider the 2 machine system same thing we have discussed. So, s and r connected by a single transmission with reactant s and the resistor r. The transmitted power P from "s" to "r" results in a difference in magnitude between the terminal voltage V_s and V_r and also a shift in phase angle. The factorial or the pressure representation of the voltage difference $V I$ is given by V_s minus V_r .

(Refer Slide Time: 20:22)

Real and Reactive Loop Power Flow Control(Cont...)

- Vectorial voltage difference, $V_l = V_s - V_r$, appears across the transmission line impedance, resulting in the line current I.
- Phasor V_l is normally considered to be composed of the resistive and inductive voltage drops IR and jIX , respectively.
- In practice, power systems are normally connected by two or more parallel transmission paths, resulting in one or more circuit loops with the potential for circulating current flow



So, we can speed this voltage into the, we have discussed this V q model we can slit this voltage by the pulse transformation by V d and V q in real and the quadrature axis.

Thus it becomes a synchronous model when you actually 3 phase A B C system from A B C to you have stationery transformation that is alpha beta, then you feed the P L L theta and thus you get the t q. And, d q they are d coupled so, analyzations is easier. The phasor V I is normally considered to be composed of the resistive and the inductive voltage drop of I X and I R, in practice the power systems are normally connected a mode than the 2 mode machines.

So, more than the 2 machine in parallel in a transmission path, resulting in the one or more circuit loop with a potential of the circulating current flow. So, there might be instantaneous power difference between 2 lines. So, for this reason there will be a circulating current here.

(Refer Slide Time: 21:48)

Real and Reactive Loop Power Flow Control(Cont...)

- Consider defined system with two parallel transmission

- Basic circuit considerations indicate that if the X/R ratio for the two lines are not equal then a circulating current will flow through the two lines.
- Decomposing both line currents, I_1 and I_2 , into an in-phase and a quadrature component with respect to the sending-end voltage V_s

IIT ROORKEE
 NPTEL ONLINE CERTIFICATION COURSE
 17

Consider that defined system with 2 parallel transmission line and since this angle is angle delta 1. So, an I 1 and I 2 will have different. So, for this reason you will have a different current flow. The basic consideration indicate that X by R ratio of this 2 lines are not equal, then circulating current will flow through the transmission line this is basically the wist and (Refer Time: 22:19) kind of thing.

The we shall decompose this both the current decomposing both the current I 1 and I 2 in phase and the quadrature, which was I was trying to explain in previous slide quadrature compensated it is expect to the sending an voltage V s, this will see this equation in next slide. So, this is the in phase component.

(Refer Slide Time: 22:43)

Real and Reactive Loop Power Flow Control(Cont...)

- Then the corresponding in-phase and quadrature voltage components for the lines can be express in terms of circuit parameter, line current and circulating current



$$V_{1d} = (I_{1d} + I_{cd})R_1 + j(I_{1q} + I_{cq})X_1$$

$$V_{1q} = (I_{1q} + I_{cq})R_1 + j(I_{1d} + I_{cd})X_1$$

$$V_{2d} = (I_{2d} - I_{cd})R_2 + j(I_{2q} - I_{cq})X_2$$

$$V_{2q} = (I_{2q} - I_{cq})R_2 + j(I_{2d} - I_{cd})X_2$$

- From the equation, if $X_1/R_1 = X_2/R_2$ then I_{cd} and I_{cq} must be equal to zero.



18

For I d 1 will be I d 1 plus the circulating current in phase with a d axis into R 1 and plus this actual reacting component there is X 1 I q into c q.

Similarly, you will have V 1 q V 1 q will be I q I 1 q plus c q into R 1 plus j I d 1 plus I c d into X 1. So, there will be a cross component of it ok. So, here it will have a real component this q with X and d with R and it will have a cross component q with r and I d with X.

So, similarly the terms of V d 2 and I q and can be written. So, this will be 2 here. So, for this reason this equation will be as follows and from this equation it is quite clear that, if this ratio X 1 R 1 and this X 2 R 2 is same then I c q and I c d both will be 0.

(Refer Slide Time: 24:07)

Real and Reactive Loop Power Flow Control(Cont...)

- The case when there is a difference in the quadrature voltage components, $V_{1q} - V_{2q}$.
- Let consider practical assumption that $R_1 \ll X_1$ and $R_2 \ll X_2$, this difference will primarily maintain the in-phase circulating current component I_{cq} .
- Thus increasing the real power in one line (line 1) and decreasing it in the other (line 2).

IIT ROORKEE | NPTEL ONLINE CERTIFICATION COURSE | 19

The case when the series and the difference in the quadrature voltage component are this one $V_{1q} - V_{2q}$ let us consider the practical assumption that you know we have we know that actually X Y ratio is are on 7 or 10.

So, this much is the constraint X_1 is much greater than R_1 and similarly X_2 is much much greater than R_2 . This difference is primarily will maintain the in phase circulating current component of I_{cq} . Thus increase in real power in 1 line and decreasing lower real power in other line.

So, you will find that more line will actually flowing through the line 1 and less power is flowing to line 2. And, this will be the phasor this is basically the V I what we have represented at this is $V_s - V_r$, this is basically V_q that you have injected and ultimately this is V_r and this is V_s .

And, similarly what you can do you can actually you can have this opposite for the phasor for the line 2 this is actually V_r and this is V_s and this is $V_s - V_r$ and ultimately c_q will be in this directions, and thus you know this value of this voltage will be actually more here and this will be s .

So, due to that what will happen? So, conduction will takes place in different line different manner. So, for this reason we require to compensate it.

(Refer Slide Time: 26:02)

Real and Reactive Loop Power Flow Control(Cont...)

- The case when there is a difference in phase component voltage components, $V_{1d} - V_{2d}$.
- This difference will primarily maintain the in-phase circulating current component I_{cdr} .
- thus change in reactive power flow balance between the lines

IIT ROORKEE NPTEL ONLINE CERTIFICATION COURSE 20

And, we write to make it this value equal and you see that we have eliminated the component actually the $c q$. In case when there is a difference in the phase component of the voltage component V_{d1} and V_{d2} . The difference will primarily maintain the in phase circulating current components $c d$ assuming and we can compensate actually these V_q and this V_{1q} and V_q are same. And, thus change in reactive current flow will balance, but there will be a difference of the real power flow.

(Refer Slide Time: 26:50)

Real and Reactive Loop Power Flow Control(Cont...)

- In a general case differences may exist between both the in-phase and quadrature voltage components which will maintain the circulating current, changing both the real and reactive power flow balance between the lines.
- The distribution of real power flow over interconnections forming loop circuits can be controlled by PAR.
- The Phase Angle Regulator injects a quadrature voltage in series with the circuit loop resulting in the flow of in-phase circulating current
- The flow of reactive power can be controlled by Voltage Regulators.
- The Voltage Regulator introduces a series in phase voltage into the loop, and quadrature current is circulated through the loop since

IIT ROORKEE NPTEL ONLINE CERTIFICATION COURSE 21

We actually come to this point then in general case the difference may exist between the both in-phase and the quadrature and the voltage component, which will maintain the circulating currents, changing both the real and the reactive power flow balance between the lines. This distribution of the real power flow over the inter connection forming the loop circuits can be controlled by P A R.

The Phase Angle Regulator injects a quadrature voltage in series thus it can effectively control the V_q better, in series when with the circuit loop resulting the flow of the in phase circulating current. So, it will increase the, $I_d 1$ and $I_d 2$, flow of the reactive power can be controlled by the voltage regulator. So, P A R can control the current regulator, voltage regulator introduces the series in phase voltage into the loop and quadrature current is circulated through the loop. Thus both by operating with the P A R and the V A R, we can regulate the power flow between this 2 line.

Thank you for your attention I shall continue with our discussions with the power angle regulator in our next class.