Cyprus University of Technology

EEN320 - Power Systems I (Συστήματα Ισχύος Ι)

Part 6: Fundamentals of power system operation

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Today's learning objectives

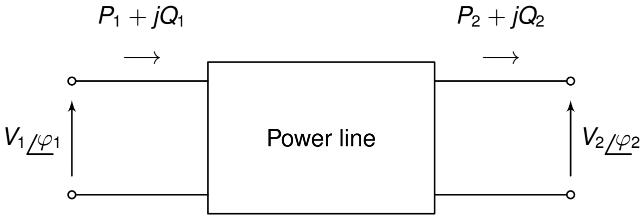
After this part of the lecture and additional reading, you should be able to ...

1. ...describe and analyse the behaviour of a transmission line under different operating conditions;
2. ...explain the Ferranti effect.

Fundamentals of power system operation - Overview

- In this part of the lecture, we investigate the stationary current and voltage relations as well as the resulting active and reactive power flows on an AC power line
- For this purpose, we use the wave equation discussed in the previous part of the lecture (Part 5)
- Thereby, we focus on a series of practically relevant scenarios
- The analysis is performed under two assumptions:
  1) The operating conditions are balanced $\rightarrow$ analysis is performed via single-phase equivalent circuits
  2) The network is in steady-state (for assessment of dynamic phenomena other models are required)
- Furthermore, we consider all powers *per phase*. The corresponding three-phase power can be calculated using the conventions introduced in Part 2.

1 Decoupled quantities - Power flow on a power line

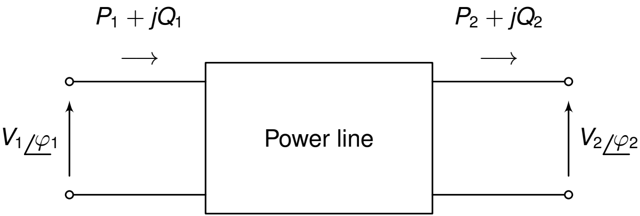


- Several ways to mathematically describe power flow over a power line
- Usually, we use complex voltage together with active and reactive powers at each end of line
- This yields 8 real quantities

$$V_1, \varphi_1, P_1, Q_1, V_2, \varphi_2, P_2, Q_2$$

- Which of the above quantities are decoupled (i.e. independent) of each other and which are not?

1 Decoupled quantities - Examples

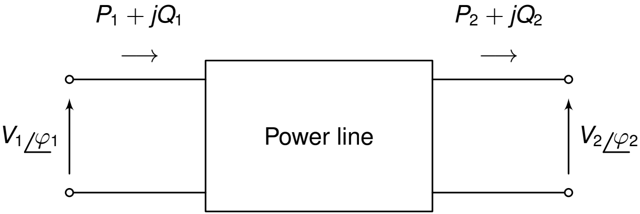


- Not all quantities in above graphic are independent of each other
- Examples:
  - $\underline{V}_1$ and $\underline{V}_2$ are coupled via line characteristics (see previous lectures)

  → Therefore it is customary to take one angle, e.g. φ_2, as reference; hence, one ”loses” one quantity in the formulas

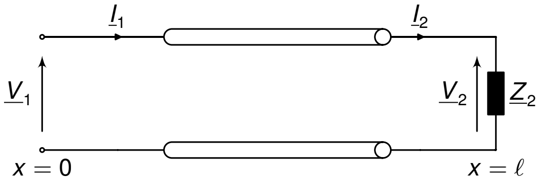
  - Power flows are also coupled; if P_1 and Q_1 are fixed, then P_2 and Q_2 can be computed if $\underline{V}_1$ *or* $\underline{V}_2$ is fixed, too
  - If $\underline{V}_1$ and $\underline{V}_2$ are fixed, P_1, P_2, Q_1 and Q_2 are also fixed and can *not* be adjusted independently

1 Decoupled quantities - Common triples



- $\mathbf{V_1}, \varphi_1, \mathbf{V_2}$: powers result from line characteristics and given quantities; practical example: power line connects two bulk "stiff" power networks
- $\mathbf{V_1}, \mathbf{P_2}, \mathbf{Q_2}$ (or $\mathbf{P_1}, \mathbf{Q_1}, \mathbf{V_2}$): By fixing voltage on one end of line and power on other end, remaining quantities follow; practical example: consumer with fixed power demand connected via power line to network
- $\mathbf{V_1}, \mathbf{P_1}, \mathbf{Q_1}$: By fixing quantities at sending end of line, voltage and powers at receiving end follow; practical example: power plant that feeds network over power line

2 Surge impedance loading - Meaning

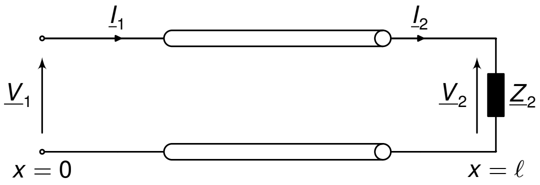


- Surge impedance loading (SIL) = power delivered when line is loaded with its surge impedance, i.e.

$$\underline{Z}_2 = \underline{Z}_w = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

- SIL also called natural loading
- In the following, we consider two cases
  - Lossless line ($R' = G' = 0$)
  - Lossy line ($R' \neq 0$, $G' \neq 0$)

2.1 SIL of lossless power line - Receiving end



- Lossless power line: $R' = G' = 0 \rightarrow$ surge impedance $Z_w = \sqrt{\frac{L'}{C'}}$
- Active power delivered at end of line

$$P_2 = \frac{|\underline{V}_2|^2}{Z_2} = \frac{|\underline{V}_2|^2}{Z_w}$$

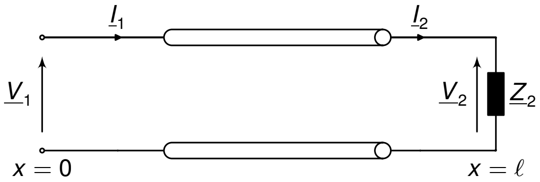
- Reactive power delivered at end of line ($Z_2 = Z_w$ is real in lossless case)

$$Q_2 = 0$$

- Current at end of line

$$\underline{I}_2 = \frac{\underline{V}_2}{Z_2} = \frac{\underline{V}_2}{Z_w}$$

2.1 SIL of lossless power line - Sending end (1)



- From solution of wave equation with $x = 0$ and $\underline{\gamma} = j\omega\sqrt{L'C'} = j\beta$ (see Part 5, Sect. 4.2)

$$\underline{V}_1 = \cosh(j\beta\ell)\underline{V}_2 + Z_W \sinh(j\beta\ell)\underline{I}_2$$

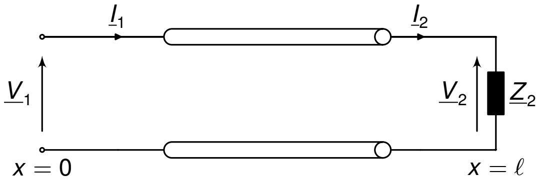
$$\underline{I}_1 = \frac{\underline{V}_2}{Z_W}\sinh(j\beta\ell) + \cosh(j\beta\ell)\underline{I}_2$$

- With $\cosh(j\beta) = \cos(\beta)$ and $\sinh(j\beta) = j\sin(\beta)$ we obtain

$$\underline{V}_1 = \cos(\beta\ell)\underline{V}_2 + jZ_W \sin(\beta\ell)\underline{I}_2$$

$$\underline{I}_1 = j\frac{\underline{V}_2}{Z_W}\sin(\beta\ell) + \cos(\beta\ell)\underline{I}_2$$

2.1 SIL of lossless power line - Sending end (2)

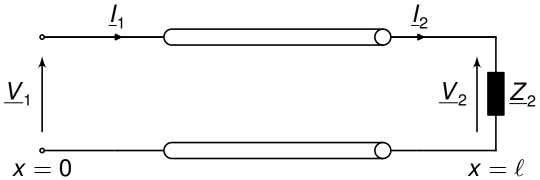


- Using $\underline{I}_2 = \frac{\underline{V}_2}{\underline{Z}_w}$ yields

$$
\begin{aligned}
\underline{V}_1 &= \cos(\beta\ell)\underline{V}_2 + jZ_W \sin(\beta\ell)\frac{\underline{V}_2}{\underline{Z}_w} \\
&= \underline{V}_2(\cos(\beta\ell) + j\sin(\beta\ell) = \underline{V}_2 e^{j\beta\ell} \\
\underline{I}_1 &= j\frac{\underline{V}_2}{\underline{Z}_W}\sin(\beta\ell) + \cos(\beta\ell)\frac{\underline{V}_2}{\underline{Z}_w} \\
&= \underline{I}_2(\cos(\beta\ell) + j\sin(\beta\ell) = \underline{I}_2 e^{j\beta\ell}
\end{aligned}
$$

→ Voltage and current are shifted by angle $\beta\ell$ at end of line
Thereby, their amplitudes remain unchanged

2.1 SIL of lossless power line - Active power



- For active power at both end of lines, we have that (as line is lossless)

$$P_1 = \underline{V}_1 \underline{I}_1^* = \underline{V}_2 \underline{I}_2^* = P_2 = \frac{|\underline{V}_1|^2}{Z_w}$$

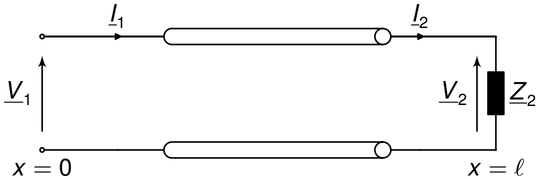
- This particular loading of line is called *surge impedance loading (SIL)*

$$P_{SIL} = \frac{|\underline{V}|^2}{Z_w}$$

- For this loading we achieve optimal transmission conditions (amplitudes of voltage and current remain constant along whole line)

- In practice, loading usually differs from SIL

2.1 SIL of lossless power line - Reactive power



- For SIL, reactive power flow on line is zero

→ At each point on line, reactive power "absorption" of line inductance *equals* reactive power "production" of line capacitance

$$Q'_C = Q'_L \quad \Rightarrow \quad V^2 \omega C' = I^2 \omega L' \quad \Rightarrow \quad \frac{V^2}{I^2} = \frac{L'}{C'} = Z_w^2$$

2.1 SIL of lossless power line - Comments on reactive power

- Surge impedance of overhead lines (OHLs) between 200 – 400 Ω
- OHL inductance significantly larger than OHL capacitance

$\rightarrow$ Reactive power "absorbed" by OHL inductance exceeds reactive power "produced" by OHL capacitance even for small currents

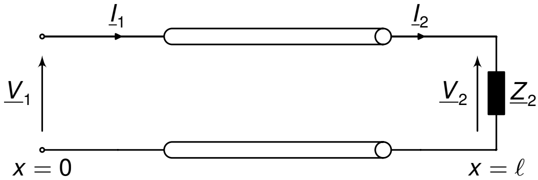
$\rightarrow$ OHLs often operated above their SIL; then they "absorb" reactive power

- Compared to OHLs, cables have very low surge impedance ($\approx$ 30 – 50 Ω)

$\rightarrow$ SIL usually above thermal limit of cable

$\rightarrow$ Cables usually "produce" reactive power

2.2 SIL of lossy power line - Sending end (1)

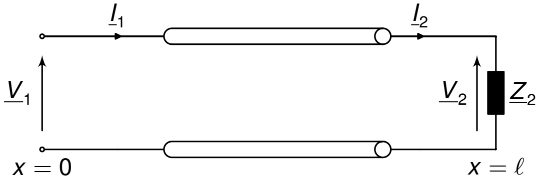


- Lossy line $\rightarrow$ $\underline{Z}_w$ is complex
- As before, we consider the case $\underline{Z}_2 = \underline{Z}_w$
- Current at receiving end of line

$$\underline{I}_2 = \frac{\underline{V}_2}{\underline{Z}_2} = \frac{\underline{V}_2}{\underline{Z}_w}$$

- Apparent power at receiving end of line

$$\underline{S}_2 = P_2 + jQ_2 = \underline{V}_2 \underline{I}_2^* = \frac{|\underline{V}_2|^2}{\underline{Z}_w^*}$$



- From solution of wave equation with $x = 0$ and $\underline{\gamma} = \alpha + j\beta$ (see Part 5)

$$\underline{V}_1 = \cosh(\underline{\gamma}\ell)\underline{V}_2 + \underline{Z}_W \sinh(\underline{\gamma}\ell)\underline{I}_2 = \cosh(\underline{\gamma}\ell)\underline{V}_2 + \underline{Z}_W \sinh(\underline{\gamma}\ell)\frac{\underline{V}_2}{\underline{Z}_w}$$

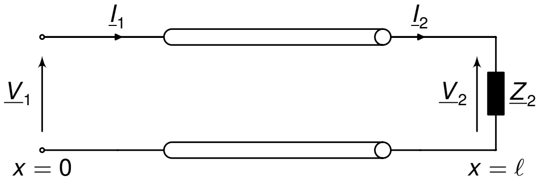
$$= \underline{V}_2\left(\cosh(\underline{\gamma}\ell) + \sinh(\underline{\gamma}\ell)\right) = \underline{V}_2 e^{\underline{\gamma}\ell}$$

$$\underline{I}_1 = \frac{\underline{V}_2}{\underline{Z}_W}\sinh(\underline{\gamma}\ell) + \cosh(\underline{\gamma}\ell)\underline{I}_2$$

$$= \underline{I}_2\left(\cosh(\underline{\gamma}\ell) + \sinh(\underline{\gamma}\ell)\right) = \underline{I}_2 e^{\underline{\gamma}\ell}$$

Note: To obtain the last equality, we have used $\cosh(x) + \sinh(x) = e^x$

2.2 SIL of lossy power line - Sending end (3)



- Apparent power at sending end

$$\underline{S}_1 = P_1 + jQ_1 = \underline{V}_1 \underline{I}_1^* = \underline{V}_2 \frac{\underline{V}_2^*}{\underline{Z}_w^*} e^{2\alpha\ell} = \underline{S}_2 e^{2\alpha\ell}$$

→ As in lossless case, phase angle between voltage and current remains constant along line; phase shift is proportional to βx

→ But now, active and reactive power decrease with line length; same applies to voltage and current

2.2 Typical values for SI and SIL of lossy power line

- Typical values for OHLs

Rated voltage in kV	132	275	400
$\underline{Z}_w$ [Ω]	373	302	296
P_{SIL} [MW]	47	250	540

Source: B. M. Weedy et al., ”Electric Power Systems”, John Wiley & Sons, 2012

- Typical values for cables

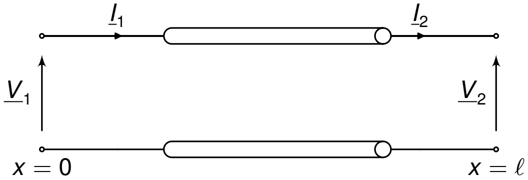
Rated voltage in kV	115	230	500
$\underline{Z}_w$ [Ω]	36.2	37.1	50.4
P_{SIL} [MW]	365	1426	4960

Source: P. Kundur, ”Power System Stability”, McGraw-Hill, 1994

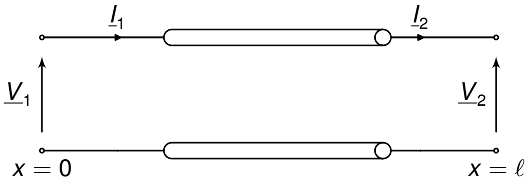
3 The two extrema - Overview

- Next, we analyse the behaviour of a power line in two special cases
  - No load
  - Short circuit
- To simplify our calculations, we restrict ourselves to the lossless case

3.1 No load conditions - Setup



- No load condition can occur if
  - Voltage is applied to unloaded line
  - Load at end of line is disconnected
- Main characteristic: $\underline{I}_2 = 0$



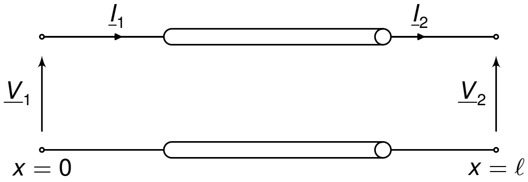
- Solution of wave equation with $x = 0$ and $\underline{\gamma} = j\omega\sqrt{L'C'} = j\beta$ yields (see Part 5, Sect. 4.2)

$$\underline{V}_1 = \cos(\beta\ell)\underline{V}_2$$
$$\underline{I}_1 = j\frac{\underline{V}_2}{\underline{Z}_W}\sin(\beta\ell)$$

- Recall that we may fix one of two voltage angles. Setting $\varphi_1 = 0$, we have

$$V_1 = \cos(\beta\ell)V_2$$
$$\underline{I}_1 = j\frac{V_2}{\underline{Z}_W}\sin(\beta\ell)$$

3.1 No load conditions - Ferranti effect



- Keeping V_1 constant, we get

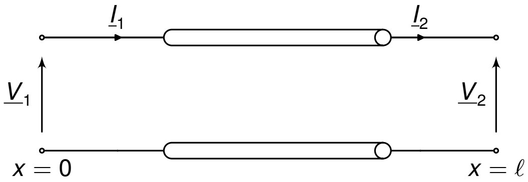
$$V_2 = \frac{V_1}{\cos(\beta\ell)}$$

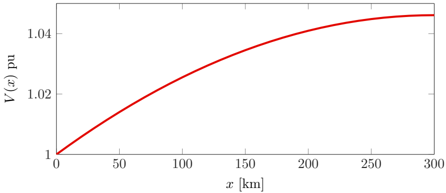
$$\underline{I}_1 = \frac{jV_2}{Z_w}\sin(\beta\ell) = \frac{jV_1\tan(\beta\ell)}{Z_w}$$

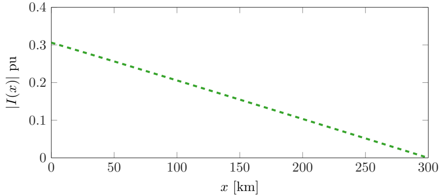
→ Voltage amplitude increases along line, while that of current decreases ($\underline{I}_2 = 0$)

- This phenomenon is called *Ferranti effect* (because it was first observed by the British engineer Sebastian Ziani de Ferranti in 1887)

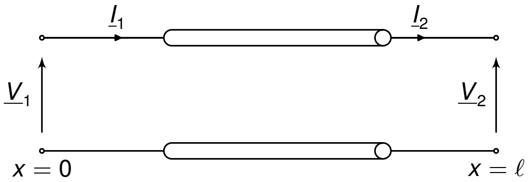
3.1 No load conditions - Ferranti effect illustration







3.1 No load conditions - Ferranti effect resonance



- It holds that (ε_0 is electric constant and μ_0 magnetic constant)

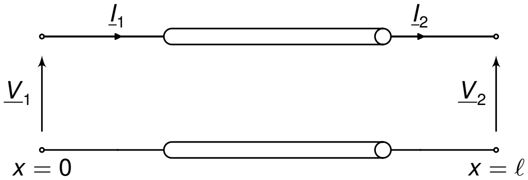
$$\beta = \omega\sqrt{L'C'} \approx \omega\sqrt{\varepsilon\varepsilon_0\mu_0}$$

- Permittivity of air $\varepsilon = 1$
- For $\omega = 2\pi 50$ [rad/s], we have that $\beta \approx \frac{6^\circ}{100\ \text{km}}$

$\rightarrow$ Extreme scenario: resonance; achieved for 50 Hz at $\ell = 1500$ km

$$\beta\ell = \frac{6^\circ \times 1500\ \text{km}}{100\ \text{km}} = 90^\circ = \frac{\pi}{2}$$

- Then $\cos(\beta\ell) = 0$ and $V_2 \rightarrow \infty$



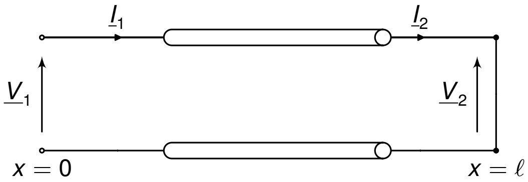
- Impedance at sending end

$$\underline{Z}_1 = \frac{\underline{V}_1}{\underline{I}_1} = -j\frac{Z_w}{\tan(\beta\ell)}$$

- We can see that impedance has *capacitive* character

$\rightarrow$ High loading currents required!

- In practice: amplitude of $\underline{V}_1$ not stiff, but additionally increased by loading currents $\rightarrow$ need to be careful with voltage rise already for line lengths of 300km



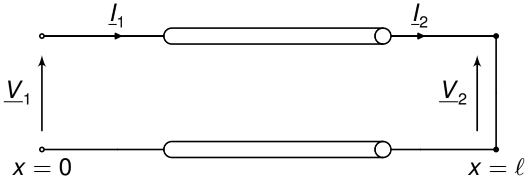
- Short circuit $\rightarrow \underline{V}_2 = 0$
- Solution of wave equation with $x = 0$ and $\underline{\gamma} = j\omega\sqrt{L'C'} = j\beta$ yields (see Part 5, Sect. 4.2)

$$\underline{V}_1 = j\underline{I}_2 Z_w \sin(\beta\ell)$$
$$\underline{I}_1 = \underline{I}_2 \cos(\beta\ell)$$

- In analogy to voltage in no load condition, now current increases along line

$$\underline{I}_2 = \frac{\underline{I}_1}{\cos(\beta\ell)}$$

3.2 Short circuit conditions - Impedance

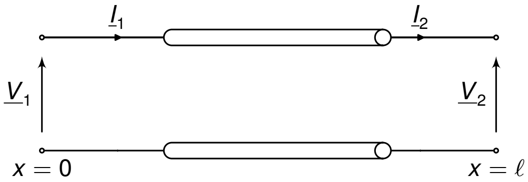


- Short circuit impedance

$$\frac{\underline{V}_1}{\underline{I}_1} = \underline{Z}_1 = jZ_w \tan(\beta\ell)$$

- For $\omega = 2\pi 50$ [rad/s], short circuit impedance is *inductive* for line lengths < 1500 km
- As before, resonance $|\underline{I}_2| \to \infty$ for $\beta\ell = \pi/2$

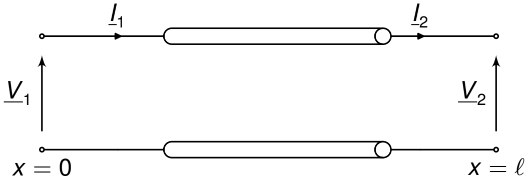
4 Reactive power demand of a power line - Motivation



- Power transmission over a power line causes losses:
  - Ohmic components of line (resistance; conductance) cause active power losses
  - Reactive components of line (inductance; capacitance) influence reactive power flow

→ Apparent power at receiving end of line differs from apparent power at sending end!

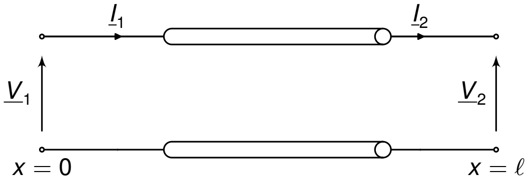
- For voltage relation along line, reactive power is most important as discussed hereafter for *lossless* line



- Wave equation for *lossless* line

$$\begin{bmatrix} \underline{V}_1 \\ \underline{I}_1 \end{bmatrix} = \begin{bmatrix} \cos(\beta\ell) & jZ_w \sin(\beta\ell) \\ j\frac{\sin(\beta\ell)}{Z_w} & \cos(\beta\ell) \end{bmatrix} \begin{bmatrix} \underline{V}_2 \\ \underline{I}_2 \end{bmatrix}$$

$\rightarrow$ Apparent power $\underline{S}_1 = \underline{V}_1 \underline{I}_1^* = P_1 + jQ_1$ at sending end is dependent on apparent power $\underline{S}_2 = \underline{V}_2 \underline{I}_2^* = P_2 + jQ_2$ at receiving end of line



- Hence, we have

$$\underline{S}_1 = \underline{V}_1 \underline{I}_1^* = P_1 + jQ_1 = j\cos(\beta\ell)\sin(\beta\ell)\left(|\underline{I}_2|^2 - |\underline{V}_2|^2 \frac{1}{Z_w}\right) + \sin^2(\beta\ell)\underline{I}_2\underline{V}_2^* + \cos^2(\beta\ell)\underline{V}_2\underline{I}_2^*$$

- For our analysis, it is convenient to fix $\underline{V}_2$ and express $\underline{S}_1$ in terms of SIL

$$P_{SIL} = \frac{|\underline{V}_2|^2}{Z_w}$$

- Using the relations

$$|\underline{V}_2|^2 = P_{SIL} Z_w$$

$$\underline{I}_2^* = \frac{\underline{S}_2}{\underline{V}_2} \quad \rightarrow \quad |\underline{I}_2|^2 = \frac{|\underline{S}_2|^2}{|\underline{V}_2|^2} = \frac{|\underline{S}_2|^2}{P_{SIL} Z_w}$$

$$\underline{I}_2 \underline{V}_2^* = (\underline{V}_2 \underline{I}_2^*)^* = \underline{S}_2^* = P_2 - jQ_2$$

$$\cos^2(\beta\ell) - \sin^2(\beta\ell) = \cos(2\beta\ell)$$

$$\cos(\beta\ell)\sin(\beta\ell) = \frac{1}{2}\sin(2\beta\ell)$$

we can rewrite the equation for $\underline{S}_1$ as follows

$$\underline{S}_1 = P_1 + jQ_1 = P_2 + j\left(Q_2\cos(2\beta\ell) + \frac{1}{2}\sin(2\beta\ell)\left(\frac{|\underline{S}_2|^2}{P_{SIL}} - P_{SIL}\right)\right)$$

- For lossless line

$$P_1 = P_2 \quad \rightarrow \quad \text{can focus further analysis on reactive power flows}$$

- Relation of reactive power flows

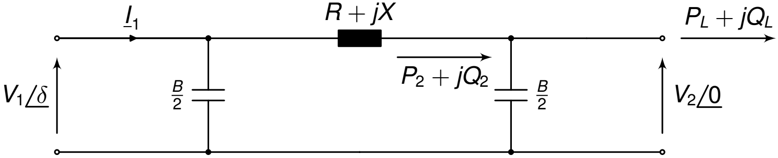
$$Q_1 = Q_2 \cos(2\beta\ell) + \frac{1}{2}\sin(2\beta\ell)\left(\frac{|\underline{S}_2|^2}{P_{SIL}} - P_{SIL}\right)$$

- Q_1 dependent on Q_2 ("load demand") and reactive power demand of line
- With simplifying approximation $\cos(2\beta\ell) \approx 1$, reactive power demand of line given by

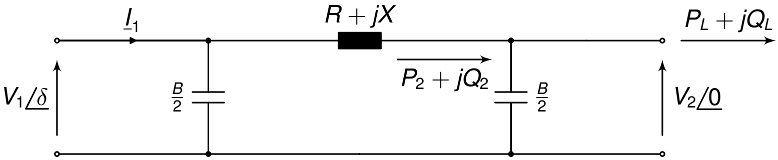
$$\Delta Q = Q_1 - Q_2 \approx \underbrace{\frac{1}{2}\sin(2\beta\ell)\frac{|\underline{S}_2|^2}{P_{SIL}}}_{\text{inductive component } Q_L} - \underbrace{\frac{1}{2}\sin(2\beta\ell)P_{SIL}}_{\text{capacitive component } Q_C}$$

- $\underline{S}_2 = P_{SIL} \rightarrow \Delta Q = 0$
- $|\underline{S}_2| = 0 \rightarrow \Delta Q <$ line produces reactive power ($Q_L = 0,\ Q_C > 0$)
- $|\underline{S}_2| > P_{SIL} \rightarrow \Delta Q > 0$ line absorbs reactive power ($Q_L > Q_C$)
- $|\underline{S}_2| < P_{SIL} \rightarrow \Delta Q < 0$ line produces reactive power ($Q_L < Q_C$)

5 Voltage drop across a power line - Setup



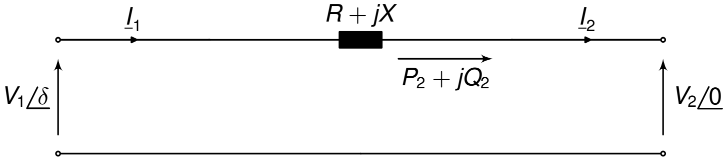
- Π-model of power line of length ℓ and $G' = 0$, $R = R'\ell$, $X = \omega L'\ell$ and $B = \omega C'\ell$
- Load at end of line: $P_L + jQ_L$
- We want to derive a formula for voltage drop across line
- For this purpose it is convenient to define V_2 on real line and denote angle between V_2 and $\underline{V}_1$ by δ



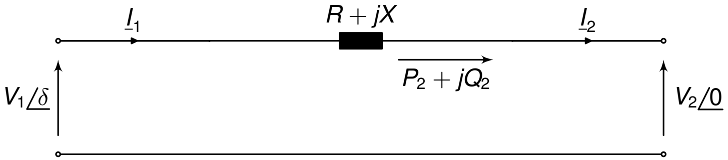
- Shunt elements B produce reactive power

→ We can obtain "net" reactive power flow Q_2 on line by subtracting reactive power Q_C produced by B from Q_L, i.e.,

$$P_2 = P_L$$
$$Q_2 = Q_L - Q_C$$



- By using $Q_2 = Q_L - Q_C$ we can simplify considered circuit as shown above



- Current $\underline{I}_2$ as function of apparent power $\underline{S}_2 = P_2 + jQ_2$ and $\underline{V}_2 = V_2$

$$\underline{I}_1 = \underline{I}_2 = \frac{\underline{S}_2^*}{V_2} = \frac{P_2 - jQ_2}{V_2}$$

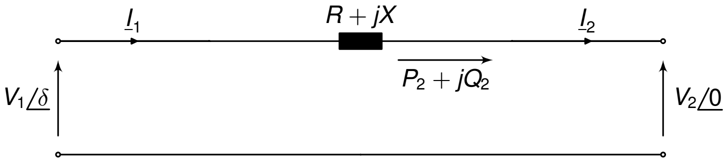
- Voltage $\underline{V}_1$

$$\underline{V}_1 = V_2 + (R + jX)\underline{I}_2 = V_2 + (R + jX)\frac{P_2 - jQ_2}{V_2}$$

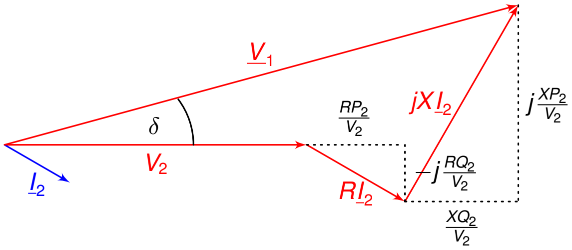
$$= \left(V_2 + \frac{RP_2 + XQ_2}{V_2}\right) + j\left(\frac{XP_2 - RQ_2}{V_2}\right)$$

$$|\underline{V}_1| = V_1 = \sqrt{\left(V_2 + \frac{RP_2 + XQ_2}{V_2}\right)^2 + \left(\frac{XP_2 - RQ_2}{V_2}\right)^2}$$

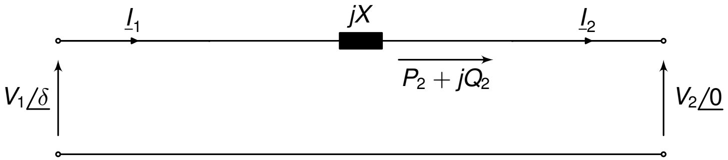
5 Voltage drop across a power line - Phasor diagram



$X \gg R$



5 Voltage drop across a power line - Lossless line



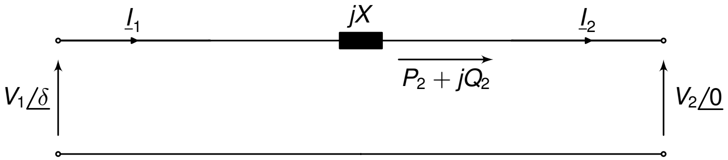
- Lossless line $\rightarrow R = 0$
- Expression for V_1 simplifies to

$$\underline{V}_1 = V_1\cos(\delta) + jV_1\sin(\delta) = \left(V_2 + \frac{XQ_2}{V_2}\right) + j\left(\frac{XP_2}{V_2}\right)$$

- Separating the real with the imaginary parts, gives

$$\boxed{P_2 = \frac{V_1 V_2 \sin(\delta)}{X}} \qquad \boxed{Q_2 = \frac{V_1 V_2 \cos(\delta) - V_2^2}{X}}$$

5 Voltage drop across a power line - Lossless line



- The magnitude of V_1 is given by

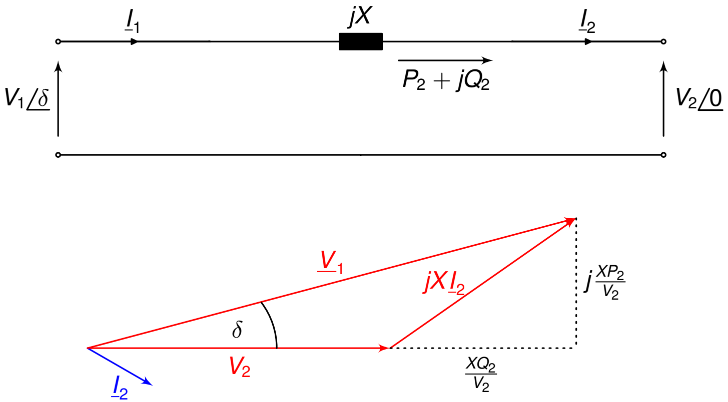
$$|\underline{V}_1| = V_1 = \sqrt{\left(V_2 + \frac{XQ_2}{V_2}\right)^2 + \left(\frac{XP_2}{V_2}\right)^2}$$

- In most scenarios $|XP_2/V_2| \ll V_2$ and expression for V_1 can be further simplified to

$$|\underline{V}_1| = V_1 \approx V_2 + \frac{XQ_2}{V_2}$$

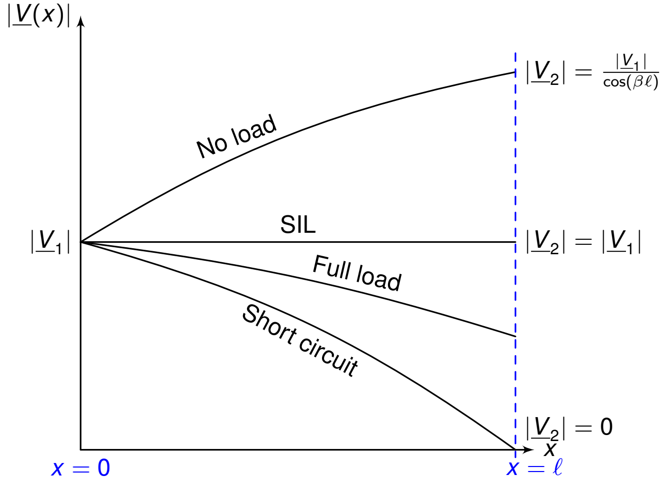
$\rightarrow$ $\Delta V = V_1 - V_2$ mainly influenced by reactive power Q_2!

5 Voltage drop across a power line - Lossless line phasor diagram

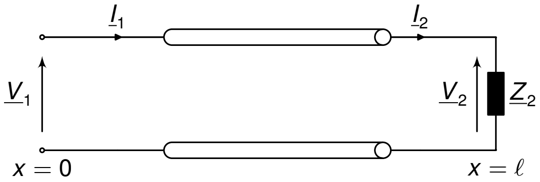


→ Phase angle δ mainly influenced by active power P_2!

- We have assumed V_2 and $\underline{S}_2$ are known and we want to calculate $\underline{V}_1$; often also V_1 and $\underline{S}_2$ given and we seek to compute $\underline{V}_2$; this can be done in an equivalent manner



- The discussed scenarios mainly apply to OHLs; cables typically have different properties



- Consider exemplary 200 km/420 kV ($= V_{LL} = \sqrt{3}V_2$) power line with following characteristics

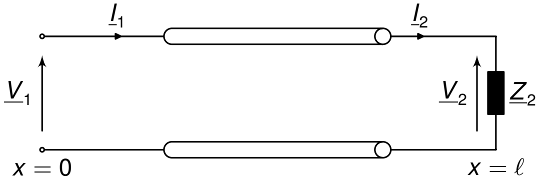
$$R' = 0.031\,\Omega/\text{km},\;\; L' = 1.06\,\text{mH/km},\;\; C' = 11.9\,\text{nF/km},\;\; G' = 0,\;\; f = 50\,\text{Hz}$$

- Assume line is loaded with surge impedance $\underline{Z}_2 = \underline{Z}_w$

- Propagation constant

$$\underline{\gamma} = \sqrt{(0.031 + j0.333)j3.74 \cdot 10^{-6}} = (0.052 + j1.117)10^{-3}$$

$$\underline{\gamma}\ell = \alpha\ell + j\beta\ell = 0.0104 + j0.2234$$



- Characteristic impedance (neglecting imaginary part)

$$Z_w = 298.5\ \Omega$$

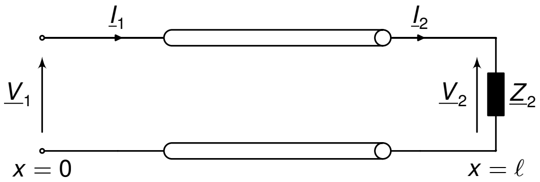
- Active power drawn by load at receiving end of line

$$P_2 = \frac{V_{LL}^2}{Z_w} \approx 591\ \text{MW}$$

- Current RMS magnitude (per phase)

$$I_2 = \frac{\frac{V_{LL}}{\sqrt{3}}}{Z_w} = \frac{420\ \text{kV}}{\sqrt{3} \cdot 298.5\ \Omega} = 812.4\ \text{A}$$

6 Efficiency of a high-voltage power line - An example (3)



- Line losses can be approximated by

$$\Delta P = P_1 - P_2 \approx 3R'\ell I_2^2 = 3 \cdot 0.031 \cdot 200 \cdot 812.4^2 = 12.3 \text{ MW}$$

- $P_1 = P_2 + \Delta P \approx 591 + 12.3 = 603.3$ MW

- **Alternative**: We can calculate exact value for P_1 from wave equation (see Part 6 Section 2.2)

$$P_1 = P_2 e^{2\alpha\ell} = 603.6 \text{ MW}$$

$\rightarrow$ Our approximation is fairly accurate

$\rightarrow$ Very high efficiency for power transmission!

$$e^{-2\alpha\ell} = 0.979 \quad \leftrightarrow \quad 97.9\%$$