Basic Concepts of Half-Wave Transmission Systems

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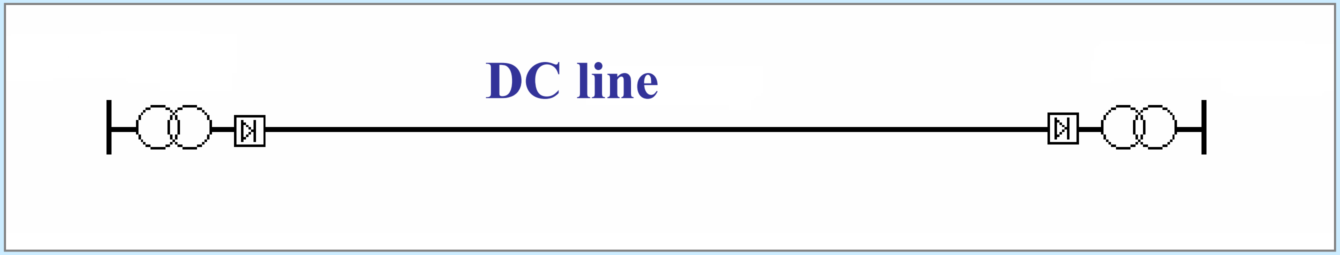
2013 Brazilian Seminar: Transmission Line with a little more than Half Wavelength

Demand for Power Delivery at very long distances over the world

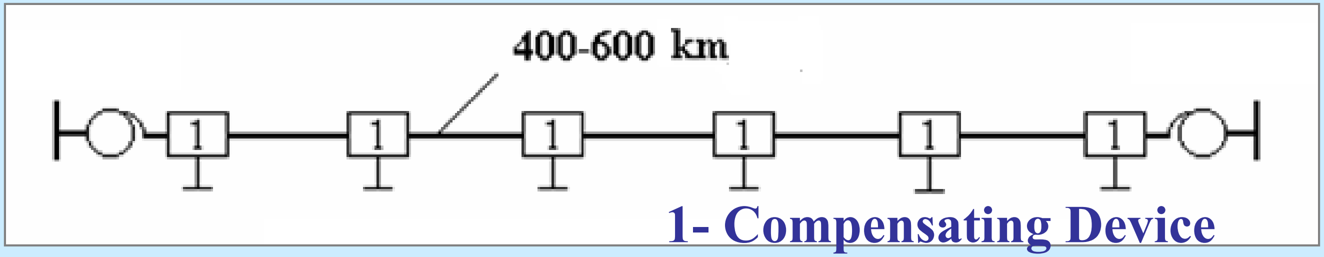
 Thermal Energy Complex (TEC)

 Hydro Energy Complex (HEC)

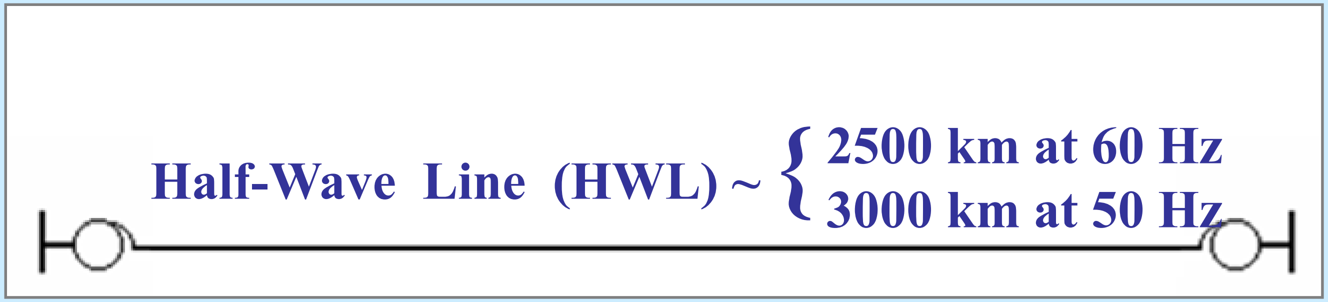
Circuit diagrams of extra long Transmission Systems



DC Transmission System (DCTC)



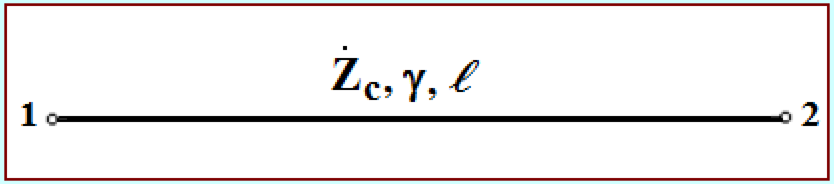
Compensated Transmission System



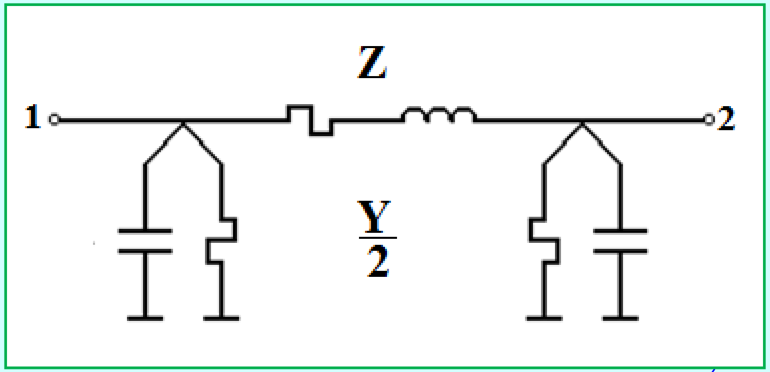
Half-Wave Transmission System (HWTS)

Property 1. The unusual equivalent Π circuit of Half Wave Line

Uniform Long Line



The equivalent Π circuit of Long Line



$\gamma = \alpha + i\beta$ **is propagation coefficient;**

α **is attenuation coefficient;**

β **is phase coefficient;**

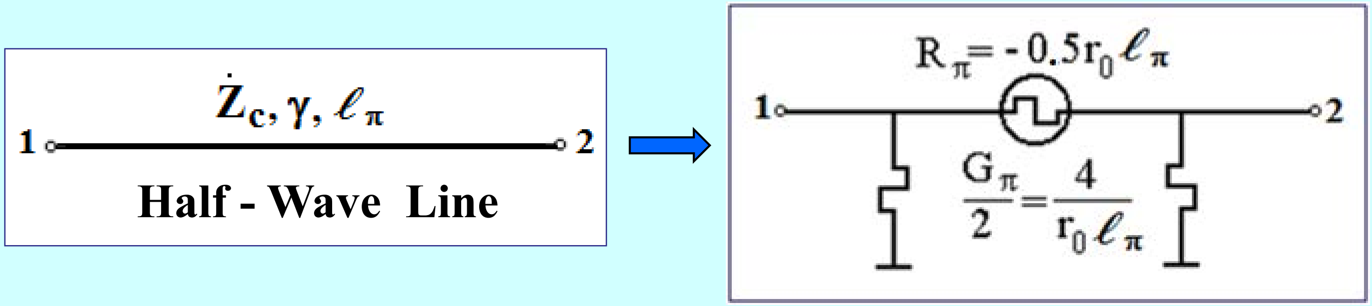
$\dot{Z}_c$ **is characteristic impedance;**

$$Z = \dot{Z}_c \mathrm{sh}\gamma\ell, \quad \frac{Y}{2} = \frac{\mathrm{th}\,\gamma\ell/2}{\dot{Z}_c}$$

Z **is series impedance;**

Y **is shunt admittance**

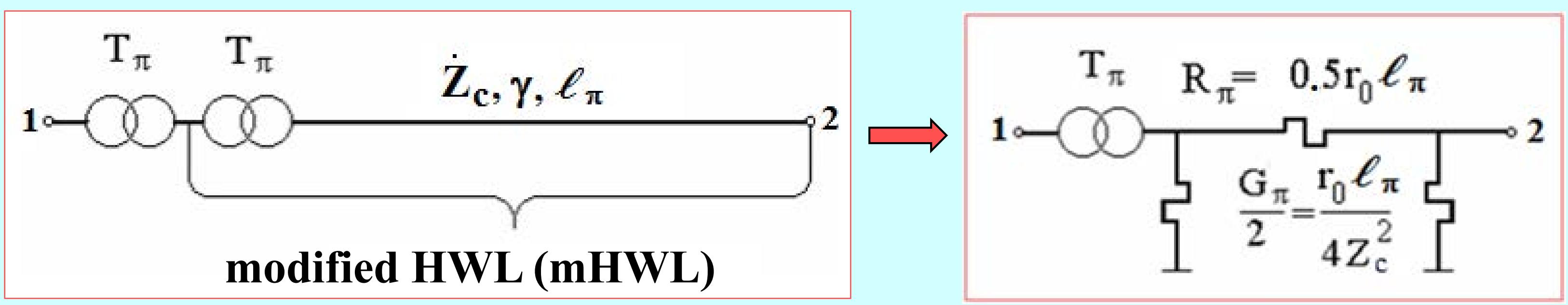
The equivalent П circuit of Half -Wave Line at the traditional approach

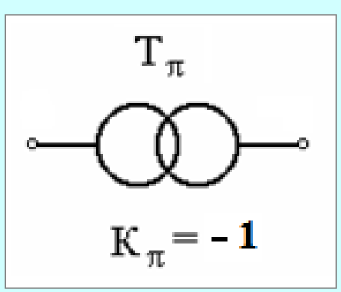


Drawbacks: negative resistance and super large conductance

r_0 is line resistance per km;

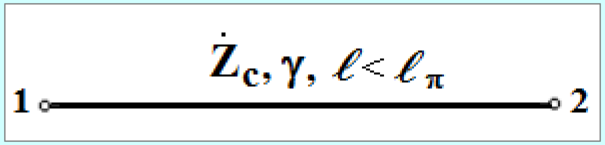
The equivalent П circuit of Half -Wave Line at the modified approach

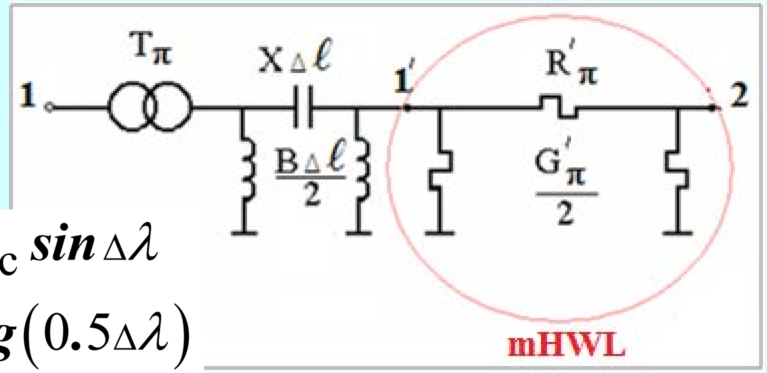




T_π is the half - wave transformer with transformation ratio $K_\pi = -1$

The equivalent Π circuit of Very Long Line in case $\ell < \ell_{\pi}$





$$X_{\Delta\ell} = Z_c \, \boldsymbol{sin}\, \Delta\lambda$$

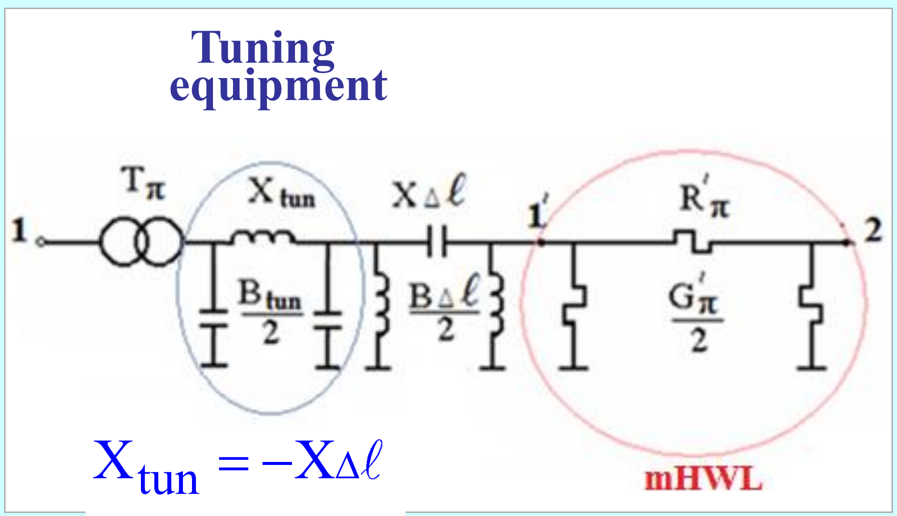
$$\frac{B_{\Delta\ell}}{2} = \frac{\boldsymbol{tg}(0.5\Delta\lambda)}{Z_c}$$

$$R'_\pi = \frac{r_0 \ell}{2}(1 - K')$$

$$\frac{G'_\pi}{2} = \frac{r_0 \ell}{4Z_c^2 (1 - K')}$$

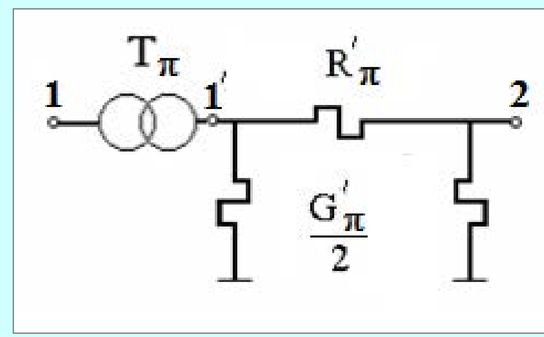
$$\Delta\lambda = \beta(\ell - \ell_\pi), \; \lambda = \beta\ell \qquad K' = \frac{\boldsymbol{cos}\,\Delta\lambda \, \boldsymbol{sin}\,\lambda}{\lambda}$$

Tuning up to half-wave length



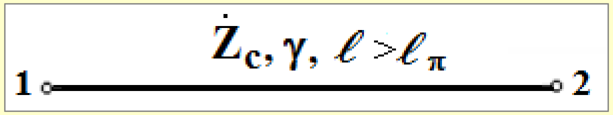
$$X_{tun} = -X_{\Delta\ell}$$

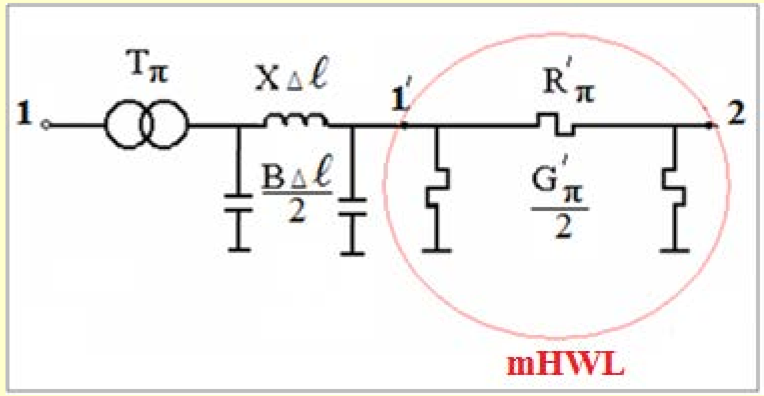
$$\frac{B_{tun}}{2} = -\frac{B_{\Delta\ell}}{2}$$



The equivalent Π circuit of Very Long Line tuned up to half-wave length

The equivalent Π circuit of Very Long Line in case $\ell > \ell_\pi$



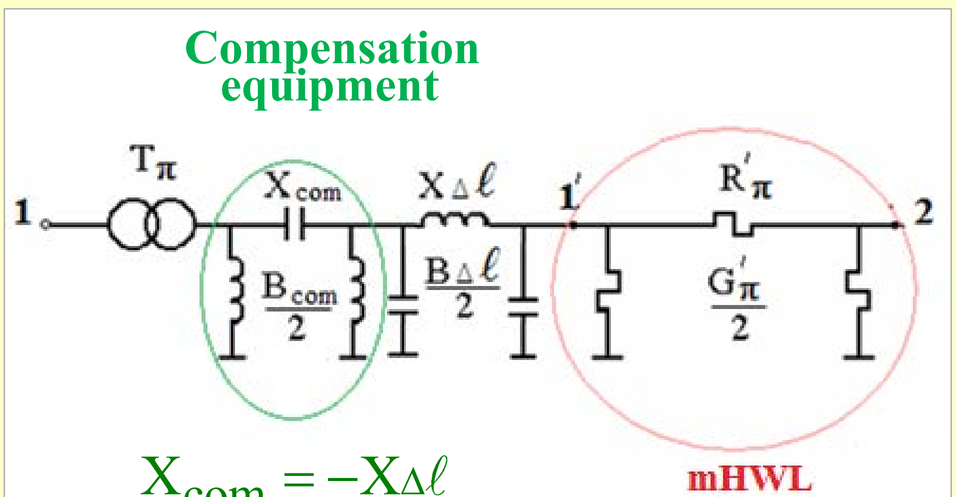


Parameters

$$R'_\pi, \frac{G'_\pi}{2}, X\Delta\ell, \frac{B\Delta\ell}{2}$$

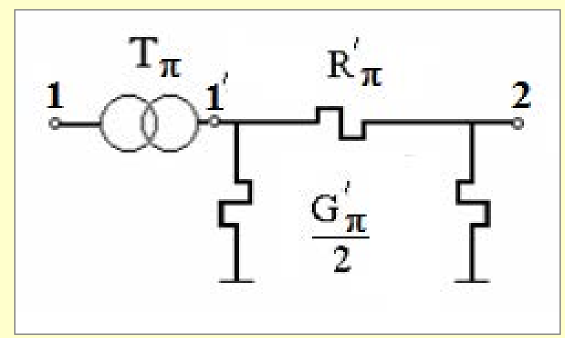
are defined by the formulas on the previous slide.

Compensation up to half-wave length



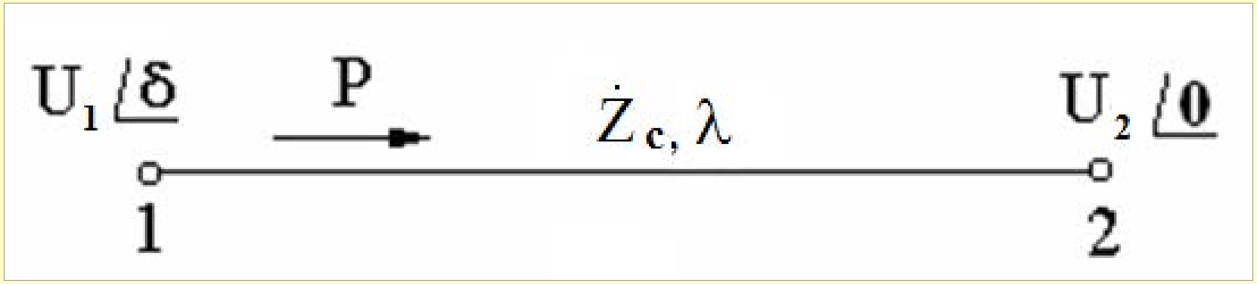
$$X_{com} = -X\Delta\ell$$

$$\frac{B_{com}}{2} = -\frac{B\Delta\ell}{2}$$



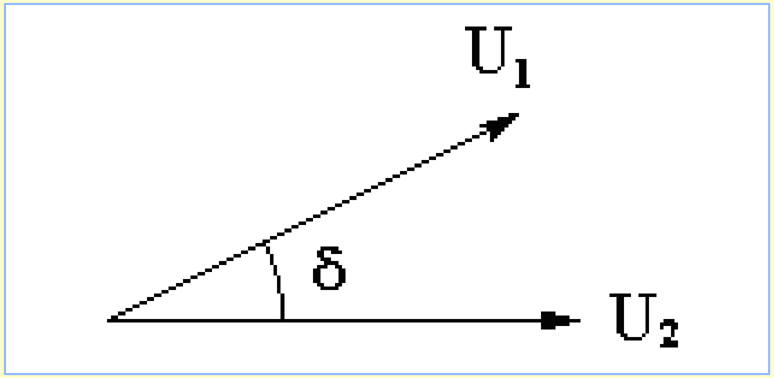
The equivalent Π circuit of Very Long Line compensated up to half-wave length

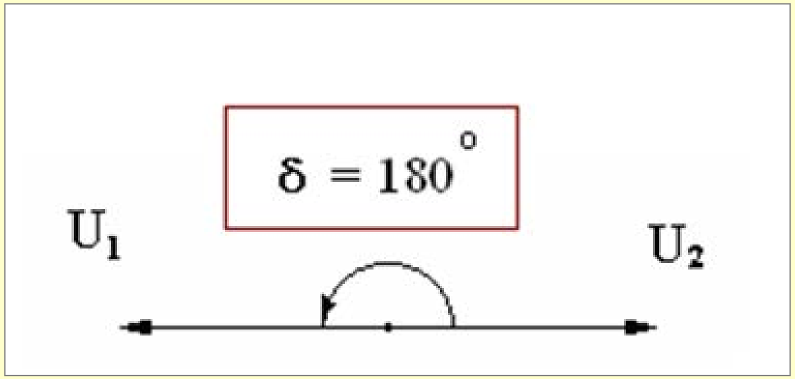
Property 2. Independence of the power angle between end voltages of HWL from transmitted power



Calculated circuit

The power angle for Long and Half-Wave Lines





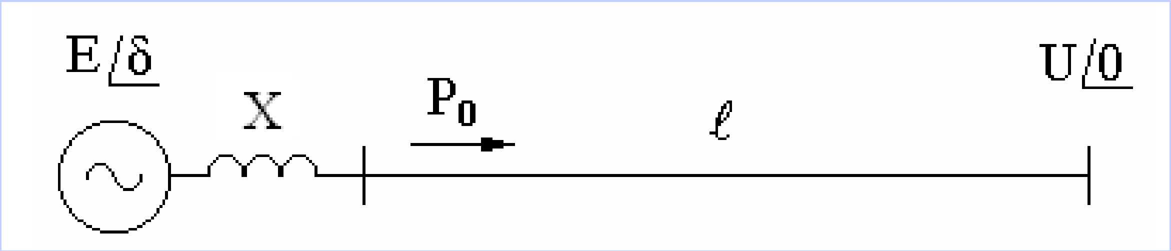
$$P = \frac{U_1 U_2}{Z_c \sin\lambda} \sin\delta$$

$$P = 2\frac{|U_1|\left(|U_1| - U_2\right)}{r_0 \ell_\pi}$$

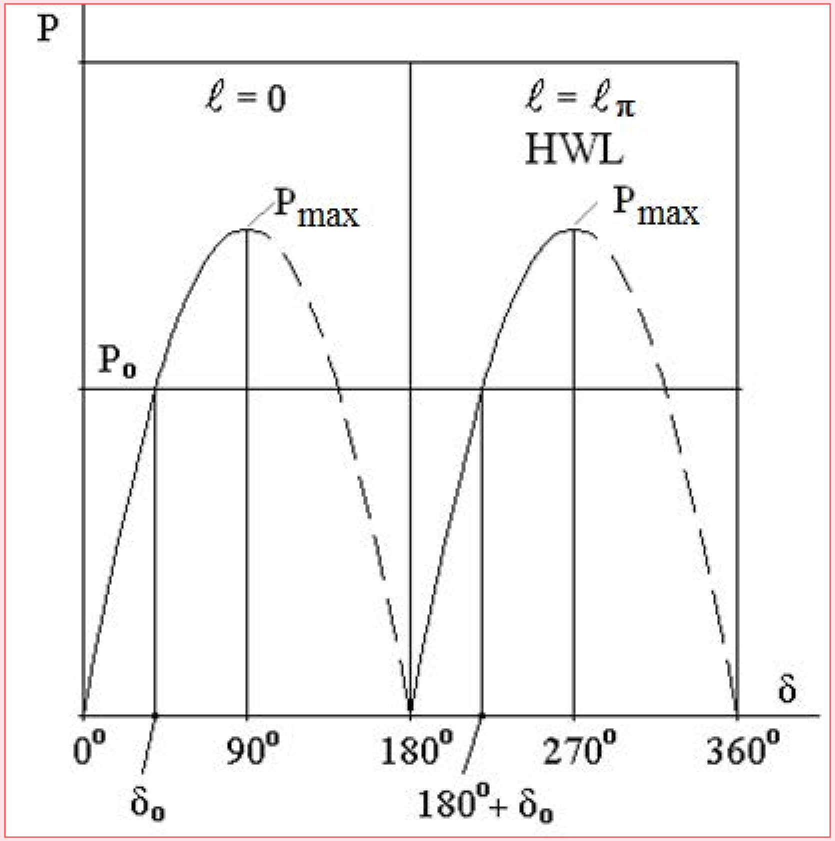
Long Line (ℓ < 1000 km)

Half-Wave Line ($\ell = \ell_\pi$)

Property 3. Identity of HWL by stability criterion with the zero length Line



Calculated circuit

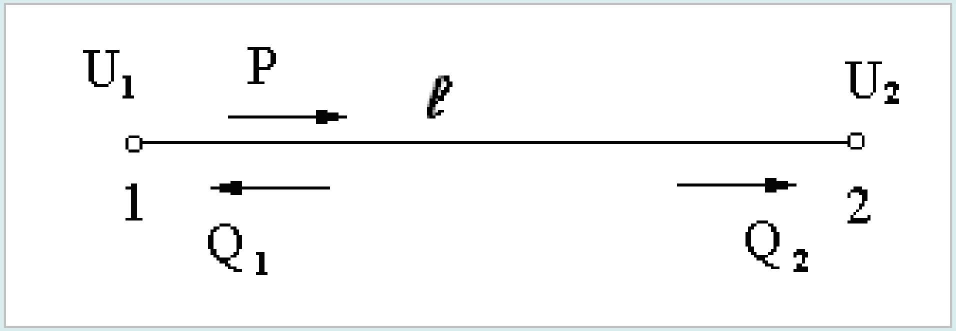


$$P_{max} = \frac{EU}{X}$$ is

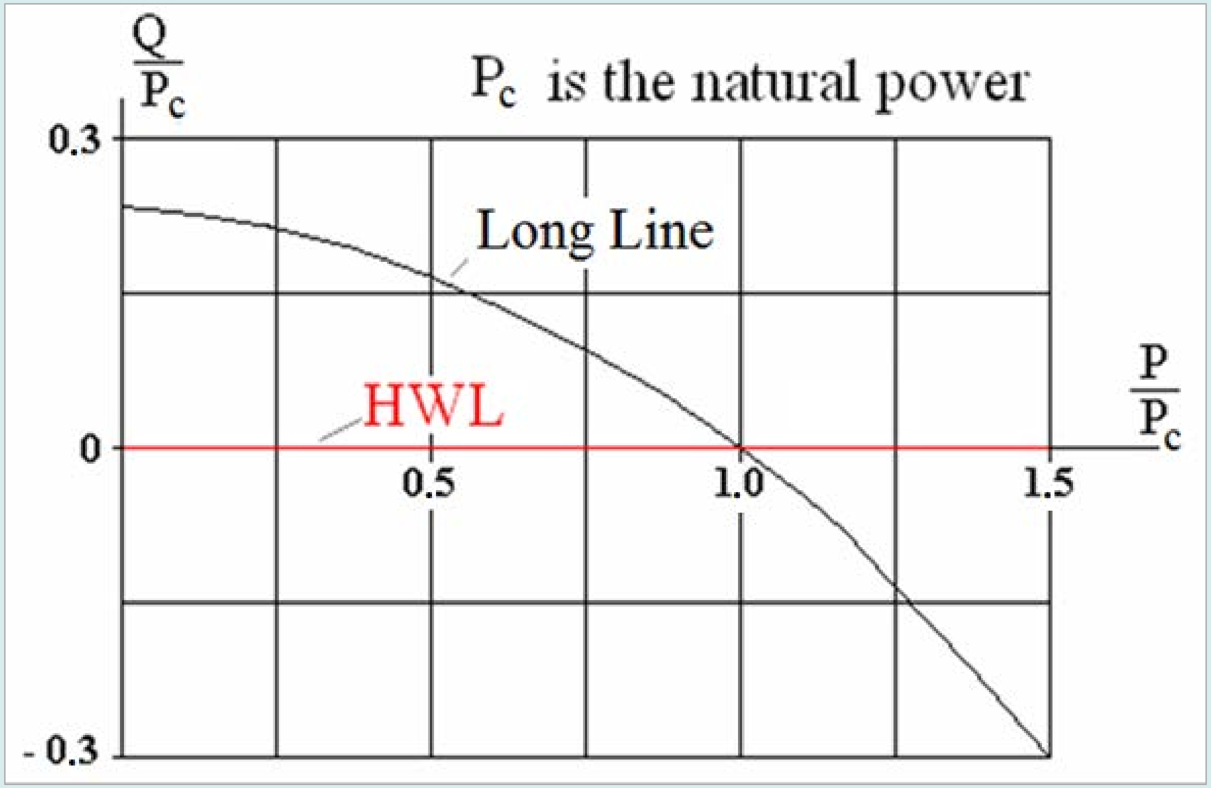
the static stability limit for HWL and the zero length Line

Power angle curves in the case of HWL and the zero length Line

Property 4. Reactive power balance for HWL in all conditions

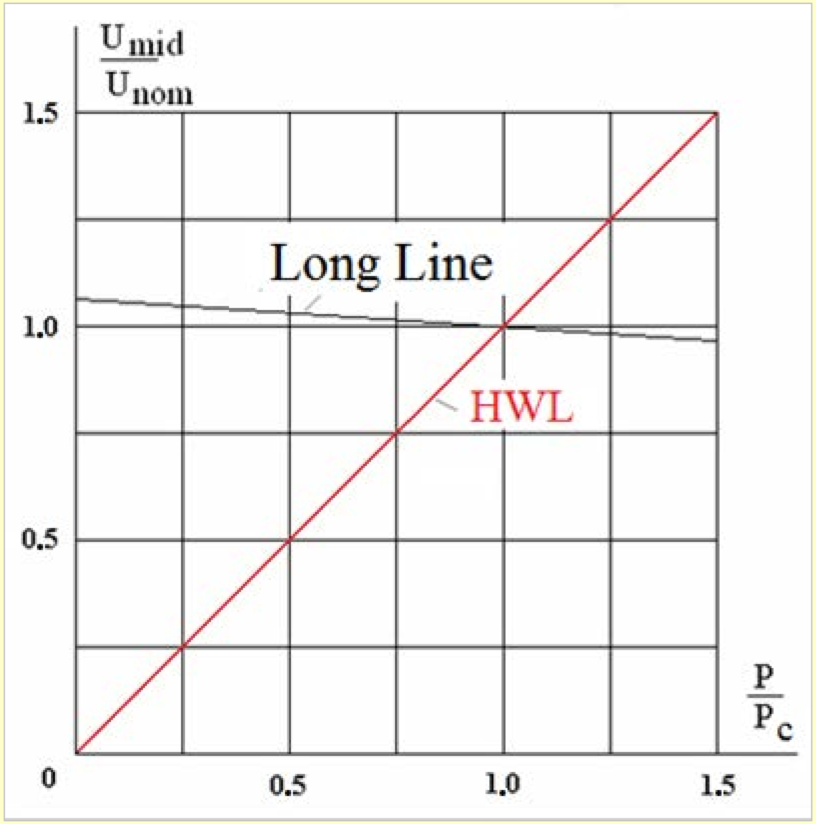


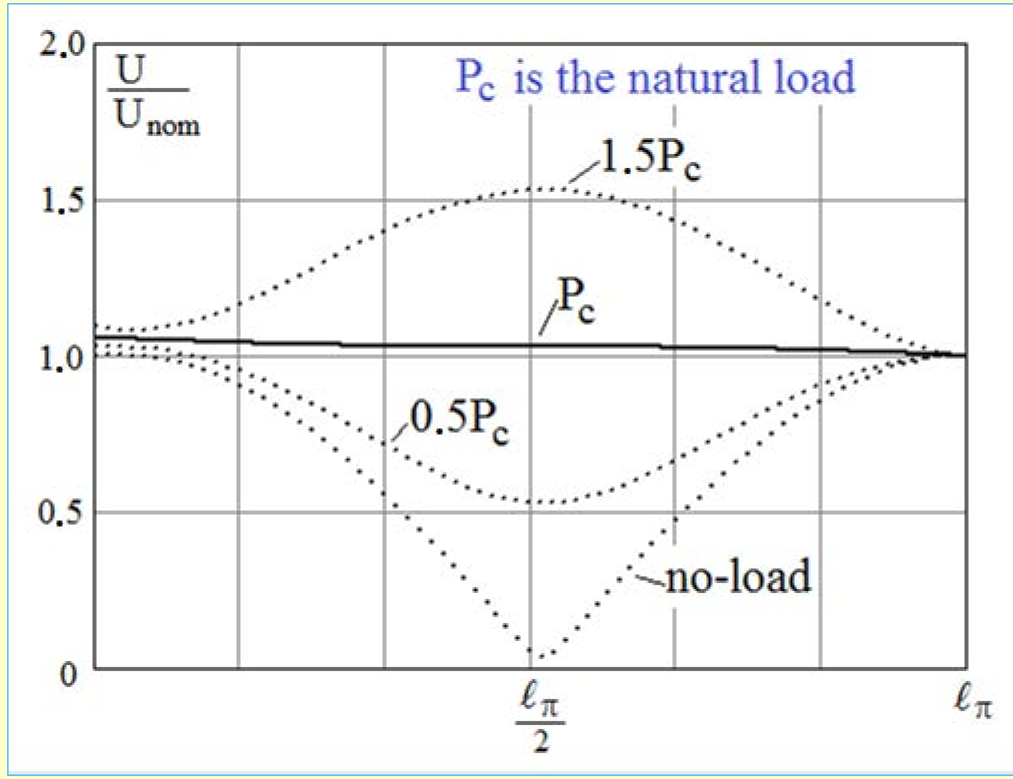
Calculated scheme



Reactive power of Long Line and HWL depending on transmitted power

Property 5. Directly proportional dependence of voltage in the middle of HWL from transmitted power

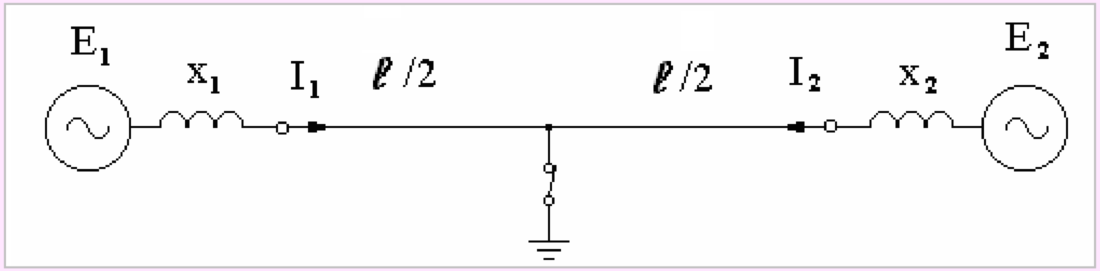




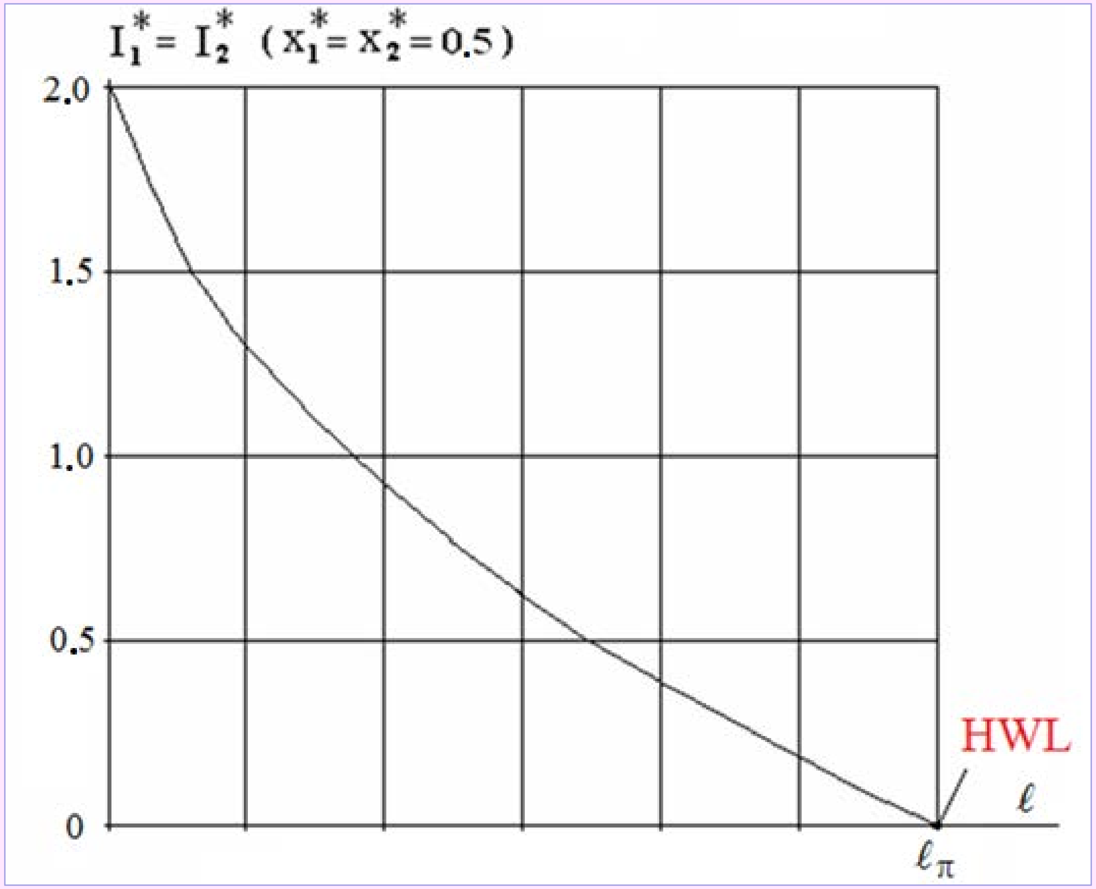
Voltage in the middle of Long Line and HWL depending on transmitted power

Voltage allocation along HWL at various transmitted power

Property 6. Opportunity of shunting of HWL in its middle point

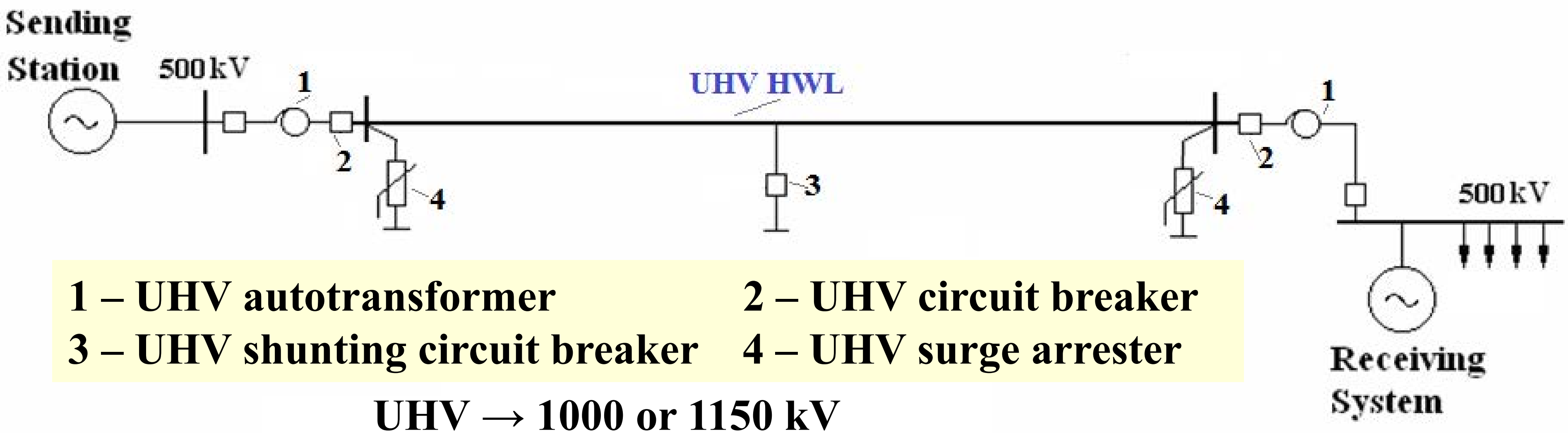


Shunting of Line in its middle point



Currents at the ends of shunted line

Electric circuit of UHV HWTS



1 – UHV autotransformer
2 – UHV circuit breaker
3 – UHV shunting circuit breaker
4 – UHV surge arrester

UHV → 1000 or 1150 kV

Transfer capability of HWTS

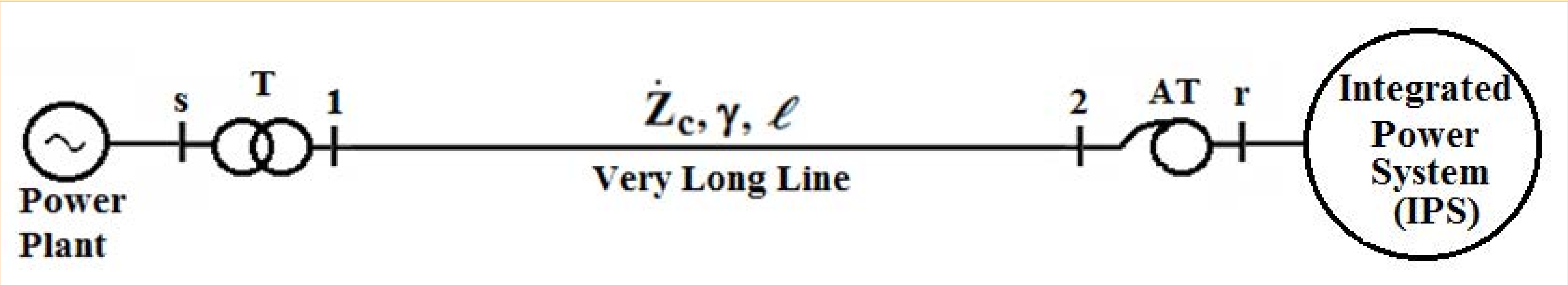
$$P_{HWTS} = \frac{U_{mid.adm}}{U_{max}} P_{c.max} \approx 6000 - 9000\ \mathrm{MW}$$

$U_{mid.adm}$ **is the admissible voltage in the middle of HWL;**

U_{max} **is the maximum operating voltage;**

$P_{c.max}$ **is the natural power of HWL at the maximum operating voltage.**

Condition for exception of self-oscillation



Z_{ss} is the short-circuit input impedance of Very Long Transmission System

$Z_{11} = \dot{Z}_c \mathrm{th}\gamma\ell$ is the short-circuit input impedance of Very Long Line

Z_T, Z_{AT} are impedances of transformer and autotransformer

To rule out self-oscillation of generators of Power Plant it is necessary to satisfy the following condition

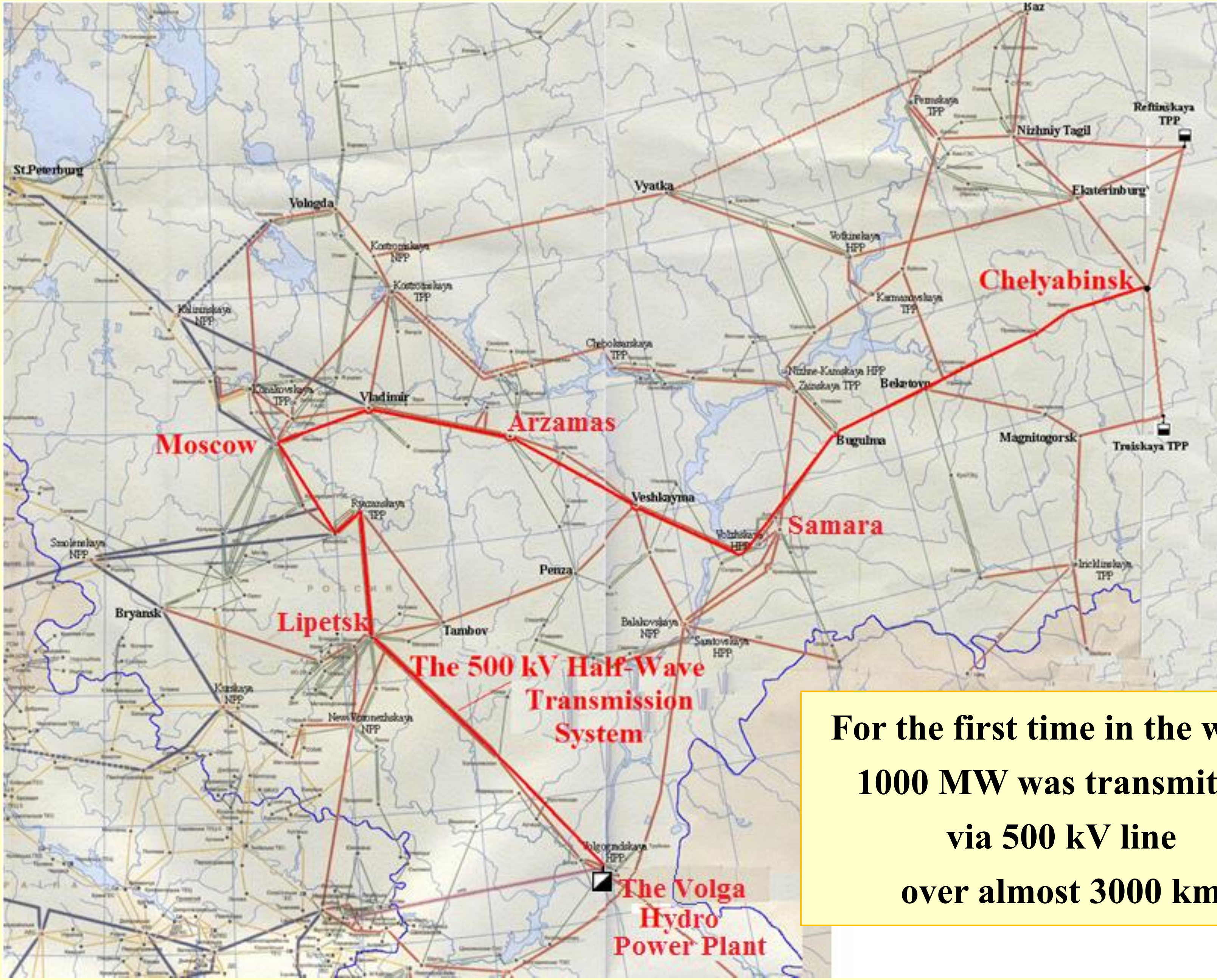
$$\boldsymbol{Im}\, Z_{SS} > 0$$

(The imaginary part of the input impedance should be inductive)

Or in more detailed view

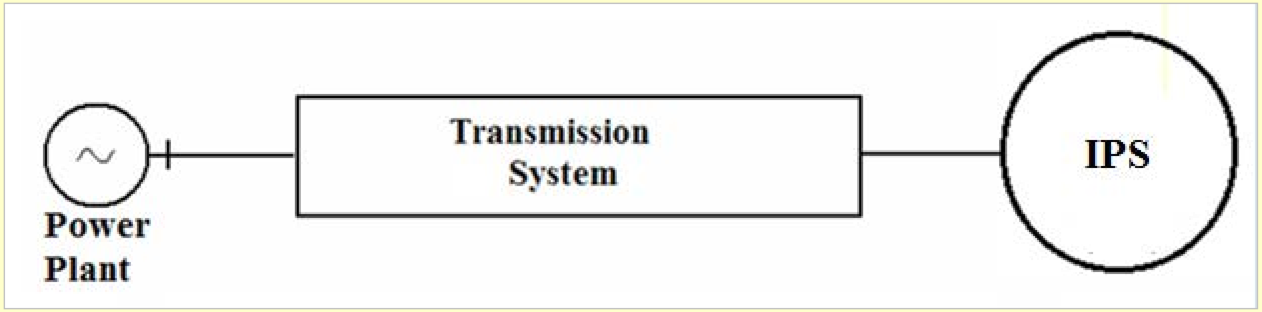
$$\boldsymbol{Im}\left[Z_T + \frac{Z_{AT}}{\mathrm{ch}\gamma\ell\left(\mathrm{ch}\gamma\ell + \frac{Z_{AT}}{\dot{Z}_c}\mathrm{sh}\gamma\ell\right)} \right] > -\boldsymbol{Im}\, \dot{Z}_c \mathrm{th}\gamma\ell$$

Scheme of field tests of the HWTS in the 500 kV Russian Grid



For the first time in the world
1000 MW was transmitted
via 500 kV line
over almost 3000 km

Transmission System outages and Power System reliability



Two aspects of Power System Reliability:
Adequacy and Security.

Adequacy means that Power System has to have sufficient installed capability to satisfy the consumer demand.

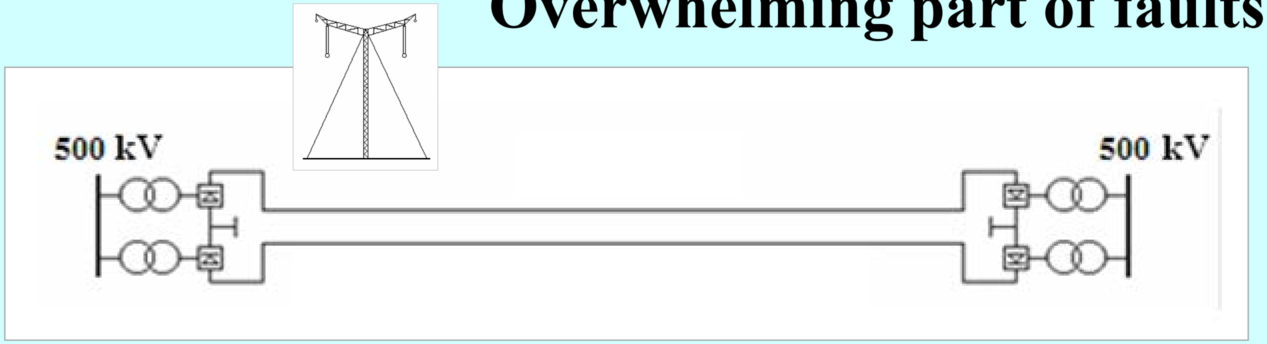
Security is the ability of Power System to withstand the impact of sudden changes which may result in major disturbances.

The N-1 criterion of Reliability

Power System is designed and operated to withstand the loss of any independent element in case of different faults.

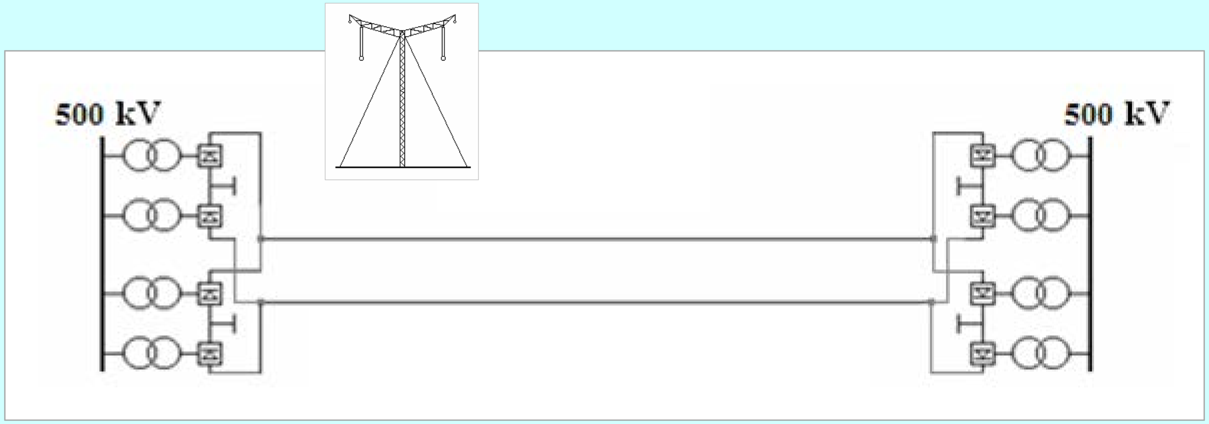
DCTS and the N-1criterion of Reliability

Overwhelming part of faults are single-pole ones



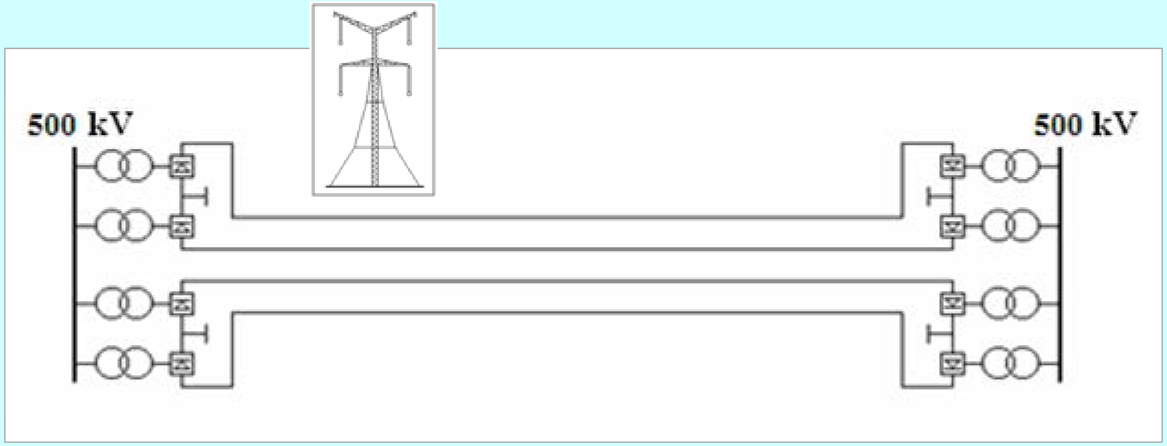
The 2-pole DCTS with one converting branch on a pole

The N-1 criterion is met only on 50 & 60%



The 2-pole DCTS with two converting branches on a pole

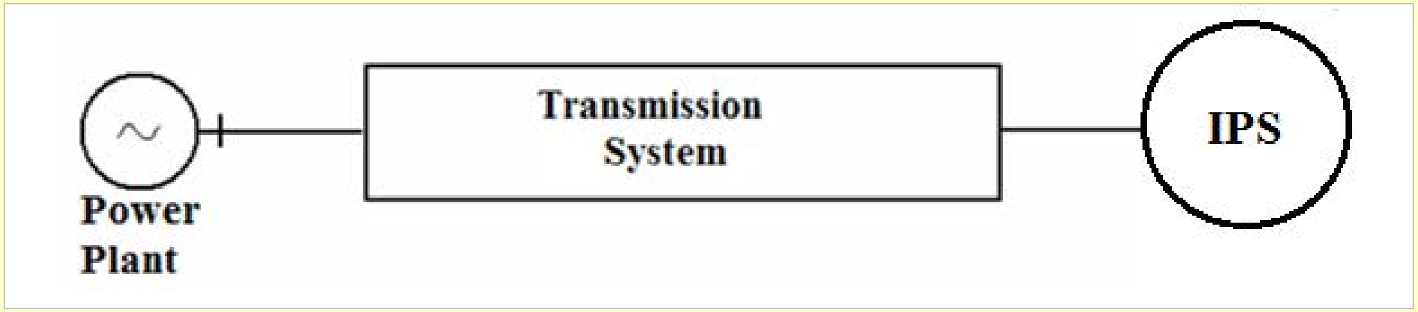
The N-1 criterion is met on 75 & 90% at substation faults and on 50 &60% at line faults



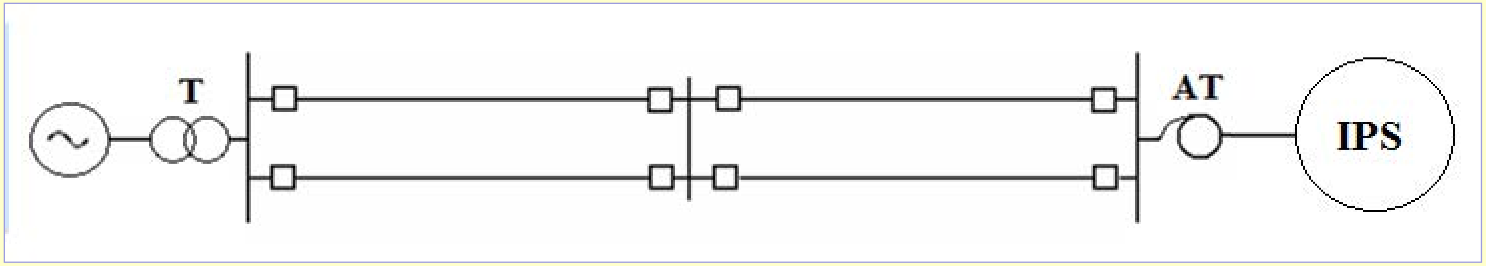
The 4-pole DCTS

The N-1 criterion is met on 75 & 90%

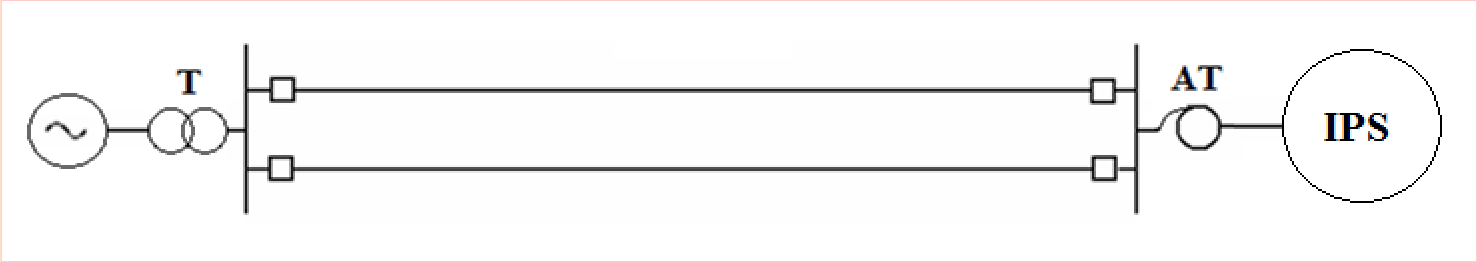
Use of double-circuit 3-phase transmission lines for increase of Reliability



Double-circuit sectioned Long Line

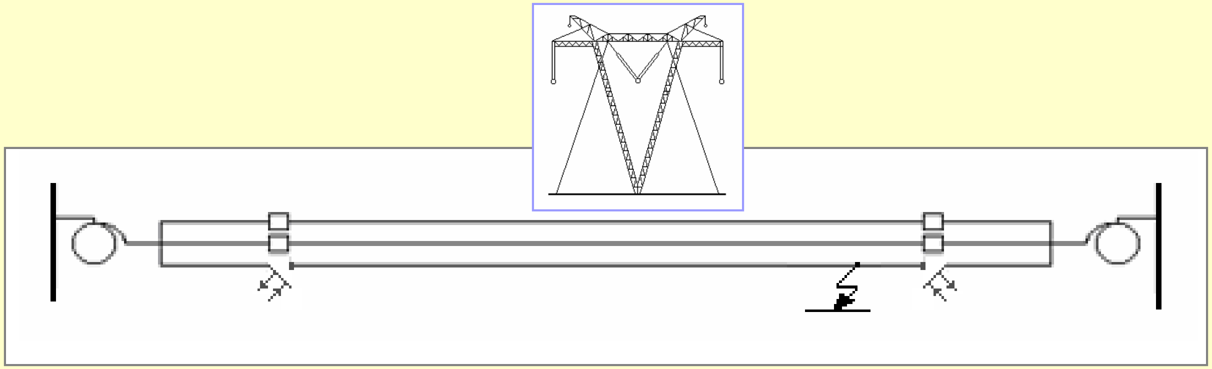


Double-circuit Half - Wave Line



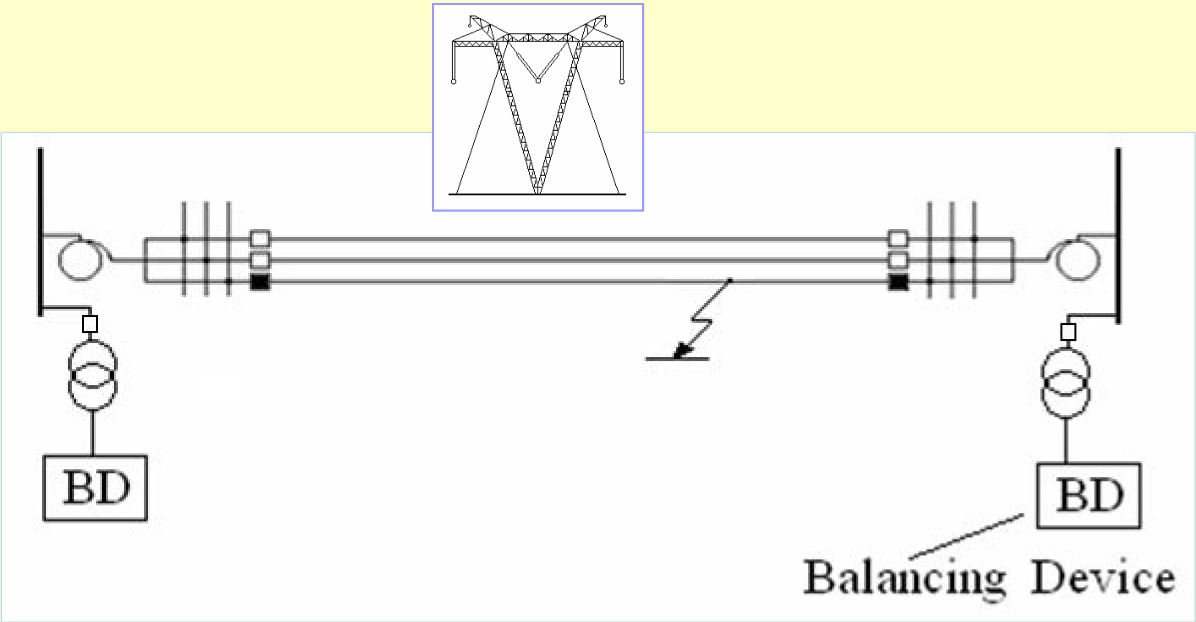
Single-phase faults at UHV TSs make more than 98%

HWTS and the N-1 criterion of Reliability



The Single Phase Automatic Reclosing is effective only at transient faults

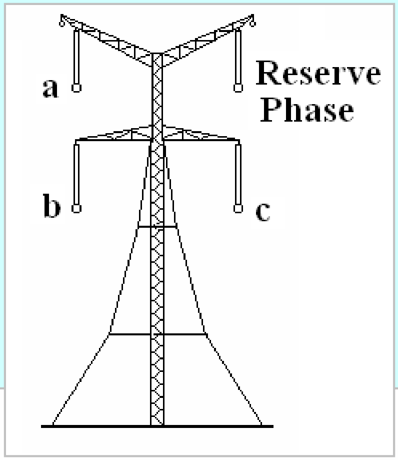
The N-1 criterion is not met

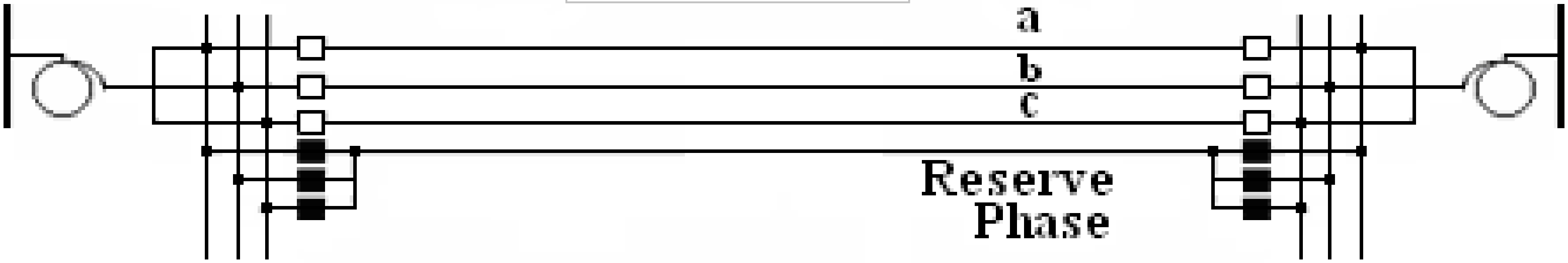


Operation under the 2-phase scheme at transient and sustained faults

The N-1 criterion is met only on 50&60%

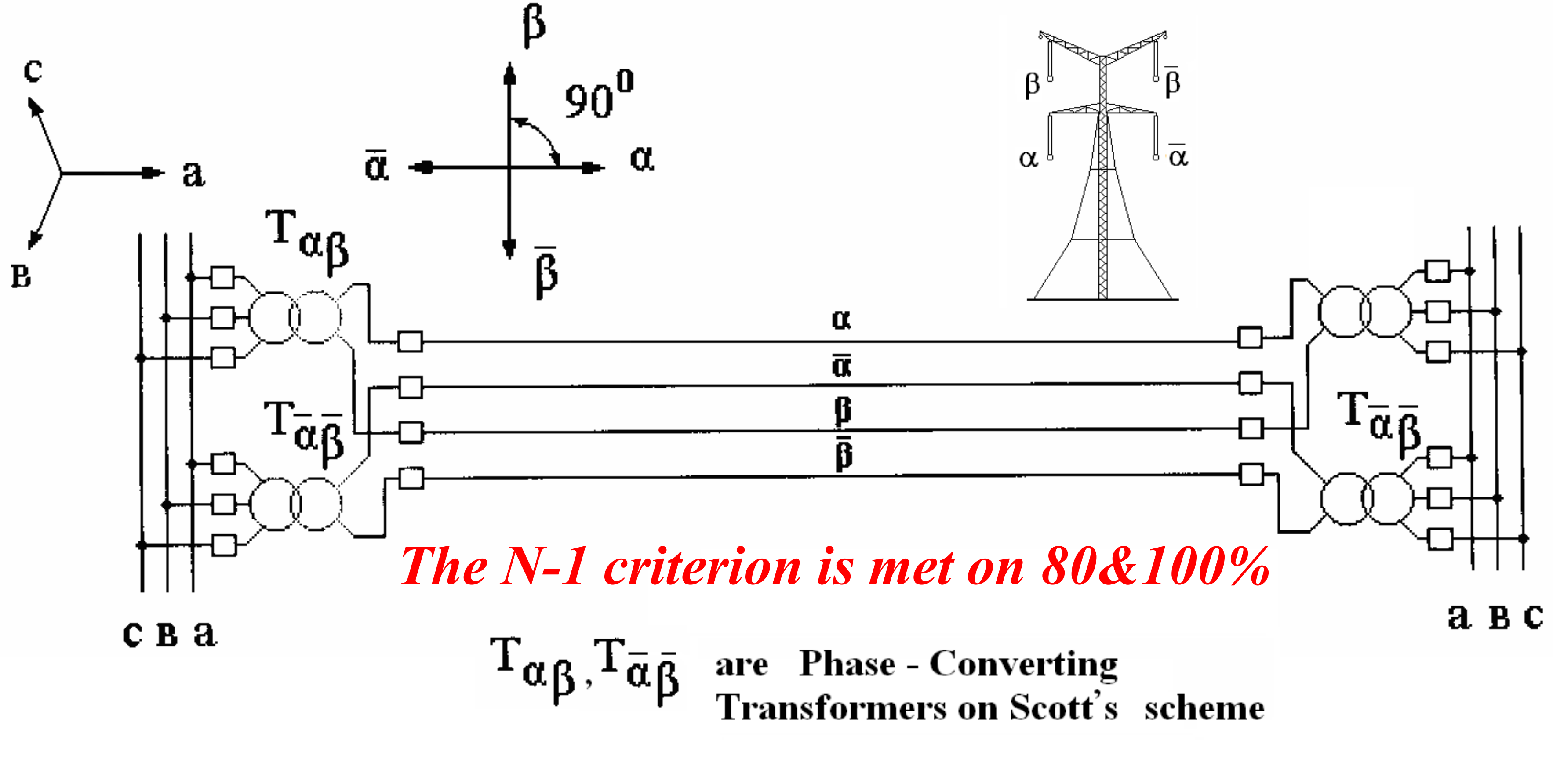
The 3-phase TS with Reserve Phase





The N-1 criterion is met on 100&100%

Electric circuit of the 4-phase TS



The distinctive features of the 4-phase TS:

- It is supplied with Phase-Converting Transformers;
- Phases of the 4-phase line form two symmetric 2-phase systems $\left(\alpha - \bar{\alpha} \text{ and } \beta - \bar{\beta}\right)$;
- Transition to a 3-phase mode is used at sustained single-phase fault.

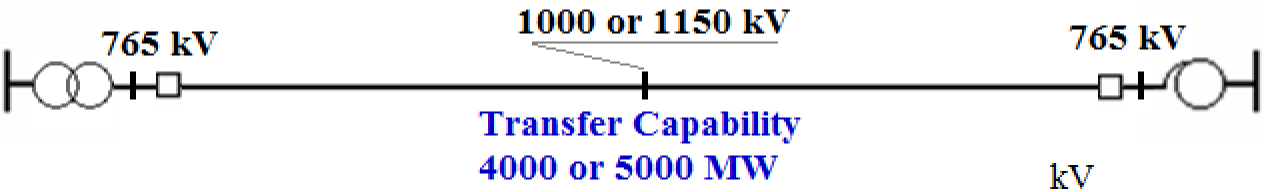
Transfer Capability of Very Long Transmission Systems

Type of Transmission System	DCTS		HWTS		
Nominal Voltage, kV	± 600	± 1000	765	1000	1150
Transfer Capability, GW	6.0	10.0	2.5* 3.5** 5.5***	4.5* 6.5** 10.0***	6.0* 9.0** 13.0***

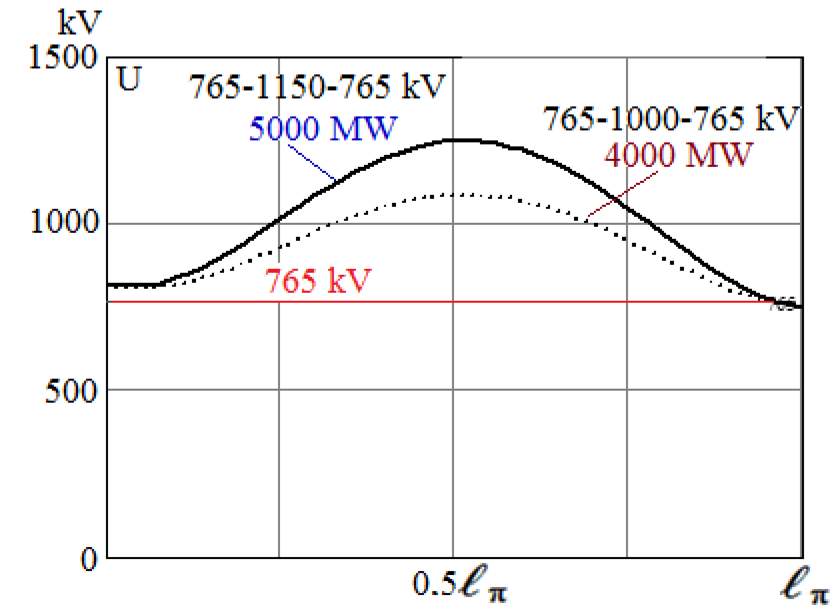
* Traditional 3-phase Line;
** Compact 3-phase Line;
*** Compact 4-phase Line.

Possible variants of HWTS with use of 765 kV equipment

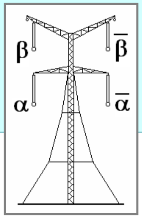
3-phase HWTS with the UH voltage in the middle of line (the humpbacked scheme 765 kV - UHV - 765 kV)

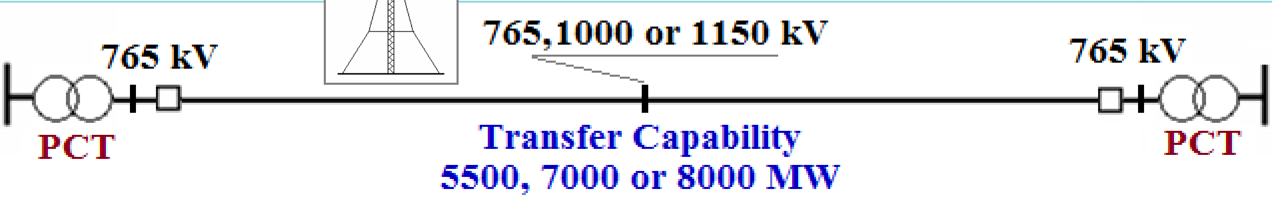


Voltage allocation along HWL at maximum transmitted power



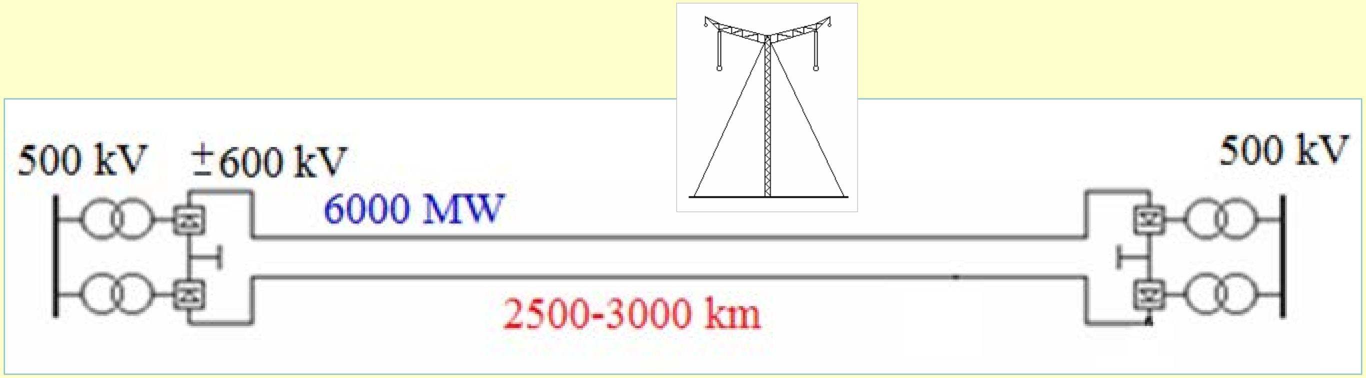
4-phase HWTS



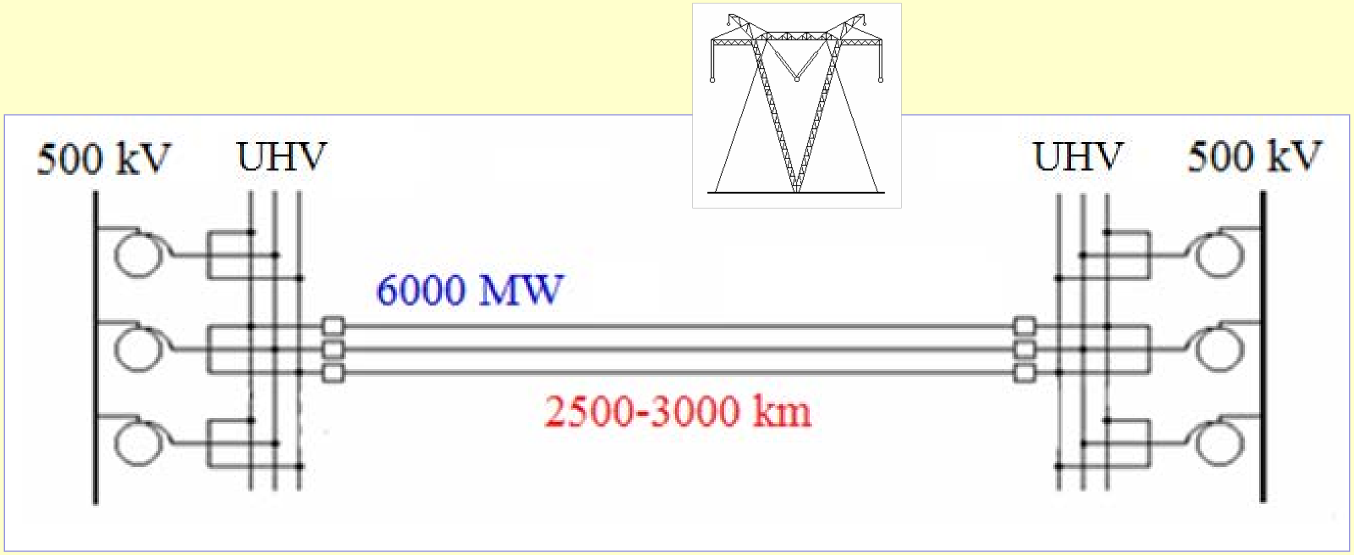


PCT is Phase-Converting Transformer

Very Long Transmission Systems with the least reliability

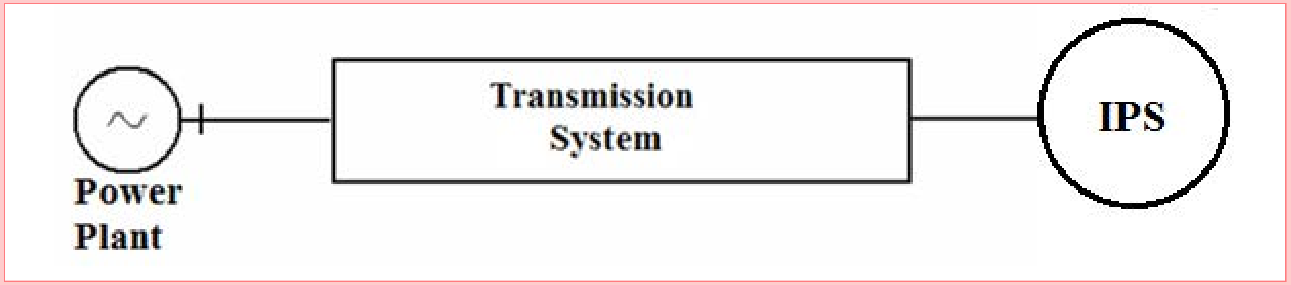


The 2-pole DCTS with one converting branch on a pole



The traditional 3-phase scheme

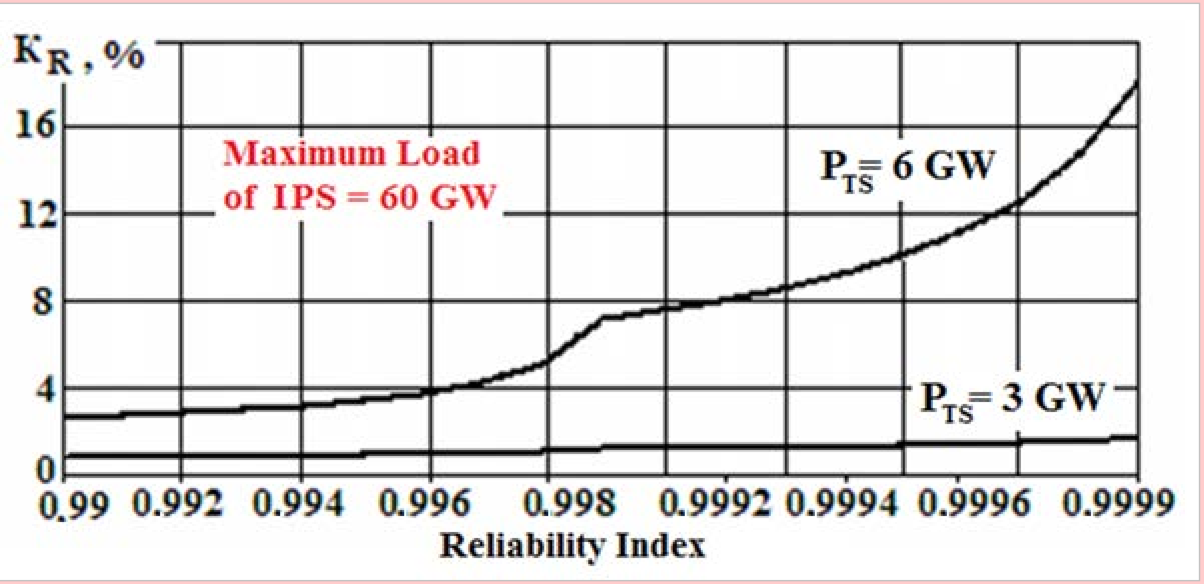
Evaluation of Reliability Worth



Reliability Index (RI) $RI = 1 - LOLP$

LOLP is Loss of Load Probability

Degree of Reserve increase depending on reliability index



Degree of Reserve increase:

$$K_R = \frac{R_{TS} - R_0}{R_0}$$

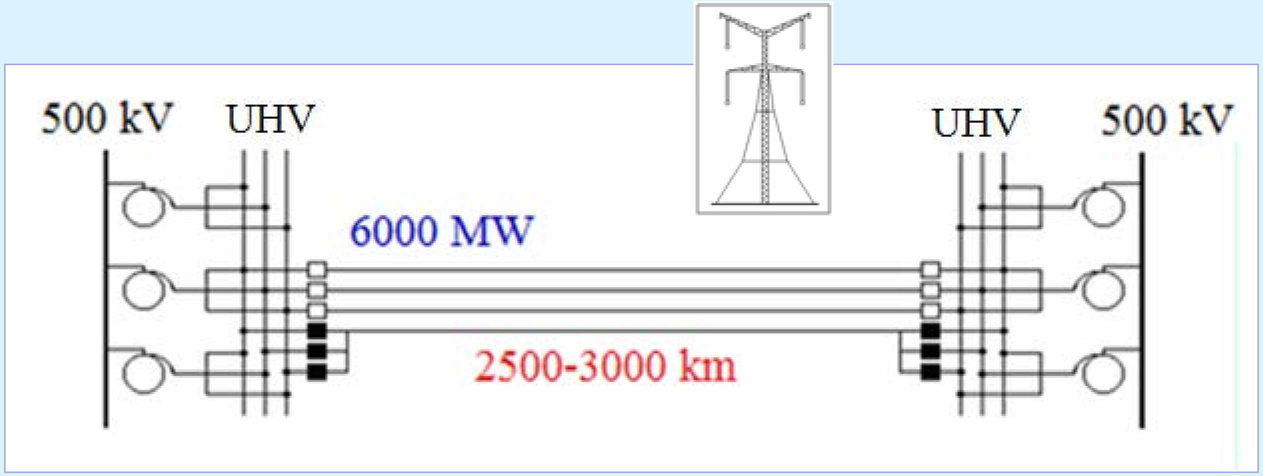
R_0 **is Reserve without regard for forced outages of TS;**

R_{TS} **is Reserve in regard to Forced outages of TS.**

Total cost : $C_\Sigma = C_{TS} + C_R$

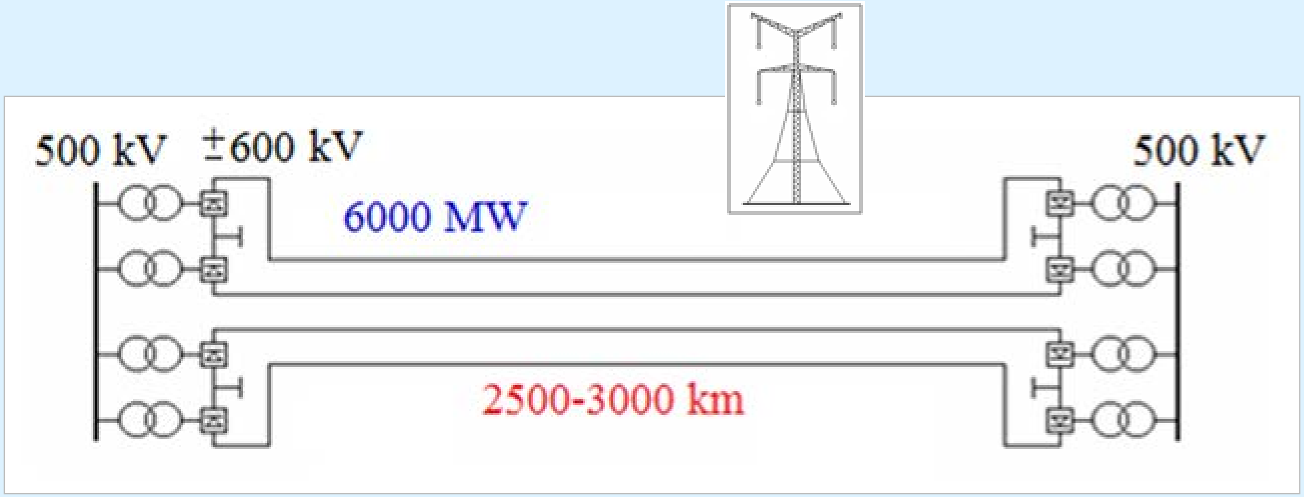
C_{TS} **is cost of TS;** C_R **is cost of the additional Reserve.**

The recommended variants of Very Long Transmission Systems



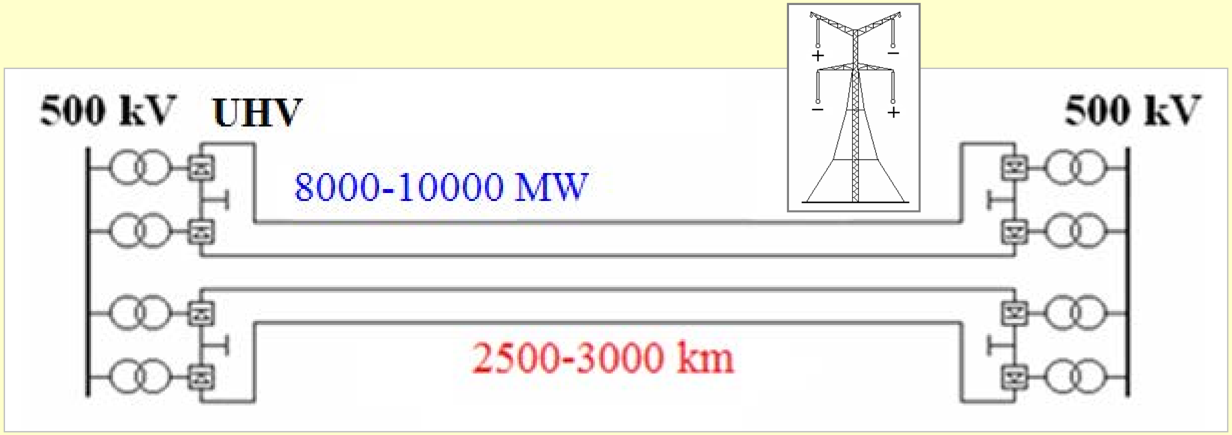
The 3-phase UHV HWTS with Reserve Phase

Expenses for the HWTS with Reserve Phase make about on 30 % less than for the 4-pole DCTS.

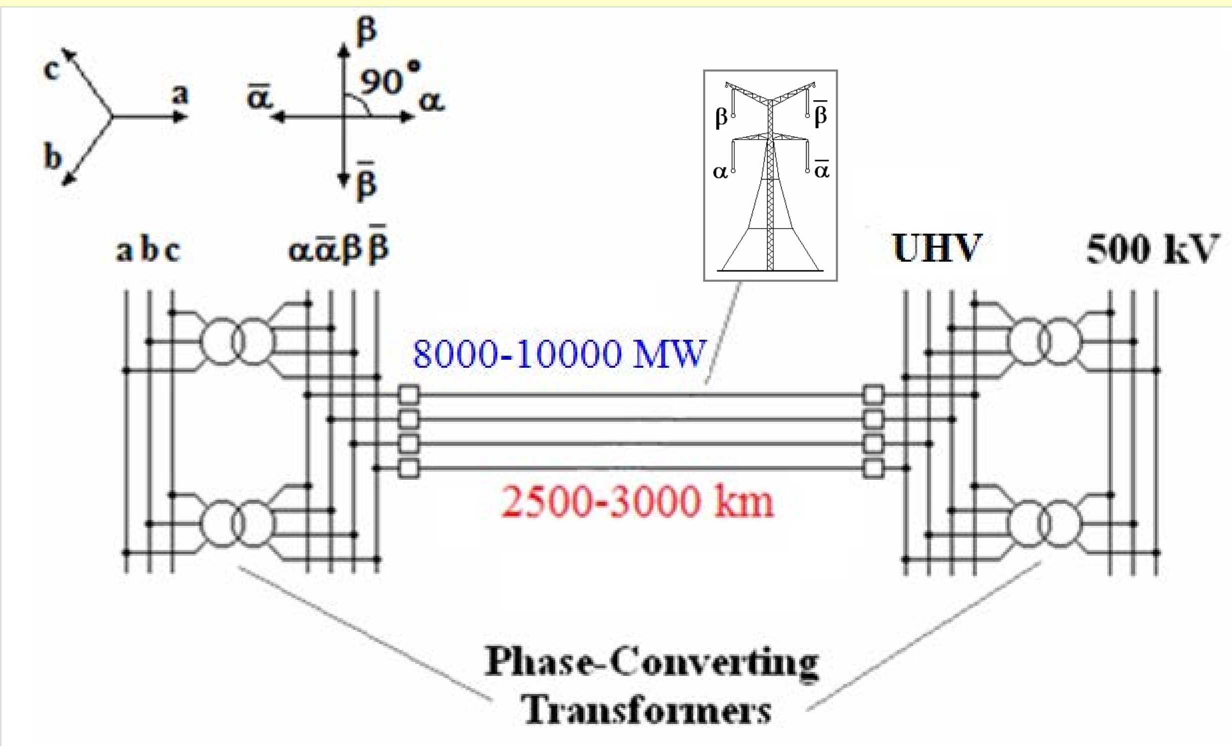


The 4-pole ± 600 kV DCTS

The advanced variants of Very long Transmission Systems



The 4-pole UHV DCTS



The 4-phase UHV HWTS

Conclusions

1. Power delivery over very long distances is possible both on DC and AC. The special attention should be given to reliability.

2. Economic and ecological reasons dictate the use of single-circuit Transmission Systems instead of double-circuit ones.

The N-1 criterion of reliability for the HWTSs is practically met by using line with Reserve Phase and the 4-phase scheme in virtue of the fact that overwhelming number of faults are single-phase ones.

3. Comparison from position of reliability and economic efficiency of the variants on AC and DC for delivery of 6000 MW over 2500 - 3000 km has shown that expenses for the Half-Wave Transmission System with Reserve Phase make about on 30 % less than for the 4-pole DCTS.

4. The basic directions of technical progress in the field of very long electricity transmission on AC:

- application of the Half-Wave Technology;
- development of the 4-phase Transmission Systems.