Compensation Technology for Electrical Length and Power Extraction System of Half-Wavelength AC Power Transmission Lines

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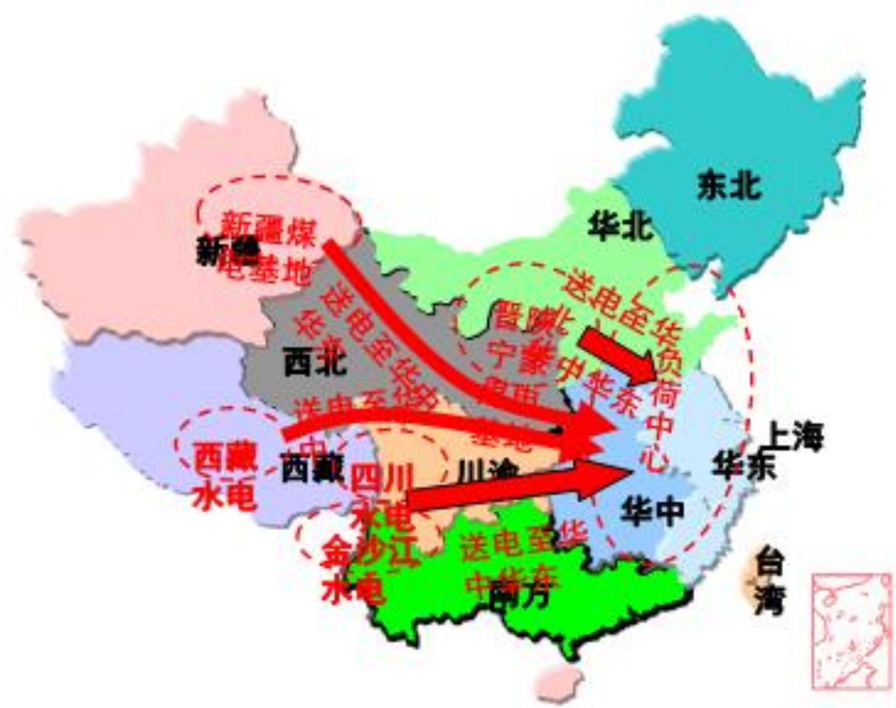
PART I. General Introduction

1. General Introduction

- **Distribution of resource and load in China**



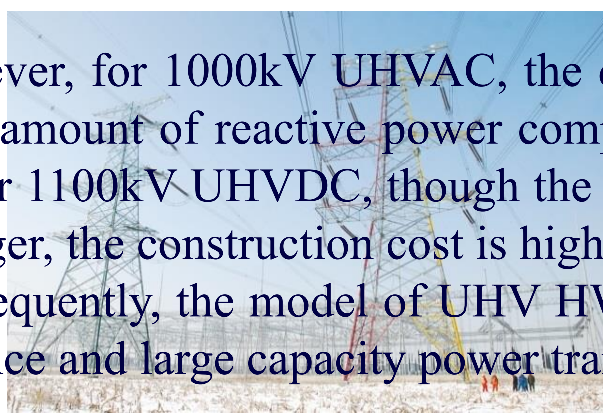
China is a vast, populous country, of which the level of development and resource distribution vary widely. In China, Exploitable power resources are mostly distribute in the west regions of China, while the power load distribute are mostly in the east. The length between east and west is about 2000~3 000km, so that the long distance, large capacity power transmission system is very useful in this kind of situation.

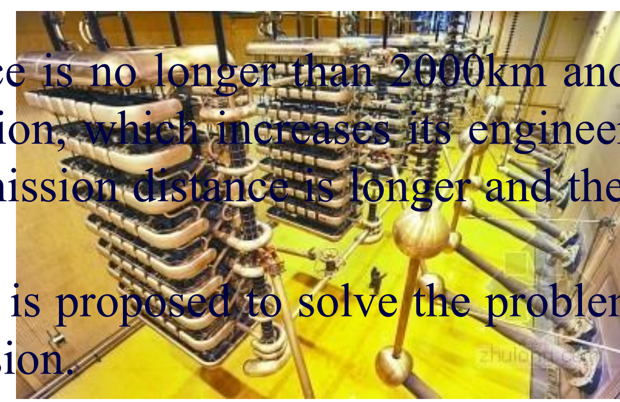
1. General Introduction

- **Current two modes of long distance large capacity power transmission system**

  1. Ultra-high voltage AC (UHVAC) transmission system
  2. Ultra-high voltage DC (UHVDC) transmission system

Type	Voltage level	Capacity	Distance
AC	500kV	1000MW	300~500km
AC	1000kV	5000MW	1000~2000km
DC	±500kV	3000MW	500~1500km
DC	±800kV/5000A	8000MW	1000~2000km
DC	±800kV/6250A	10000MW	1000~2000km
DC	±1100kV/5000A	11000MW	1500~3000km





However, for 1000kV UHVAC, the distance is no longer than 2000km and it needs large amount of reactive power compensation, which increases its engineering cost. As for 1100kV UHVDC, though the transmission distance is longer and the capacity is larger, the construction cost is high.

Consequently, the model of UHV HWACT is proposed to solve the problem of long distance and large capacity power transmission.

1. General Introduction

➢ Advantages of UHV HWACT

- No need to install any reactive-load compensation equipment
- No need to build any Switching Station
- Lower overvoltage level
- Better economy efficiency

1. General Introduction

2009.07~2011.09, sponsored by State Grid, four institutes of scientific research have joined the research team on UHV Half Wavelength AC Transmission (HWACT) system. They are China Electric Power Research Institute, State Power Economic Research Institute, State Grid Electric Power Research Institute and North China Electric Power University.

Researches are on different aspects of HWACT and the following part will introduce the research results on macro level.

1. General Introduction

➢ **Different research aspects of UHV HWACT**

- **Insulation Coordination**
- **Electromagnetic Transient Characteristics**
- **Steady-State Operation Characteristics**
- **Current Differential Protection Principle for HWACT**
- **Economic Analysis and Reliability Assessment**
- **Compensation Technology for Electrical Length and Power Extraction System of HWACT (**This is what this presentation is mainly about, and the details are in the following part of the presentation)

1. General Introduction

➢ Results of research on UHV HWACT

- JIAO Chongqing, QI Lei, CUI Xiang, Compensation Technology for Electrical Length of Half-wavelength AC Power Transmission Lines[J]. Power System Technology, 2011, 35(9): 17-21.
- XIAO Shiwu, CHENG Yanjie, WANG Ya, A Bergeron Model Based Current Differential Protection Principle for UHV Half-wavelength AC Transmission Line [J]. Power System Technology, 2011, 35(9): 46-50.
- ZHANG Zhiqiang， QIN Xiaohui. Research on 1'ransient stability of UHV Half wavelength AC 1'ransmission in the Plan of Sending out Electric Power From Xinjiang Region[J]. Power System Technology, 2011, 35(9): 42-45.
- HAN Bin， LIN Jiming， BAN Liangeng, Analysis on Electromagnetic Transient Characteristics of UHV Half wavelength AC Transmission System[J]. Power System Technology, 2011, 35(9): 22-27.
- SONG Yunting ZHOU Xiao, LI Bihui, Economic Analysis and Reliability Assessment of UHV Half-wavelength AC Transmission[J]. Power System Technology, 2011, 35(9): 2-6.

1. General Introduction

➢ Results of research on UHV HWACT

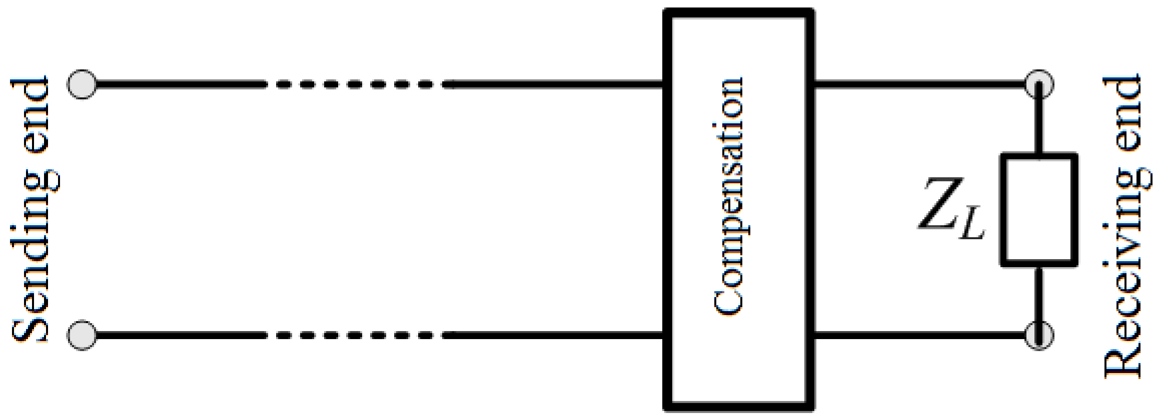
- ZHOU Jingshu1, MA Jin1. Steady State and Transient Operational Characteristics of UHV Half-wavelength AC Transmission System[J]. Power System Technology, 2011, 35(9): 28-32.
- ZHANG Zhiqiang, QIN Xiaohui, WANG Haohuai, Steady State Voltage Characteristic of UHV Half-wavelength AC Transmission Line[J]. Power System Technology, 2011, 35(9): 33-36.
- WANG Lintao， CUI Xiang. Research on Steady-state operation Characteristics Of UHV Half-wavelength AC Power Transmission Line[J]. Power System Technology, 2011, 35(9): 7-12.
- LI Zhanchun, WANG Lingtao. Preliminary Research on Power Extraction System Laid out Along UHV Half-wavelength AC Transmission Line[J]. Power System Technology, 2011, 35(9): 37-41.
- ZHANG Liuchun, ZHANG Cuixia, Insulation Coordination of UHV Half-wavelength Power Transmission System [J]. Power System Technology, 2011, 35(9): 13-16.

PART II. Compensation Technology

Compensation system of HWACT

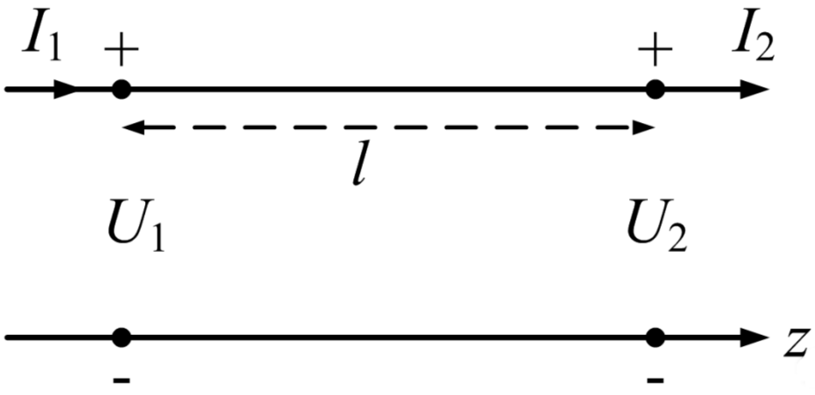
The electrical length of the HWACT is about half a wavelength, and the length is about 3000km (50Hz) or 2500km (60Hz) . Subject to conditions, the practical line length between the two ends is hard to be exact a half-wavelength. When the length is shorter than the half-wavelength, appropriate technology should be employed to increase the electrical length up to a half-wavelength.

Theoretically the compensation circuit and the compensated line should have the same transfer parameter matrix, so that the voltage and current distribution of the other part of the transmission line will not be affected.



Transfer parameter matrix of the transmission line

Model of uniform lossy transmission line



parameter matrix T

$$\begin{bmatrix} U_2 \\ I_2 \end{bmatrix} = \boxed{\begin{bmatrix} \cosh(\gamma l) & -Z_c \sinh(\gamma l) \\ -\frac{1}{Z_c}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix}} \begin{bmatrix} U_1 \\ I_1 \end{bmatrix}$$

Characteristic impedance： $Z_c=[(R_0+j\omega L_0)/(G_0+j\omega C_0)]^{1/2}$

Propagation constant： $\gamma=[(R_0+j\omega L_0)(G_0+j\omega C_0)]^{1/2}$

2.2 Computational Models

By and large, power transmission line is a low loss transmission line with its p.u.l. (per unit length) reactance ωL_0 being much more than its p.u.l. resistance R_0 and its p.u.l. susceptance ωC_0 being much more than its p.u.l. conductance G_0. So that the parameter matrix T can be approximated as the following parameter matrix.

$$\boldsymbol{T}=\begin{bmatrix} \cos\left(\omega\sqrt{L_0C_0}l\right) & -j\sqrt{\dfrac{L_0}{C_0}}\sin\left(\omega\sqrt{L_0C_0}l\right) \\ -j\sqrt{\dfrac{C_0}{L_0}}\sin\left(\omega\sqrt{L_0C_0}l\right) & \cos\left(\omega\sqrt{L_0C_0}l\right) \end{bmatrix}$$

Two types of compensation circuit

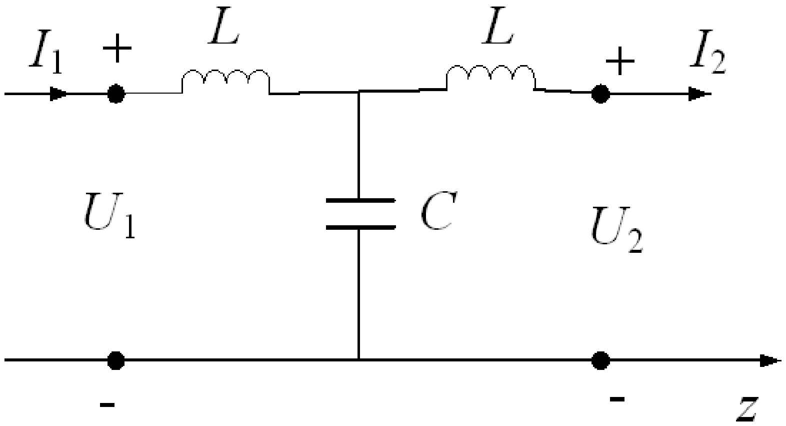
1. T compensation circuit (2 inductances and 1 capacitance)
2. Π compensation circuit (1 inductance and 2 capacitances)

The capacitance value in T compensation circuit is greater than that in Π compensation circuit, and the Inductance value in T compensation circuit is less than that in Π compensation circuit.

Compared with the real transmission line, the compensation circuit given can completely fit the reactance and susceptance parts of the transmission line, and the resistance and conductance parts of are ignored.

2.2 Computational Models

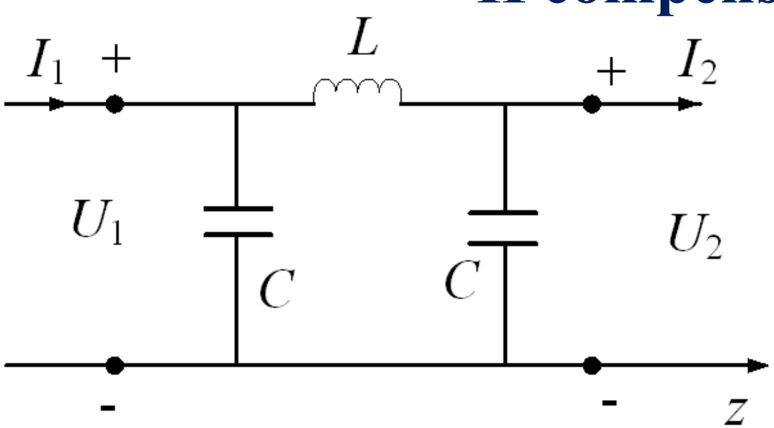
T compensation circuit



$$C = \frac{1}{\omega}\sqrt{\frac{C_0}{L_0}}\sin\left(\omega\sqrt{L_0C_0}l\right)$$

$$L = \frac{1}{\omega}\sqrt{\frac{L_0}{C_0}}\frac{1-\cos\left(\omega\sqrt{L_0C_0}l\right)}{\sin\left(\omega\sqrt{L_0C_0}l\right)}$$

Π compensation circuit



$$C = \frac{1}{\omega}\sqrt{\frac{C_0}{L_0}}\frac{1-\cos\left(\omega\sqrt{L_0C_0}l\right)}{\sin\left(\omega\sqrt{L_0C_0}l\right)}$$

$$L = \frac{1}{\omega}\sqrt{\frac{L_0}{C_0}}\sin\left(\omega\sqrt{L_0C_0}l\right)$$

A 1000kV ultra-high voltage AC transmission line

The p.u.l. positive sequence impedance

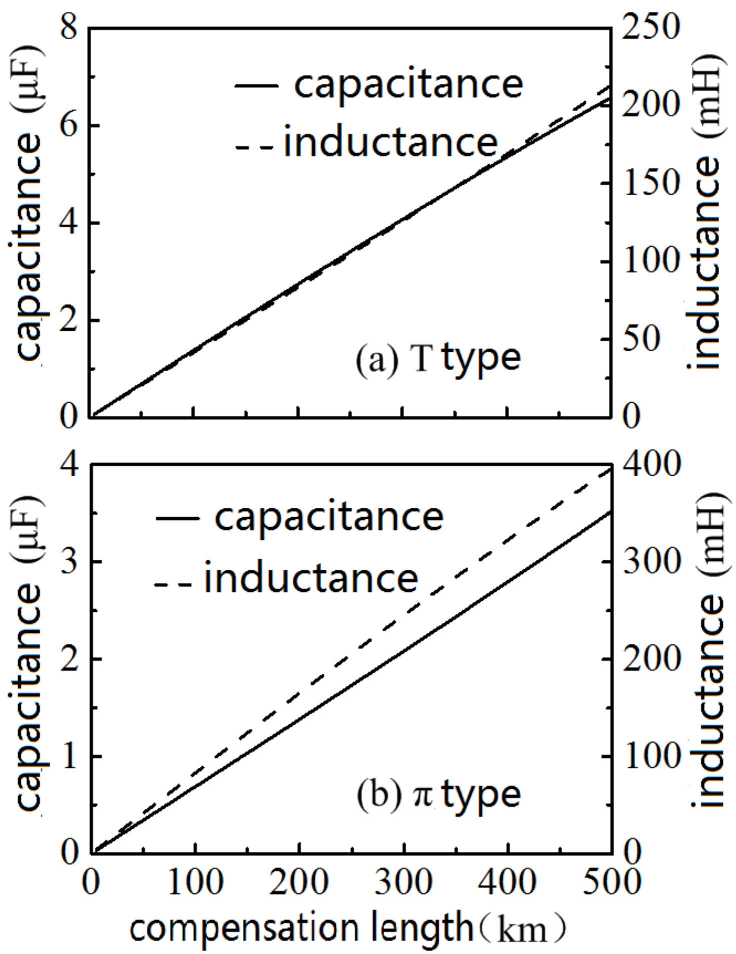
$$Z_0=0.0081+0.2615j\ \Omega/km$$

The p.u.l. positive sequence admittance

$$Y_0=(0.0002+0.4328j)\times 10^{-5}\ S/km$$

2.3 Results and Discussions

1）Dependence of capacitance and inductance on compensation length



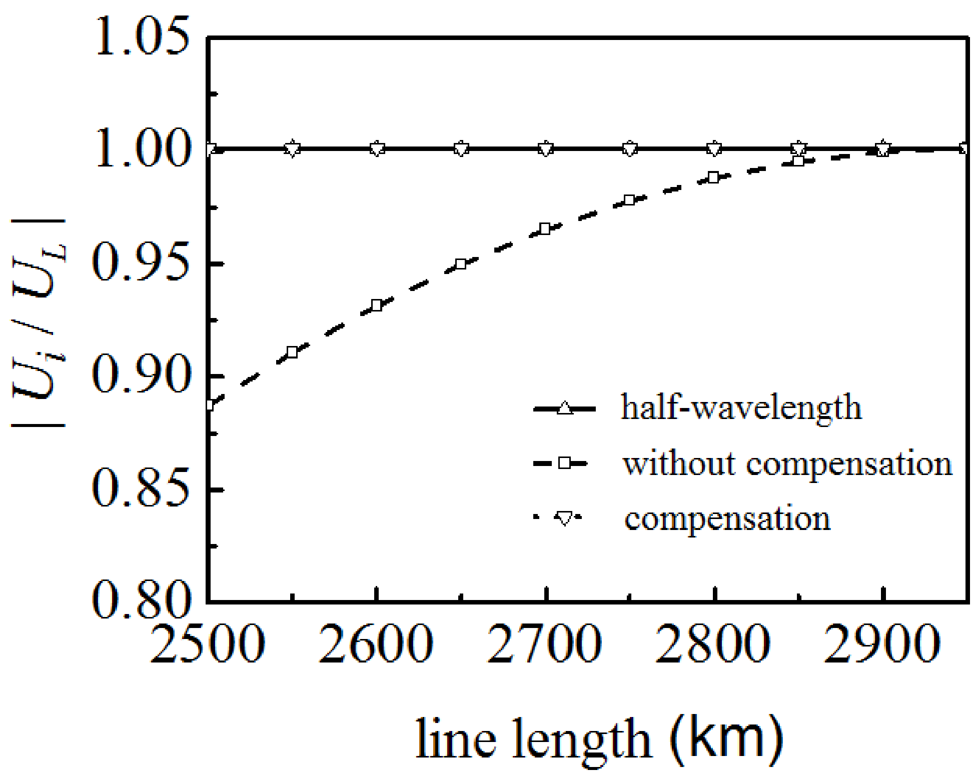
Within the range of compensated length been considered (0～500 km), the values of compensating capacitor and Inductance are approximately proportional to the Compensation Length. The value of the compensating capacitor in T compensation circuit is about twice as in Π compensation circuit, and the value of compensating inductance in Π compensation circuit is about twice as in T compensation circuit. The value of compensating capacitor is about several microfarad, and the value of compensating inductance is larger, and the maximum value is equal to hundreds of millihenries

2.3 Results and Discussions

The sending and receiving ends approximately have the same voltage amplitude and input impedance, which is an important characteristic of HWACT. The value of input impedance at the sending end will be very large if there is no load at the receiving end. But the value of input impedance maybe small if the practical line length is shorter than half wavelength due to the transmission line effects. At this time, there will be still some load at the sending end even if there is no load at the receiving end.

2.3 Results and Discussions

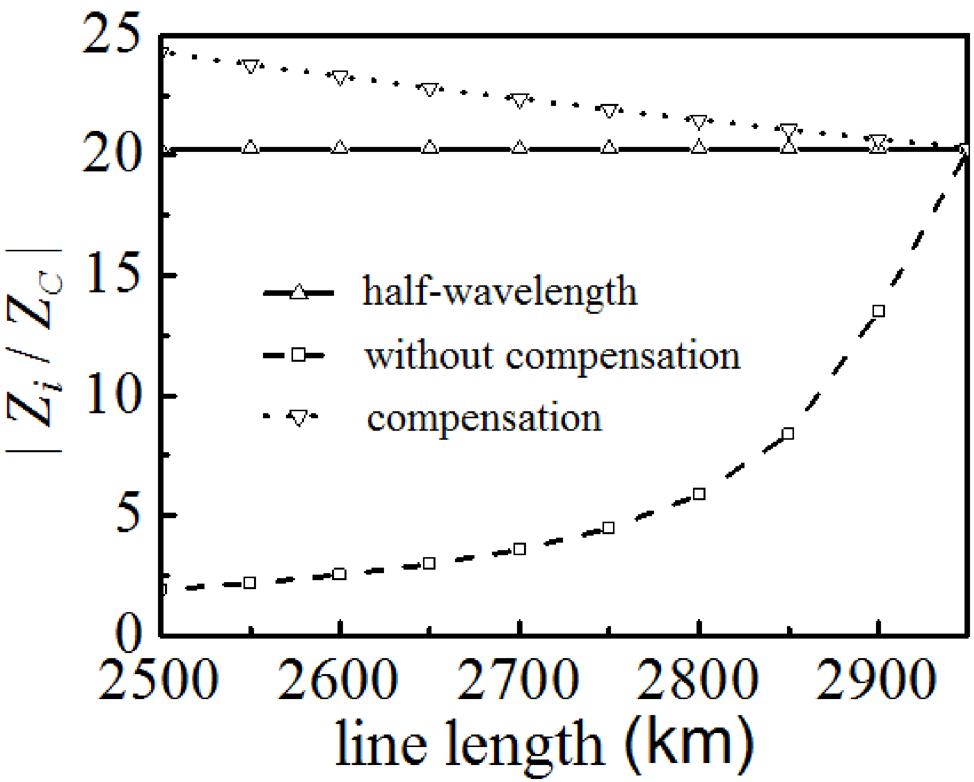
(2) Voltage at sending end versus line length with receiving end opened



Compensation can be helpful to achieve the same results as HWACT. The voltage amplitude at the sending end U_i is equal to that at the receiving end U_L. The voltage at the sending end will be significantly less than that at the receiving end without compensation. The greater of the distance difference between the practical line length and half wavelength, the higher the overvoltage level.

2.3 Results and Discussions

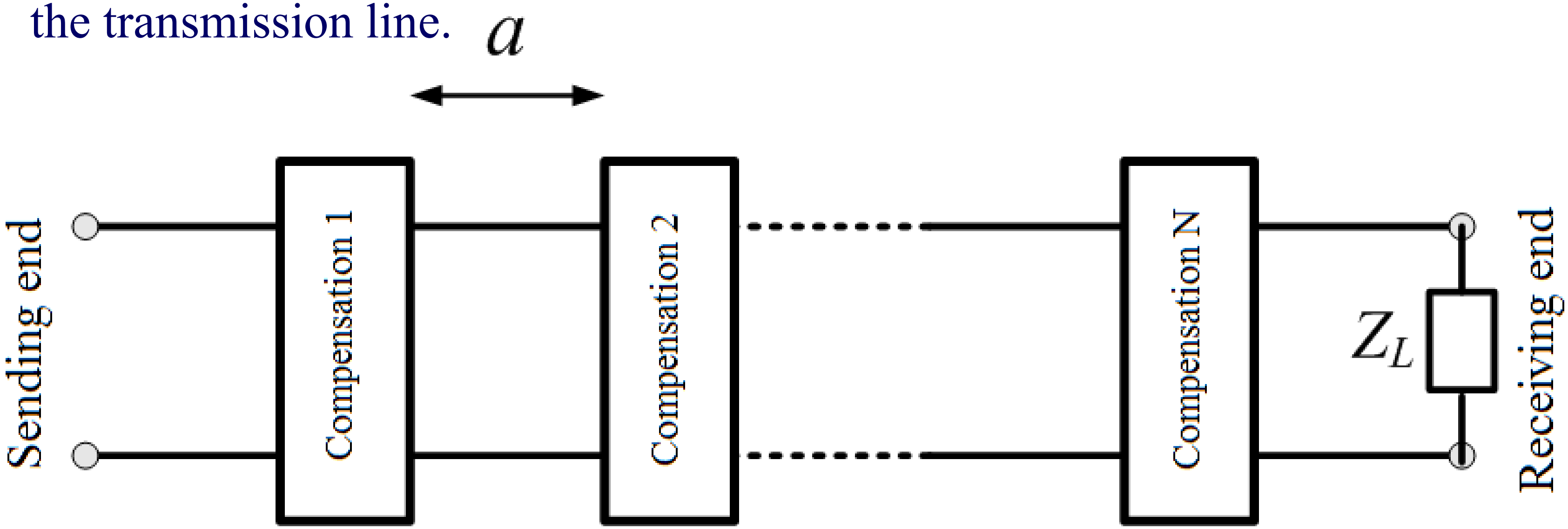
(3) Input impedance at sending end versus line length with receiving end opened



When the practical line length is half wavelength, the value of input impedance at the sending end Z_i will be about 20 times larger than the value of characteristic impedance Z_c, and the value of Z_i will be more than 20 times larger than the value of Z_c within compensation. The value of input impedance at the sending end will be smaller without compensation, so the sending end will still output 20% natural power even if there is no load at the receiving end.

2.3 Results and Discussions

Distributed compensation points can be considered to reduce the claims of compensating inductance. Some Compensation points are evenly distributed in the transmission line.



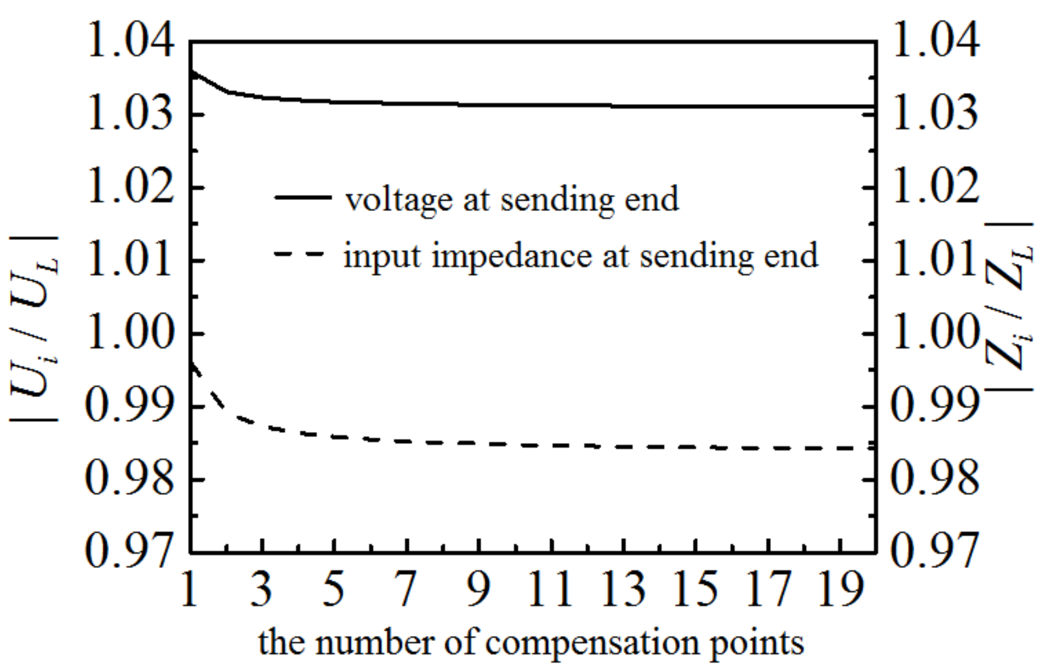
a → the distance between two compensation points.

N → the number of compensation points.

The length of line is (N+1)a， and each compensation length l=[λ/2-(N+1)a]/N

2.3 Results and Discussions

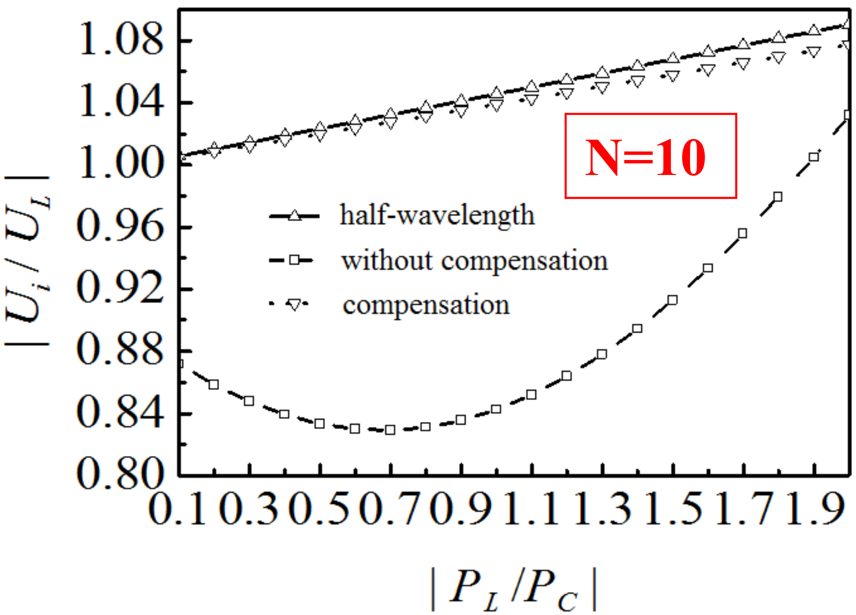
Influence of the number of compensation points on compensation effectiveness



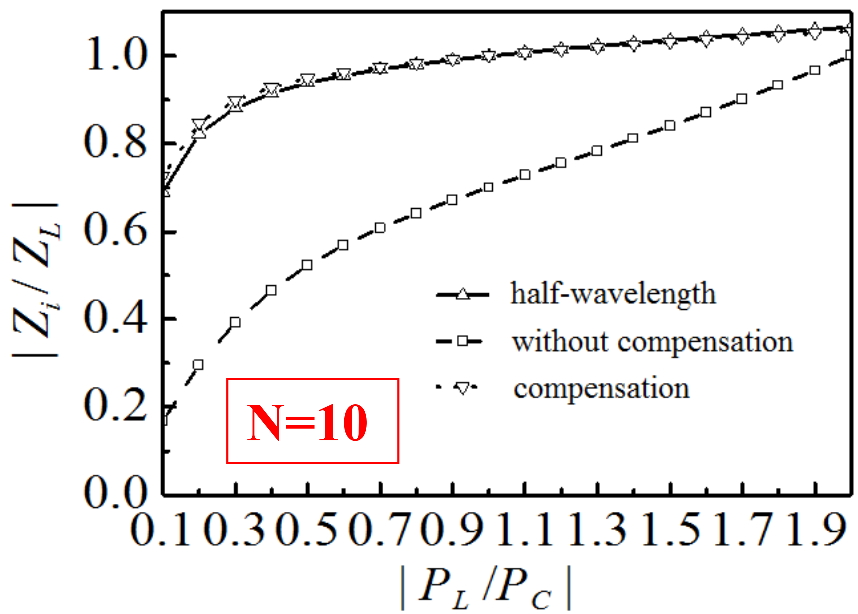
Suppose the length of the transmission line is 2500km, and the apparent power at the receiving end is 80% natural power with the power factor 0.9, we can see that the compensation effect has reached the stable if the number of compensation points is more than 5. It means that more compensation points are not necessarily better.

2.3 Results and Discussions

Influence of power at receiving end on voltage at sending end



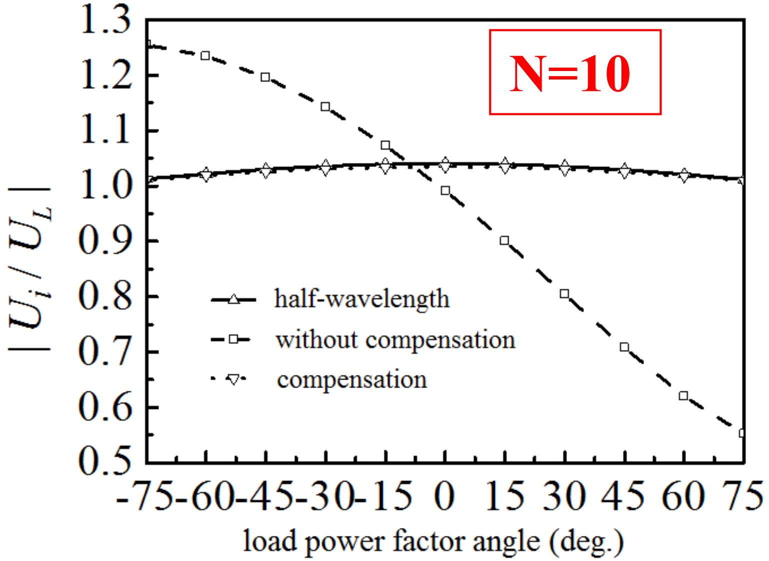
Influence of power at receiving end on input impedance at sending end



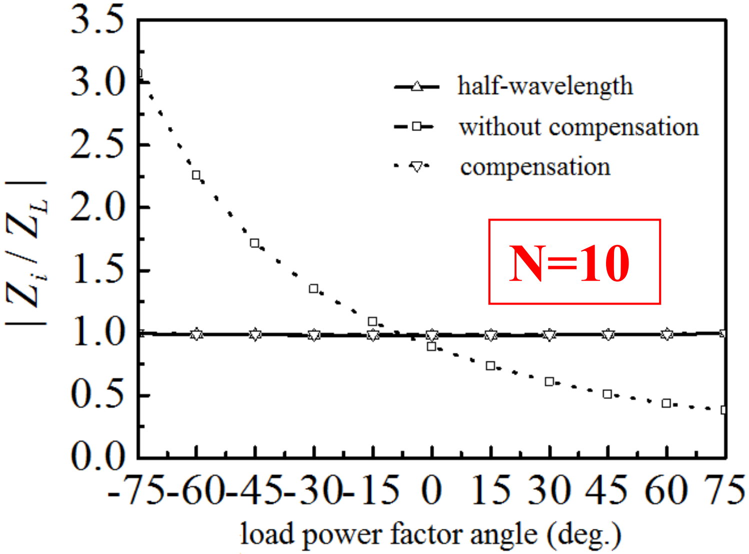
The values of voltage and input impedance at the sending end are basically same as that in the half wavelength transmission line within compensation. The values of voltage and impedance at the sending end will be significantly less than that in the half wavelength transmission line without compensation, and the lower power at the receiving end, the greater the difference.

2.3 Results and Discussions

Influence of power factor angle at receiving end on voltage at sending end



Influence of power factor angle at receiving end on input impedance at sending end



The values of voltage and input impedance at the sending end are basically same as that in the half wavelength transmission line within compensation. The values of voltage and impedance at the sending end will be significantly less (larger) than that in the half wavelength transmission line without compensation when the power-factor angle is less (more) than 0 degree, and the greater the reactance component of the load, the greater the difference.

PART III. Power Extraction System

➢ Reason For The Power Extraction System

Considering China's national conditions, the HWACT transmission lines often pass the places where the economies are less developed.

When HWACT is only from one end to another, it does no good to the places where it passes by. However, by applying the power extraction system this problem could be solved. It’s not hard in practical engineering and also economical.

➢ Comparison Between Different Extraction Systems

- **Substation**
  The most traditional methods. But the cost is high.

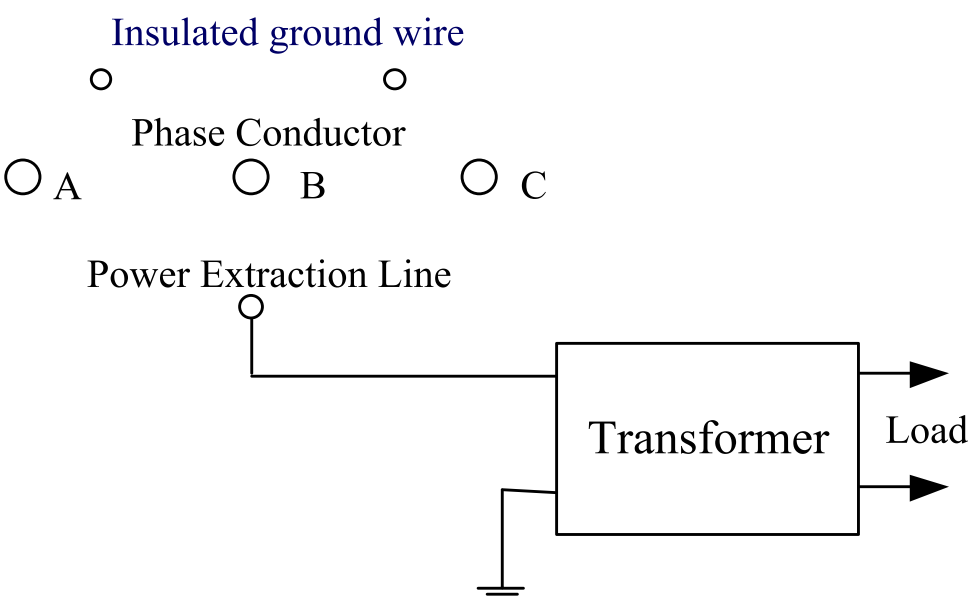
- **Insulated ground wire**
  The capacity is low, it can only provide very limited power to the local load or the communication equipment.

- **Energy Extraction Reactor**
  Cost is high and it requires site or switching station.

- **Parallel Energy Extraction line (Recommended method)**
  Economical, flexible, and easy to be implemented in practical engineering.

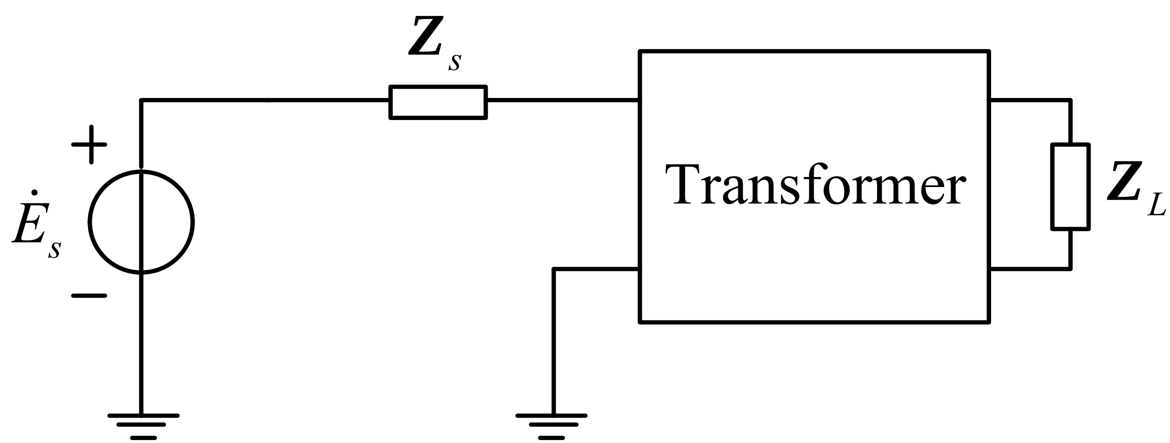
➢ Basic Principle of the Scheme

According to the theory of electromagnetic field, due to the electrostatic induction between the energy extraction line and the transmission line, there will be certain voltage to earth on the energy extraction line.



Cross-section diagram of AC transmission lines and extraction line

➢ Equivalent circuit of power extraction system



In this figure, E_s is the equivalent Open-circuit voltage, which comes from electromagnetic induction. Z_s is the internal impedance of the equivalent source. These two parameters are decided by the space electromagnetic coupling between the transmission lines and the power extraction lines.

- **Research on Parameters of Power Extraction System**

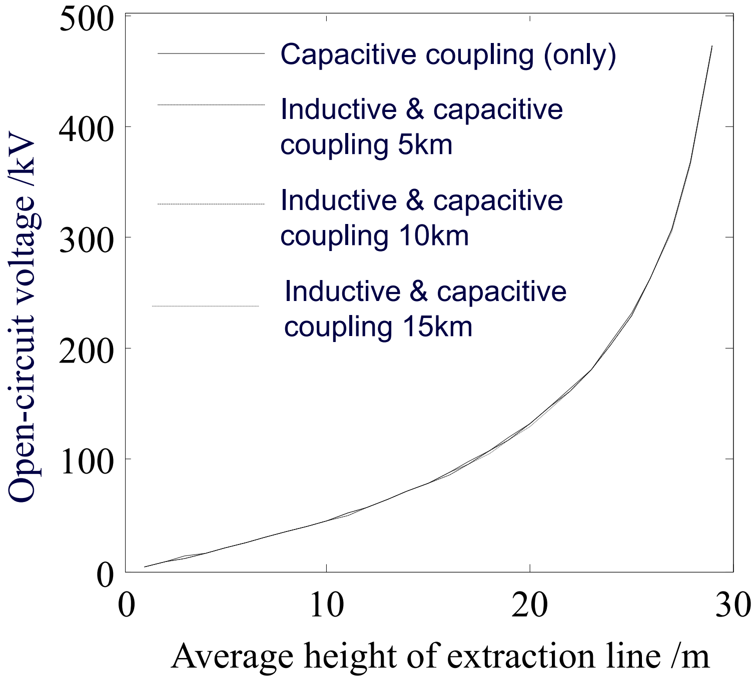
  Based on the Half Wavelength AC Transmission system, a simulation model has been built for the transmissions lines and power extraction lines. The equivalent Open-circuit voltage is gained by applying the Multi-conductor transmission line theory. Thevenin equivalent is done for the power extraction system and the parameters of equivalent source are calculated.

  The following part will demonstrate how the different factors influence the parameters of equivalent source.

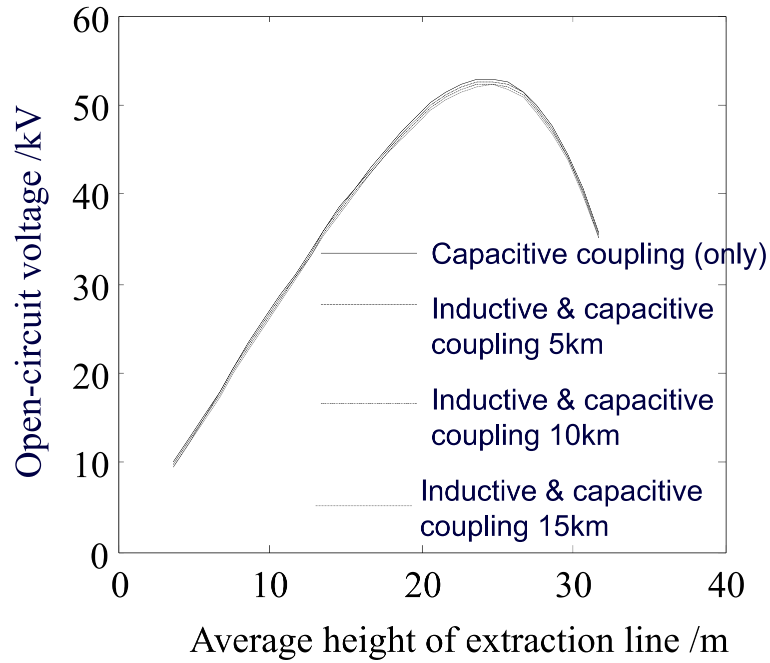
3.2 Basic Principle of the Scheme

➢ Open-circuit voltage

Transmission line in horizontal arrangement



Transmission line in triangular arrangement



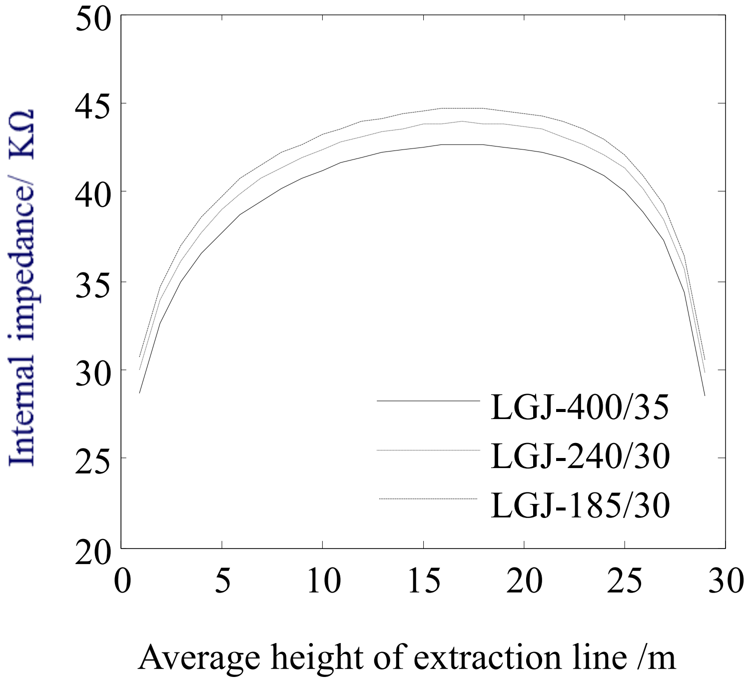
When the transmission line is in horizontal arrangement, the open-circuit will increase when the average height increases. When the transmission line is in triangular arrangement, when the average height increases, the open circuit voltage will increase first and the decrease.

The length of the extraction line makes little difference when it come to open circuit voltage.

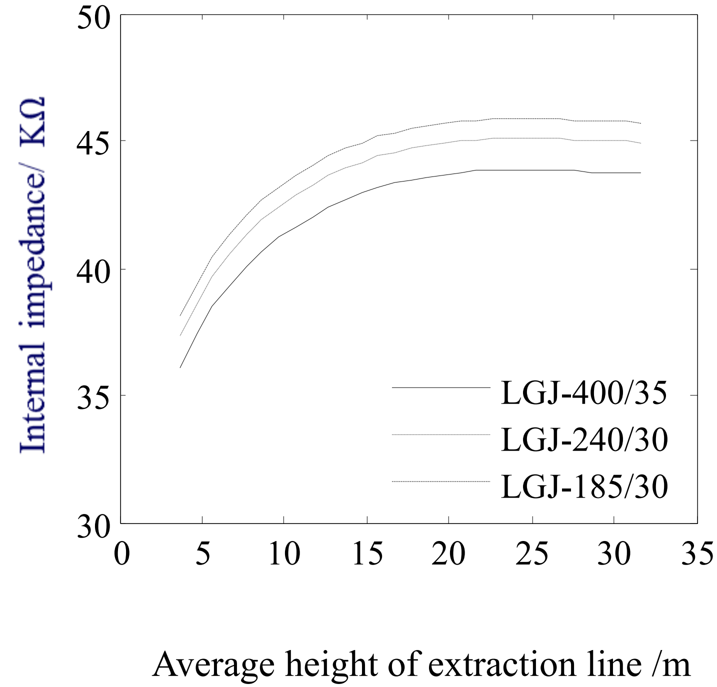
3.2 Basic Principle of the Scheme

➢ Internal impedance (1)

Transmission line in horizontal arrangement

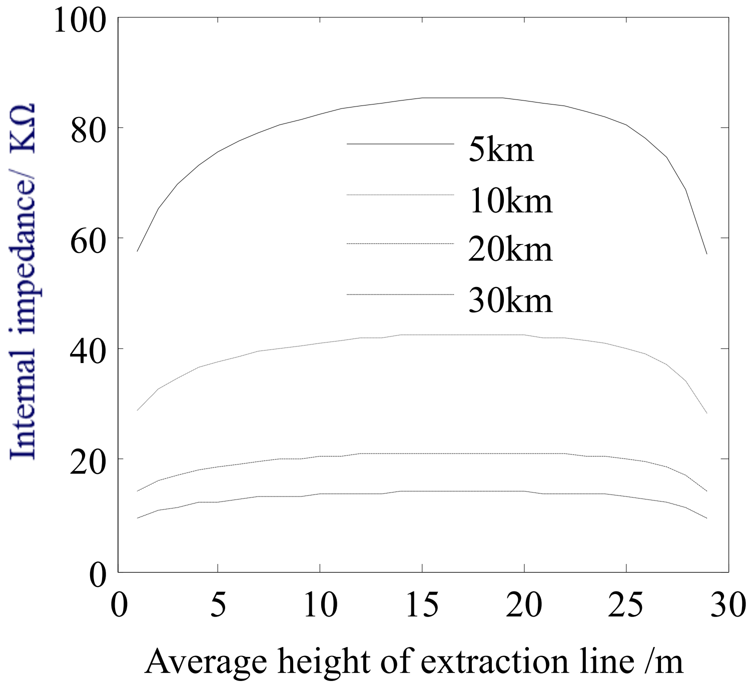


Transmission line in triangular arrangement

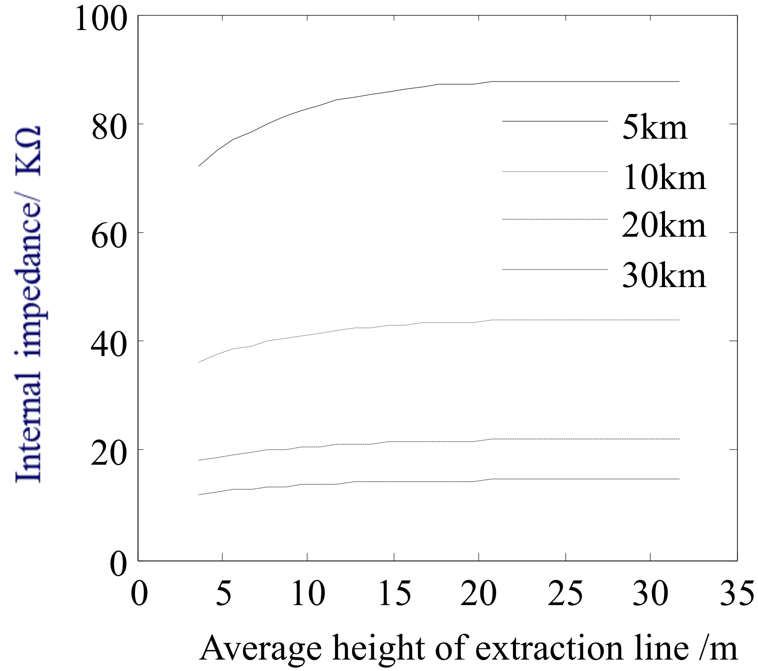


Internal impedance (2)

Transmission line in horizontal arrangement



Transmission line in triangular arrangement



It could be concluded from the figures that the longer the length and the bigger the radius, the smaller will the internal impedance be. When the transmission line is in horizontal arrangement, at the height of 5~28m, the change of the internal impedance is small. When the transmission line is in triangular arrangement, when the height is above 10m, the internal impedance gets saturated.

3.2 Basic Principle of the Scheme

Considering the practical engineering, the length of the extraction lines are made to be 10 km. Using the current voltage level as open-circuit voltage and the corresponding extraction lines are chosen. The results are shown below:

- The average height of the extraction line in horizontal arrangement

Open-Circuit voltage (kV)	Average height (m)	Lowest height (m)	comment
$66/\sqrt{3}$	8.65	4.32	Abandoned (too low)
$110/\sqrt{3}$	12.92	8.59	Fine
$220/\sqrt{3}$	19.64	15.31	Fine

- The average height of the extraction line in triangular arrangement

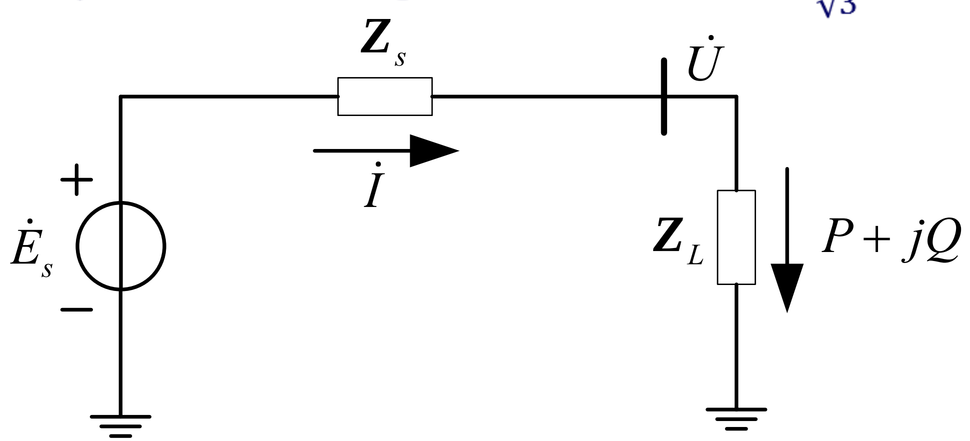
Open-Circuit voltage (kV)	Average height (m)	Lowest height (m)	comment
$66/\sqrt{3}$	14.52	10.19	Fine
52.50 (max)	24.60	20.27	Abandoned(special voltage level)

Load Characteristics

Power extraction systems are usually built in the places where the economies are less developed, so that the industry power consumption is relatively small. This presentation mainly focus on the pure resistance load and the load with the power factor of 0.9.

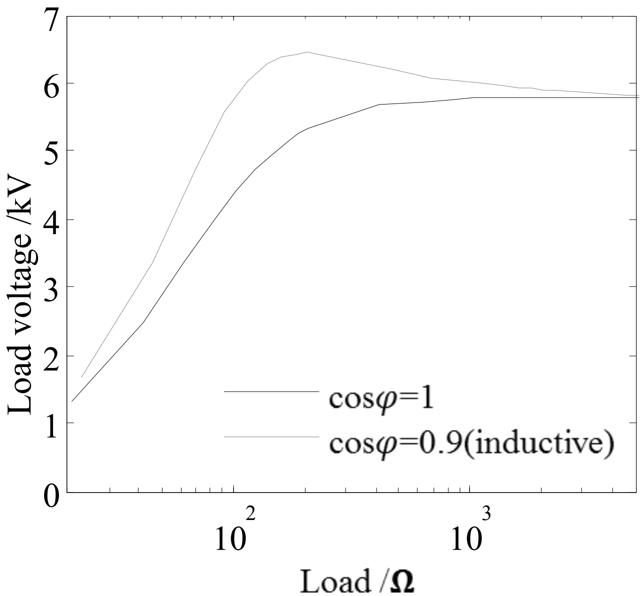
The figure below is the Equivalent circuit of power extraction system. ***U*** is the voltage at the load end, ***P*** and ***Q*** are the power consumed by the load.

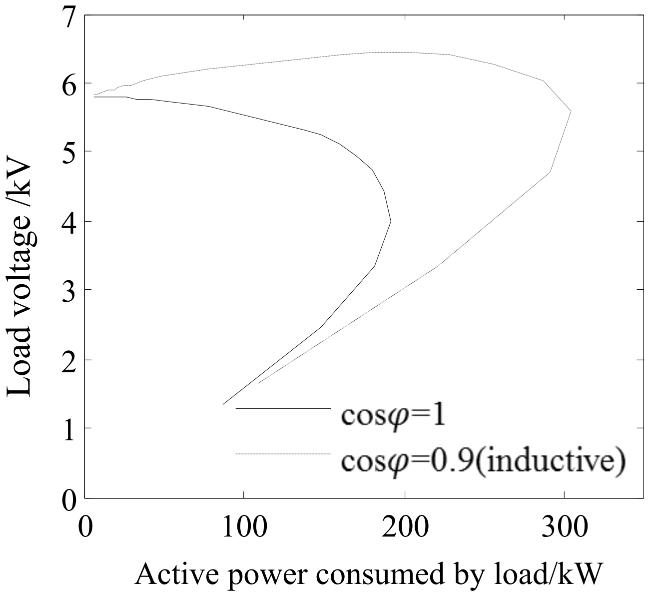
According to the analysis, the Load Characteristics on different voltage levels ($\frac{200}{\sqrt{3}}$kv, $\frac{100}{\sqrt{3}}$kv, $\frac{66}{\sqrt{3}}$kv) are basically the same. This presentation will use $\frac{200}{\sqrt{3}}$kv as example.



Equivalent circuit of power extraction system

➢ Load Characteristics





From the figure above, it could be concluded that when the load of the power extraction system increases, the voltage on the load end will decrease rapidly.

Load Characteristics

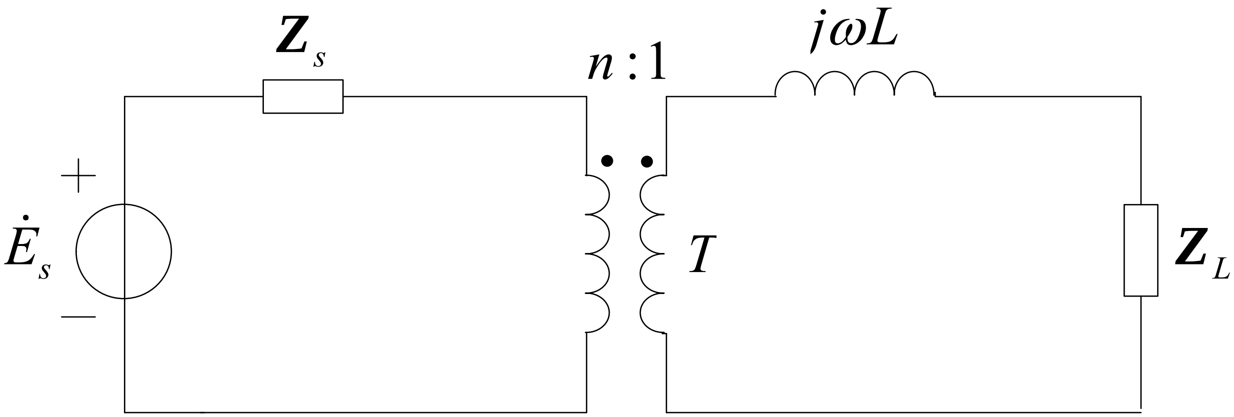
Power supplied by power extraction system

Load type	$220/\sqrt{3}$ kV(kW)		$110/\sqrt{3}$ kV(kW)		$66/\sqrt{3}$ kV(kW)	
	critical power	qualified power	critical power	qualified power	critical power	qualified power
Resistive	192	130	48	30	16	12
cosφ=0.9 (inductive)	305	75	76	19	26	6

Set the low-voltage side of the power extraction system to be 10 kV. According to China's relative standard GB/T 12325—2008, the variance of the voltage should be within ±7%. The chart above shows the critical power, which is the maximum power that the system can provide, and the qualified power, which meet the power quantity requirement. Compared with resistive load, the inductive load has worse performance, which means that improving the power factor is of great significance.

➢ Improvement Methods of Load Characteristics

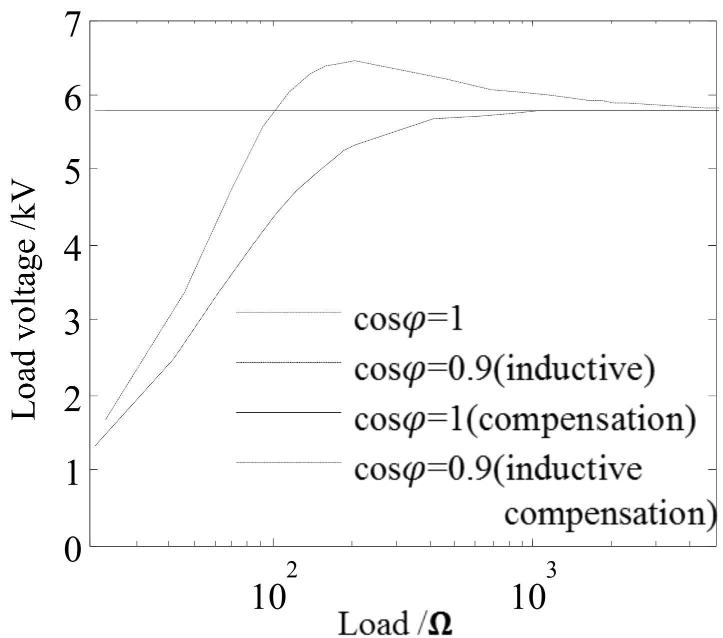
Equivalent circuit of power extraction system after reactance compensation

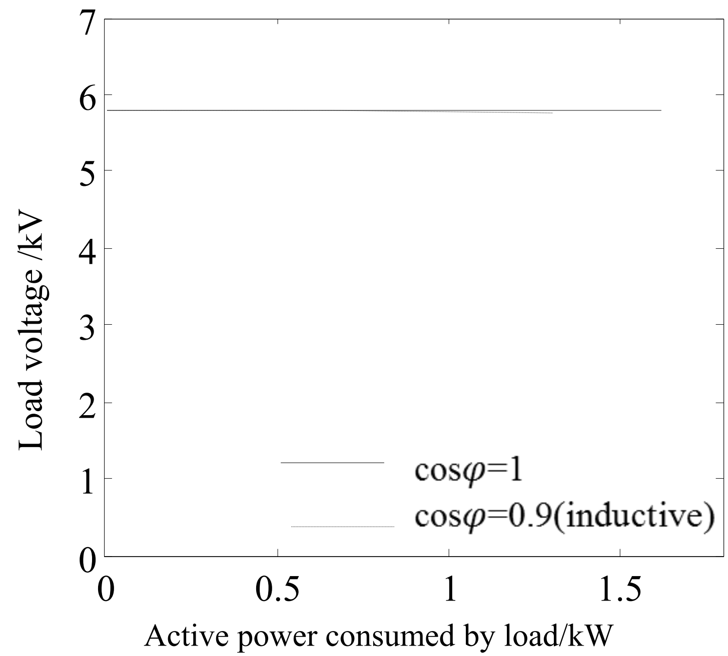


It because of the large the internal impedance of the extraction system that the system has very low ability to provide power to load. Since the internal impedance is mostly capacitive, series compensation reactor could be installed on the secondary side of the transformer to improve the performance.

If full compensation is wanted, for voltage level of $\frac{200}{\sqrt{3}}$kv, $\frac{100}{\sqrt{3}}$kv, $\frac{66}{\sqrt{3}}$kv, compensation inductance should be 0.279, 1.11, 3.24H respectively.

➢ Improvement Methods of Load Characteristics





The results after compensation are shown above. It could be seen that after the compensation, the performance improves significantly. However, it is at the cost that the compensation reactor absorbs a large amount of inactive power. Consequently, the load of the system should not be too large, or it will have high requirement for the capacity of the compensation reactor.

Improvement Methods of Load Characteristics

Before compensation

Power supplied by power extraction system

Load type	$220/\sqrt{3}$ kV(kW)		$110/\sqrt{3}$ kV(kW)		$66/\sqrt{3}$ kV(kW)	
	critical power	qualified power	critical power	qualified power	critical power	qualified power
Resistive	192	130	48	30	16	12
cosφ=0.9 (inductive)	305	75	76	19	26	6

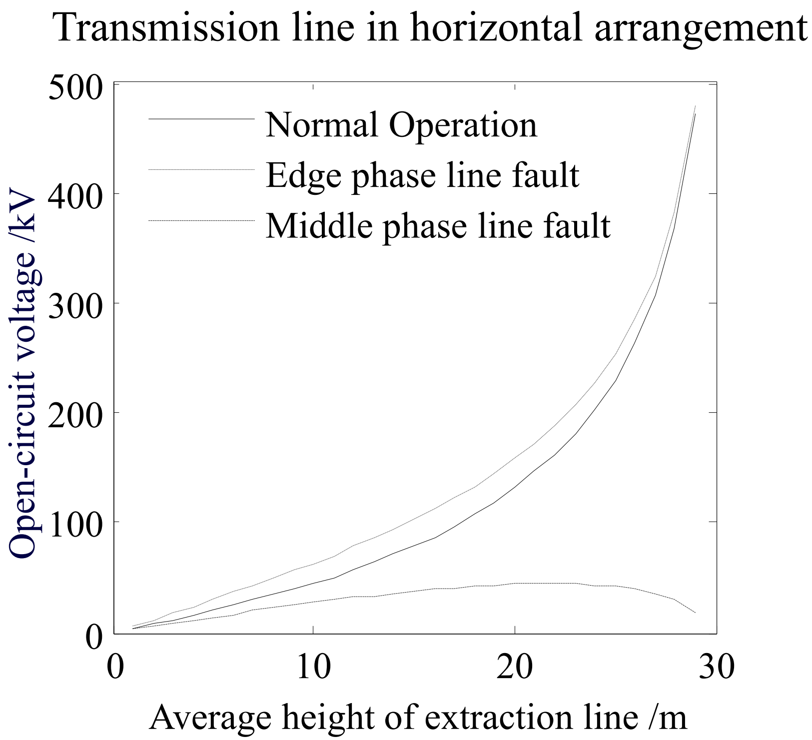
After compensation

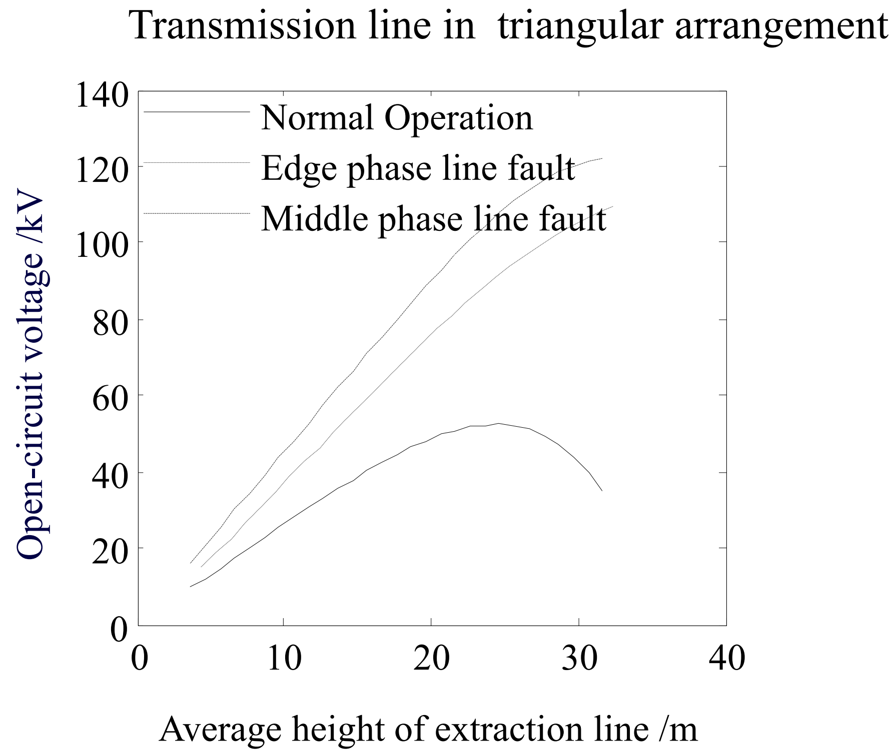
Power supplied by power extraction system

Load type	$220/\sqrt{3}$ (MW)	$110/\sqrt{3}$ (MW)	$66/\sqrt{3}$ (MW)
Resistive	1.6	0.4	0.15
cosφ=0.9(inductive)	1.3	0.3	0.1

3.4 Line Fault Influence

➢ single-phase earth fault occurred in the UHV HWACT line





Results of transmission line in different arrangement are shown above. In horizontal arrangement, the edge phase line fault will cause the equivalent voltage to increase while the middle phase line fault will cause the equivalent voltage decrease significantly. In triangular arrangement, both kinds of faults will cause the equivalent voltage to increase. And generally, the higher the extraction lines are, the more severe the results will be.

3.4 Line Fault Influence

➢ Single-phase Earth Fault Occurred In Load Line

The line current of high voltage side before reactance compensation

Load type	$220/\sqrt{3}$ kV (A)		$110/\sqrt{3}$ kV (A)		$66/\sqrt{3}$ kV (A)	
	Max power	Line fault	Max power	Line fault	Max power	Line fault
Resistive	1.10	3.01	0.52	1.51	0.33	0.87
cosφ=0.9 (inductive)	0.58	3.01	0.29	1.51	0.16	0.87

The line current of high voltage side after reactance compensation

Load type	$220/\sqrt{3}$ kV(A)		$110/\sqrt{3}$ kV(A)		$66/\sqrt{3}$ kV(A)	
	1.6 MW	Line fault	0.4 MW	Line fault	0.1 MW	Line fault
Resistive	12.75	1453.50	6.33	892.10	3.92	247.82
cosφ=0.9 (inductive)	11.43	1453.50	5.71	892.10	3.42	247.82

PART IV. General Conclusions

4. General Conclusions

➢ **Conclusions for Compensation Technology**

- The compensation circuit composed of capacitance and inductance can effectively compensate the missing length of the transmission line even if the loss of line is ignored through the comparison of the voltage and input impedance at the sending and receiving ends in several conditions.
- The value of the compensating capacitor in T compensation circuit is about twice as in Π compensation circuit, and the value of compensating inductance in Π compensation circuit is about twice as in T compensation circuit. The value of compensating capacitor is about several microfarad, and the value of compensating inductance is larger, and the maximum value is equal to hundreds of millihenries.
- Distributed compensation points can be considered to reduce the claims of compensating inductance, but the compensation effect will reach the stable if the compensation points had reached a certain number, and more compensation points are not necessarily.
- For the condition that the length of transmission line is less than half-waveform, the voltage and impedance characteristic will be different from that in HWACT without compensation, and the technical advantage of point to point transmission of HWACT is nonexistent without compensation employed.

4. General Conclusions

➢ Conclusions for Power Extraction System

- Through the research of HWACT system's basic principle, the elementary parameters of the power extraction system are analyzed. The results show that it is practical to build power extraction system ($\frac{200}{\sqrt{3}}$ kv, $\frac{100}{\sqrt{3}}$kv, $\frac{66}{\sqrt{3}}$ kv) by using power extraction lines.
- Adding series compensation reactors to the power extraction system could improve its load characteristics and enlarge the power capacity of the system. And relative current/voltage protection device should be added to the build power extraction system.
- Power extraction system has very important economical and social effect. Compared with WWWW, using power extraction lines could provide larger power capacity and compared with power extraction reactors, power extraction lines are more economical, which make it a good possible choice.
- The impact that power extraction system cause to the power system and its technical &economic feasibility still need further study.

That’s all, thank you!