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The Pricing model for Transmission and Distribution Tariff Under Different Voltage Levels Based on the Long-run Marginal Cost Method

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Abstract: An incremental load model during peak load period in which both load rate and simultaneity of load is given. To mitigate the influence of irregular putting into operation of transmission and distribution equipment on fluctuation of marginal cost of transmission and distribution, an annuity calculation method of average incremental cost is proposed, and a calculation model based on long-term marginal cost, which can rationally share the expense of voltage classes, is built. According to incremental load during peak load period and the final average incremental cost to be borne by different voltage classes, the transmission and distribution prices for different voltage classes are calculated. Case study on long-term marginal cost of a certain regional power network is carried out, and calculation results show that the proposed transmission and distribution pricing method can reflect economic trend in the future and is favorable to eliminate cross-subsidies as well as make the electricity prices borne by various consumers in different voltage classes more fair and reasonable.

1. INTRODUCTION

With the national economy smoothly and relatively rapid development, electrovalence reform had been one of the key factors in power industry reform and development; it is also an important tool that reflects power industry management thought and industry development direction. Applying science, reasonable, regulatory pricing methods to set electrovalence have the important theory value and practical significance for electrovalence must be given lull play in the allocation of power resources.

Methods of setting electrovalence fall into two main groups, accounting cost pricing method and marginal cost pricing method. Traditional embedded cost method includes postage stamp method [1-2], contract route method [3], line by line calculation method and MK km method [4-6] and so on. Literature [7-8] improved MK km method. Literature [7] researches reactive power based on comprehensive cost allocation in the electricity market of associated operation pattern based on power flow composition analysis, and proposes a kind of functional computational method. Literature [8] proposes a transmission service pricing method based on physical path capital flow tracking, relative to MW km method, the method is known as capacity flow-capacity path method. Literature [9] considers system reliability and providing economy information method relatively. These methods have a common characteristic that focus on compensating the actual cost for Power Grid Corp [10]. At

the same time, these methods have some shortcomings, such as postage stamp method crossing subsidy seriously, contract route method' routes uncertainly and loop network problem inextricability, line by line calculation method' results relating to calculation transport business order.

Different from accounting cost method setting electrovalence, long-term marginal cost method based mainly on incremental situation of the generation and grid investment and incremental situation of load power capacity to calculate marginal cost in the future planning period, and then form all kinds of electrovalence. It reflects future economic cost changing trend and future resources value; therefore, it can bring about real economic signal for users.

Electric power system long-term marginal costs always include long-term generation marginal cost [11, 12] and long-term transmission and distribution marginal cost. Long-term transmission and distribution marginal cost is the increase of the transmission and distribution expenses for meeting users' future unit load demand growth. As a result of transmission and distribution equipment its own characteristics, relative to electricity load uniform growth, transmission and distribution equipment investment exists superior non uniformity, especially is higher voltage level, construction and operation of equipment to achieve the rated operating conditions after a few years later. Therefore, comparing with load increasing situation, its investment volatility is great. In order to gentle the impact of putting into the kind of equipment' non uniformity for transmission and distribution marginal cost fluctuation, the paper adopts long-term average incremental cost method [13] to calculate transmission and distribution long-term marginal cost, each voltage

classes peak load incremental, expense incremental and average incremental cost and annuity in the planning period.

2. PEAK INCREMENTAL LOAD CALCULATING METHOD AND MODEL

2.1. Peak Load Calculating in the Planning Period

As a result of long-term marginal cost pricing method considering the impact of increasing of future load for the increasing of electric power system cost, therefore, electric power system load forecast is the foundation of calculating electric power system long-term marginal cost.

In order to calculate each voltage classes' incremental load in the system peak period, we need to forecast all kinds of load electricity consumption yearly of each voltage classes, then according to all kinds of users load rate, calculating each users' highest power consumption load of corresponding yearly maximum load day. Because each user's load characteristic is different, the highest load occurrence time and load rate are different, the impact for system highest load is different. In order to describe the impact of each user highest load for system highest load, after considering each load simultaneity factor, we need calculate each voltage classes load of system peak load period.

Assuming the planning period is n year; $t = 1, 2, \mathrm{L}, n$ the voltage class from high to low are 500kV, 220kV, 110kV, 35kV, 10kV, 380/220V, $k = 1, 2, \mathrm{L}, 6$; each voltage class user type is $p, p = 1, 2, \mathrm{L}, P$. Assuming user p base year electricity capacity is Q_p^k of voltage class k, the electricity quantity growth rate of user p is r_p every year.

$$Q_{t,p}^k = Q_p^k \left(1 + r_p\right)^{(t-1)} \tag{1}$$

Where, $Q_{t,p}^k$ is user p' power consumption of voltage class k in the t year.

Each voltage classes load demand when system peak load is:

$$D_t^k = \sum_{p=1}^P \left(Q_{t,p}^k \eta_{CFp}^k / \eta_{LFp}^k\right) / 8760 \tag{2}$$

Where, D_t^k is peak load demand of voltage class k in the t year; η_{LFp}^k is user p'load rate of voltage class; η_{CFp}^k is user p'simultaneity factor of voltage class k.

Simultaneity factor is the ratio between system highest load and the sum of maximum loads each user. There is a relationship between users' simultaneity factor and the load ratio. Normally, the load ratio is higher, simultaneity factor is higher; otherwise, the load ratio is lower, simultaneity factor is lower. We can get the relationship between the load

ratio and simultaneity factor though investigating and counting.

2.2. Transmission and Distribution Loss Calculation Model

After getting the highest load demand of the maximum load day in view of each voltage class of simultaneity factor, we need calculate electric power transfer relationship of each voltage class at peak load period year after year. Firstly, we need confirm line loss rate and variable loss rate of each voltage class at peak load period. The article carry out calculating based on the benchmark year.

According to transmission line, converting substation' physical properties, we can calculate and get the proportional relationship between copper losses of line and converting substation and iron losses.

$$\begin{cases} \eta_L^{k/(k+1)} = \eta_{LossL}^k / \eta_{LossL}^{k+1} \\ \eta_T^{k/(k+1)} = \eta_{LossT}^k / \eta_{LossT}^{k+1} \end{cases} \tag{3}$$

Where, η_{LossL}^k is the line loss rate of voltage class k; η_{LossT}^k is the variable loss rate which voltage class k supply power to lower voltage class; η_{LossL}^{k+1} and η_{LossT}^{k+1} is line loss ratio and variable loss rate of adjacent voltage class respectively.

Assuming voltage class k' power supply load is S^k, including power plants' power supply output of the voltage in the area and the power supply output of the higher voltage class; the users' load of voltage class k is D^k; S^{kl} is the supply power load from voltage class k to low voltage class l, V^{kl} is the supply power load from high voltage class k to voltage class 1, electric power balanced model is given as:

$$\begin{cases} S^k = \left(D^k + \sum_{l<k} S^{kl}\right) / \left(1 - \eta_{LossL}^k\right) \\ S^{kl} = V^{kl} / \left(1 - \eta_{LossT}^k\right), l < k \\ \delta_{k,lj} = V^{kl} / V^{kj}, l < k, j < k \\ \sum_{k=1}^6 G^k = \sum_{k=1}^6 D_{LOSST}^k + \sum_{k=1}^6 D_{LOSSL}^k + \sum_{k=1}^K D^k \end{cases} \tag{4}$$

Where, $\delta_{k,lj}$ is the supply power ratio from high voltage class k to low voltage class 1 and j; D_{LOSST}^k and D_{LOSSL}^k is substation losses load and line losses load of voltage class k respectively; G^k is power plant output of voltage class k, including purchasing power; $\delta_{i,jk}$ is the supply power ratio from high voltage class i to low voltage class j and k; G^k is supply power load; users' power load D^k and $\delta_{k,lj}$ are known number, others are unknown number.

We can get line loss rate and substation loss of each voltage class though adjusting $\eta_L^{k/(k+1)}$ and $\eta_T^{k/(k+1)}$, $k = 1, 2, \cdots, 5$ and iterative computation which making each voltage class achieve to balance between supplying power and consumption power.

2.3. Each Voltage Class Incremental Load Calculation

Beginning from the lowest voltage class, according to each voltage class' supply power relationship, we can calculate each voltage class' the highest supply power load of system peak load period to high voltage class.

For the lowest voltage class 380/220V, the supply power load of system peak load in t-th year is:

$$\begin{cases} S_t^6 = P_{DTt}^6 / \left(1 - \eta_{LossL}^6\right) \\ P_{DTt}^6 = D_t^6 \end{cases} \tag{5}$$

Where, P_{DTt}^6 is the total peak load demand of voltage class 380/220V; D_t^6 is the highest load demand of voltage class 380/220V; η_{LossL}^6 is peak load line loss rate of voltage class 380/220V in the highest load of system.

For higher voltage class, the next class supply power load must be considered when calculating the highest supply power load of the maximum load day. The highest demand power load of the voltage class is the sum of the highest supply power load of the next class and the highest load demand of the class. Assuming there is the power plant accesses to the next voltage class, deducting supply power load of the next class power plants in the highest load of system when calculating the highest supply power load. If the highest load demand of voltage class k in the t-th year is D_l^k, the total peak load demand of voltage class k in the t-th year is:

$$P_{DTt}^K = D_l^k + \sum_{l<k} \left[V^{kl} / \left(1 - \eta_{LossT}^k\right) \right] \tag{6}$$

Where, P_{DTt}^K is the total peak load demand, including the load demand of the class and the supply power load demand to the next class.

The highest supply power load of voltage class k in the t-th year is:

$$S_t^k = P_{DTt}^k / \left(1 - \eta_{LossL}^k\right) \tag{7}$$

Calculating from the lowest voltage class to high voltage class step by step, we can solve the total peak load demand and the highest supply power load of the biggest load day of each voltage class.

The difference between the next year and the same year' the highest supply power loads of each voltage class, which is the highest supply power load incremental of each voltage class in the year. Therefore, the highest supply power load incremental of voltage class k in the t-th year is:

$$\Delta S_t^k = S_{t+1}^k - S_t^k \tag{8}$$

The total load demand incremental is:

$$\Delta P_{DTt}^k = P_{DTt+1}^k - P_{DTt}^k \tag{9}$$

3. LONG-TERM MARGINAL COST CALCULATING AND ALLOCATION MODEL

3.1. Average Incremental Cost Calculating Model

Firstly, we need forecast the planning period line and power transformation' investment quantity of each voltage class each year, and carry out discounting according to a certain discounted rate:

$$\eta_{NPV}\left(I_L^k\right) = \sum_{t=1}^n \frac{I_{t,L}^k}{\left(1+i\right)^n} \tag{10}$$

$$\eta_{NPV}\left(I_T^k\right) = \sum_{t=1}^n \frac{I_{t,T}^k}{\left(1+i\right)^n} \tag{11}$$

Where, $I_{t,L}^k$ and $I_{t,T}^k$ is line investment quantity and power transformation investment quantity of voltage class k in t-th year respectively; i is discounted rate.

Long-term average incremental cost calculating formula is:

$$S_{AICL}^k = \eta_{NPV}\left(I_T^k\right) / \eta_{NPV}\left(\Delta S^k\right) \tag{12}$$

$$S_{AICT}^k = \eta_{NPV}\left(I_T^k\right) / \eta_{NPV}\left(\Delta P_{DT}^k\right) \tag{13}$$

Where, S_{AICL}^k and S_{AICT}^k is line and power transformation long-term average incremental cost of voltage class k respectively.

Finally, according to years investment recovery coefficient and considering operation and maintenance cost, calculating the planning period line and power transformation annuity of each voltage class in each period. Line average incremental cost annuity of voltage class k calculating formula is:

$$A_L^k = S_{AICL}^k \left(A/P, i, n\right) + C = S_{AICL}^k \frac{i\left(1+i\right)^n}{\left(1+i\right)^n - 1} + S_{AICL}^k \beta_c \tag{14}$$

Where, C are operation and maintenance cost each year; β_c is operation and maintenance cost.

In like manner, we can get power transformation average incremental cost annuity of voltage class k, the formula is given as:

$$A_L^k = S_{AICL}^k S_{AICL}^k \frac{i\left(1+i\right)^n}{\left(1+i\right)^n - 1} + S_{AICL}^k \beta_c \tag{15}$$

3.2. Long-term Marginal Cost' Allocation Methods and Models between Each Voltage Classes

After calculating planning period each voltage class annuity in each stage, we allocate above-mentioned cost between each voltage classes. Using peak responsibility allocation methods, according to peak load demand and power transmission and power receiving relationship of each voltage class, we will annuity of each link allocate to each voltage class.

Assuming 500kV is the highest voltage class of provincial power grid, it only undertakes transmissions line incremental cost of the class. The calculating formula is given as:

$$S_{AT}^{l} = A^{l} = A_{L}^{l}\eta_{NPV}\left(\Delta S^{l}\right)/\eta_{NPV}\left(\Delta\eta_{DT}^{l}\right) \quad (16)$$

Where, S_{AT}^{l} is the total long-term marginal cost annuity which voltage class k undertake.

The other each voltage class not only undertakes the class' transmission and distribution capacity cost, but also undertakes transmission and distribution capacity cost of the last voltage class according to inputting incremental power flow from the last class. There is some low voltage classes' power from many high voltage classes, for example, normally 35kV voltage class' power from 110kV and 220kV voltage class, so it should undertake two high voltage class' expenses which are allocated according to incremental power flow ratio. Voltage class $k\left(k \neq 1\right)$ should undertake high voltage class expenses calculating formula is expressed as:

$$A_{H}^{k} = \sum_{h>k}\left[\left(S_{AT}^{h}\eta_{NPV}\left(\Delta S^{h}\right)\right)\left(\eta_{NPV}\left(\Delta V^{hk}\right)/\eta_{NPV}\left(\Delta P_{DT}^{h}\right)\right)\right]/\eta_{NPV}\left(\Delta P_{DT}^{k}\right) \quad (17)$$

Where, A_{H}^{k} is voltage class k should undertake the last class transmission and distribution power marginal cost annuity; ΔV^{hk} is the supply power incremental load from high voltage class h to voltage class k.

Because a voltage class supplies power to the lower voltage class though reduction voltage, so transformer substation incremental expense should share to the lower voltage class which is related to the voltage class. This is deemed to the lower voltage class' expense, the expense calculation formula is given as:

$$A^{k} = \left[\sum A_{T}^{h}\eta_{NPV}\left(\Delta V^{hk}\right) + A_{L}^{k}\eta_{NPV}\left(\Delta S^{k}\right)\right]/\eta_{NPV}\left(\Delta P_{DT}^{k}\right) \quad (18)$$

The total expense which is undertaken to voltage class k is:

$$S_{AT}^{k} = A_{H}^{k} + A^{k} \quad (19)$$

Finally, it will calculate each stage transmission and distribution price of different voltage class of planning period. After calculating transmission and distribution annuity of each voltage class, according to each stage load hours of different voltage class, it will turn transmission and distribution annuity into transmission and distribution price which is electricity price form.

4. THE MEASURE OF POWER GRID LONG-TERM MARGINAL COST OF *A* AREA

4.1. The Electric Power Development Planning of *A* Area

According to *A* area electric power company development planning, forecasting *A* area grid electricity demand in the planning period, and each type user of electricity consumption of *A* area grid each voltage class and the ratio of each voltage class electricity consumption. Through analyzing each type user of electricity trend in the future, we calculate each year each type user of each voltage class' electricity consumption in the planning period. According to *A* area electric power demand situation, the technical and economic indexes of power grid source which is existing and will be built, we optimize *A* area future power extension situation through adopting the planning method that is based on the minimum expense, and get power planning program and electric power balanced situation. According to *A* area electric power company development planning, we can get *A* area each year all classes of power grid constructing program and the static investment year by year in the computing period.

4.2. The Measure of Each Voltage Class of Incremental Load

According to the statistic data in the *A* area, we can get each voltage class each type user of load rate, simultaneity factor, as shown in the Table (**1**). The voltage class is higher, load rate is higher. For different industry, great industry users' load rate is the highest, lighting users' load rate is the lowest; the simultaneity factor of lighting users and great industry users is relatively high, and the simultaneity factor of agricultural users is relatively low.

According to each voltage class each type user of forecasting electric quantity in the planning period, and each type user of load rate and simultaneity factor, we can calculate and get each voltage class supply power load incremental year by year and the discounted value of incremental load, the results are shown in Table (**2**).

According incremental load and each voltage class electricity generation output situation, we calculate each voltage class incremental load from low voltage class step by step, and the results are shown in Table (**3**).

4.3. The Measure of Each Voltage Class Long-term Incremental Cost

The paper offers the measure steps of each voltage class long-term incremental cost is given as:

Firstly, the article solved each voltage class each year highest load incremental in the period, and calculated each voltage class net present value of the total load incremental.

Table 1. Occurrence time of maximum load, load rate, simultaneity factor of each type user at each voltage level.

Voltage Level	User Class	Rush Time	Load Rate	Simultaneity Factor
380/220V	Non and General Industrial Users	11:00	64	86
	Agricultural Users	20:00	52	66
	Business Users	18:00	51	80
	Residential Users	20:00	42	80
	Lighting Users	20:00	34	96
10kV	Great Industrial Users	11:00	82	92
	Non and General Industrial Users	11:00	67	87
	Agricultural Users	20:00	55	68
	Business Users	18:00	53	85
	Residential Users	20:00	44	85
	Lighting Users	20:00	34	98
	Wholesale Users	18:00	51	7
35kV	Great Industrial Users	11:00	86	94
	Non and General Industrial Users	11:00	70	88
	Agricultural Users	20:00	57	70
	Business Users	18:00	56	90
	Wholesale Users	20:00	62	80
110kV	Great Industrial Users	10:00	86	94
	Non and General Industrial Users	10:00	70	88
	Wholesale Users	10:00	78	90
220kV	Send to Other Provinces	10:00	91	90

Table 2. Incremental load of each voltage level year after year and discounted present value of total incremental load.

Time	Load/MW					
	380/220V	10kV	35kV	110kV	220kV	500kV
First Years	9	38	46	89	54	27
Second Years	11	49	60	115	134	14
Third Years	13	61	76	145	184	0
Forth Years	18	77	87	172	212	5
Fifth Years	20	84	93	186	246	367

Table **2**. contd…

Time	Load/MW					
	380/220V	**10kV**	**35kV**	**110kV**	**220kV**	**500kV**
Sixth Years	21	88	99	195	262	555
Seventh Years	24	97	105	212	264	193
Eighth Years	26	107	112	229	280	8
Ninth Years	29	113	112	235	285	9
Tenth Years	32	126	118	255	330	771
Discounted Present Value of Total Incremental Load	101	426	473	943	1134	870

Table 3. Discounted value of incremental load of each voltage level.

Programs	380/220V	10kV	35kV	110kV	220kV	500kV
The Level Peak Load Demand Incremental/MW	96	302	432	227	0	152
The Total Power Supply Load Incremental/MW	101	426	473	943	1134	869
The Total Load Incremental/MW	96	406	455	919	1098	848
Power Supply Incremental From 10kV/MW	-	101	0	0	0	0
Power Supply Incremental From 35kV/MW	-	0	22	0	0	0
Power Supply Incremental From 110kV/MW	0	404	281	0	0	0
Power Supply Incremental From 220kV/MW	0	0	192	898	0	0
Power Supply Incremental From 500kV/MW	0	0	0	0	693	0
The Level Plants Power Supply Load Incremental/MW	0	0	0	45	441	869
The Level Peak Load Line Loss Rate/%	5.65	4.73	2.58	2.55	3.15	2.41
The Level Peak Load Variable Loss Rate/%	0.00	2.13	2.48	0.85	0.78	0.47

Secondly, according to < *A* area electric power develop-ment plan> of *A* area electric power company and each year 500kV and 220kV grid construction program and static in-vestment net present value year by year of regional power grid in the period, the paper calculated each voltage class the annual investment and the total investment net present value in the future.

Finally, the article calculated each voltage class transmis-sion and distribution average incremented cost. If electric transmission and transformation equipment life is 25a, the discount rate is 12%, the operation and maintenance cost is 2% of the assets, we can calculate each voltage class annuity. Each voltage class average incremental cost and annuity is shown in the Table (**4**).

4.4. The Distribution Method of Long-term Marginal Cost Between Each Voltage Class

According to the parameter of Table **3** and Table **4**, the paper solved each voltage class long transmission and trans-formation marginal cost and annuity.

The total transmission and transformation capacity mar-ginal cost and annuity of 500 kV voltage class is 345 yu-an/(kW$^{\cdot}$ a).

35kV voltage class undertakes the long-term transmis-sion and transformation marginal cost and annuity of 220kV and 110kV voltage class is (594*193+1021*284)/455=878 yuan/(kW$^{\cdot}$ a).

Table 4. Average incremental cost and annuity of each voltage level.

Voltage Level	Asset Types	Average Incremental Cost/(yuan/kW)	Annuity/(yuan/kWa)
380/220V	Line Section	854	126
10kV	Transformation Section	888	131
	Line Section	474	70
35kV	Transformation Section	4562	673
	Line Section	732	108
110kV	Transformation Section	556	82
	Line Section	638	94
220kV	Transformation Section	2334	344
	Line Section	2394	206
500kV	Transformation Section	1753	259
	Line Section	2280	336

Table 5. Details of average incremental cost of each voltage level.

Voltage Level	Undertaking Higher Level Expense/(yuan/kW·a)	Undertaking the Level Expense/(yuan/kW·a)	Total Transmission Cost/(yuan/kW·a)
500kV	0	345	345
220kV	218	376	594
110kV	586	436	1021
35kV	878	306	1184
10kV	1110	203	1313
380/220V	1543	275	1819

The level long-term transmission and transformation capacity marginal costs of 35kV voltage class include transformation and transmission. The long-term transmission and transformation marginal cost and annuity of 35kV voltage class is (334*192+82*2811+108*473)/455=306 yuan/(kW·a).

Therefore, 35kV voltage class undertakes the long-term transmission and transformation capacity marginal cost and annuity is 878+306=1184 yuan/(kW·a).

In like manner, we can get the long-term transmission and transformation capacity marginal cost and annuity of others voltage classes. The measure results are shown in Table (**5**). Due to low voltage class need undertake high voltage class expense, with the decline of voltage class, the undertaken an annual expense will gradually increase. Each voltage class long-term incremental annuity are shown in the Table (**5**), according to the calculating results translate into transmission price (the single electricity price or two-part tariff), or according to each type user' user characteristics, design user sale price together with the long-term generation marginal cost.

CONCLUSION

Marginal cost pricing method which is based on marginal cost is gotten according to the system actual power supply cost increase as a result of each type user power consumption increasing. It will reflect actual power supply cost of different power supply voltage, different load characteristic user, and it is advantage of eliminating cross-subsidization, making electricity price which each voltage class undertake more reasonable and fair. Through calculating and sharing long-term marginal cost, and getting each voltage class long-term marginal capacity cost share into each type user. It will form scientific, reasonable user electricity price with power supply quantity cost.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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