Supporting the flexibility and reliability of power systems: Optimal scheduling approach

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ABSTRACT
The optimal scheduling of the electricity market requires a holistic approach that incorporates demand-side measures, energy storage systems, renewable energy integration, market mechanisms, and system operations. The power system can achieve greater flexibility, reliability, and efficiency by leveraging these strategies. Therefore, in this paper, we modelled the electricity market, which can reward generators for maintaining a certain capacity level on the system. In addition to the mathematical models of Unit Commitment (UC) for the Mongolian Energy System, the optimal placement of Phasor Measurement Units (PMUs) has also been computed. The computed results from the optimal placement of PMUs can provide a set of locations where the PMUs can be installed to achieve maximum power system observability. This result can improve the system's reliability by providing real-time information about the state of the power system and allowing operators to detect and respond to potential problems efficiently. To further enhance the effectiveness of this approach, we consider incorporating other strategies such as energy storage systems and renewable energy integration.

Keywords: *electricity market, real-time pricing, regulation, unit Commitment, phasor measurement units*

1. INTRODUCTION

Achieving optimal scheduling in electricity markets requires a comprehensive approach considering various factors, such as demand-side management, energy storage, renewable energy integration, market mechanisms, and system operations. Demand-side management involves actively managing energy consumption on the demand side, such as through load shifting or curtailment, to reduce peak demand and increase system flexibility. Energy storage systems can help to balance the grid by storing excess energy during low-demand periods and releasing it during peak-demand periods. Renewable energy integration is another critical strategy for optimal scheduling in electricity markets. Integrating renewable energy sources into the grid can reduce carbon emissions. However, it also poses challenges due to the variable nature of renewable energy output. Market mechanisms such as real-time pricing, capacity markets, and demand response programs can also play a role in achieving optimal scheduling in electricity markets. These mechanisms help incentivize efficient energy use and promote investment in flexible resources. This paper proposes math models of UC for the Mongolian Energy system, which includes reducing imports from Russia and increasing the system's reliability. Also, we computed the optimal placement of PMU for supporting high system control.

2. MATHEMATICAL MODELS OF UC FOR MONGOLIAN ELECTRIC SYSTEM (EPS)

The unit commitment (UC) model selects the system with the lowest cost of generating units based on the capacity of the unit that can be loaded on the market by the companies, taking into account the electricity market of the previous week, and calculates the generating cost, start-up and turn off cost. In this selection, thermal units will be considered. The business process of Unit

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commitment technology involves the following two types of planning [1, 2].

The day ahead market: According to the power supply contract, a program for the next day will be processed. The program consists of two parts. The first part is a form of market equilibrium, and the second is to calculate the wholesale market price due to a bilateral agreement between the power plant and the customer.

Real-time dispatching: The system operator will adjust to current market balancing plans. In the second stage, the system operator gives the command according to the rules, depending on the electrical load. In other words, the most expensive part of the plant will be disconnected, and low-cost electricity will be used.

The following advantages of deciding electricity market trading by unit commitment model exist [3-9].

1. The software generating planning, its mathematical model's boundary conditions and data are always independent. This independence gives the program solver a wide range of possibilities.

2. While the traditional planning method does not use the price of power generation and related variables, the UC model determines the essential cost of the electricity generation block and the minimum fuel price and creates fair competition in the market for the lowest electricity price.

3. A wide range of limits (constraints) can be used for modelling. For example, Limits of undispatchable energy sources (wind power plants), limits for unplanned load changes during energy planning, fuel consumption and manoeuvrability of thermal power plants during hot reservation.

4. Modelling specifies emission limits of toxic substances, which has the advantage of positively affecting environmental pollution.

2.1. Math models of Unit commitment for a unit selection into a thermal power plant (TPP)

The mathematical model of cost-based Unit commitment presents a solution to the problem of optimizing generation companies to select the lowest cost for the day's energy planning [4-6].

$$min_{P_{i,t}^k, u_{i,t}, y_{i,t}, z_{i,t}} OF = \sum_{i,t} FC_{i,t} + STC_{i,t} + SDC_{i,t} \quad (1)$$

Where:

$FC_{i,t}$ – i unit fuel cost at t time, ($/hour)

$STC_{i,t}$ - i unit start cost at t time, ($/hour),

$SDC_{i,t}$ – i unit shut down cost at t time, ($/hour)

Every unit commitment problem has three main cost components: fuel, start-up, and shut-down costs.

Let us propose the math models for the Mongolian electric system. 1st stage we proposed here study the possibility of selecting the load block of a Thermal Power Plant#2 to participate in the electricity market. The required characteristics of the TPP equipment, such as the Boiler and turbine generator, are also known to be in a state of on/off for connection and disconnection of the equipment. The following optimization methods can be used to select a thermal unit. At 2nd stage, we will compute and realize the UC model for Mongolian Central Electric System (EPS).

a) ***Mathematical model for modelling TPPs in economic efficiency.*** The following mathematical model determines the generator fuel cost coefficient.

$$C_i^{th}(P_i^{th}) = a_i^{th}(P^{th})_i^2 + b_i^{th}P_i^{th} + c_i^{th}, \ i \in \Omega_{th} \quad (2)$$

Where a_i, b_i, c_i are the fuel cost coefficients of the i -th unit. The total fuel cost (TC) is calculated as follows:

$$TC = \sum_{i\in\Omega th} C_i^{th}(P_i^{th}) \quad (3)$$

The operating limits are defined as follows:

$$P_i^{th,min} \leq P_i^{th} \leq P_i^{th,max}, \quad i \in \Omega_{th} \quad (4)$$

$P_{max/min}$ are the maximum/minimum power outputs of i -th thermal unit.

The overall thermal unit cost-based dynamic economic dispatch is formulated as follows:

$$min_{P_i^{th}} TC = \sum_{i\in\Omega th} C_i^{th}(P_i^{th}) \quad (5)$$

$$C_i^{th}(P_i^{th}) = a_i^{th}(P^{th})_i^2 + b_i^{th}P_i^{th} + c_i^{th}, \ i \in \Omega_{th} \quad (6)$$

$$P_i^{th,min} \leq P_i^{th} \leq P_i^{th,max}, \ i \in \Omega_{th} \quad (7)$$

$$\sum_{i\in\Omega th} P_i^{th} = L_e \quad (8)$$

b) ***The combined (cogeneration) heat and power production model.*** The technology can generate heat and electric power simultaneously. In the previous section, thermal energy generation will be selected based on fuel consumption, just as heating will be selected based on fuel consumption. The economic dispatch problem can be modelled as follows:

$$min_{p_i^{th}, p_j^{chp}, q_j^{chp}, q_k^h} OF = F^{th} + F^h + F^{chp} \quad (9)$$

Where, F^{th} – costs of thermal units, F^{chp} – costs of CHP units, F^h – heat only units.

$$F^{th} = \sum_{i\in\Omega th} a_i^{th}(P_i^{th})^2 + b_i^{th}P_i^{th} + c_i^{th} \quad (10)$$

Here, P_i^{th} - variable of heat only unit.

$$F^h = \sum_{i\in\Omega th} a_i^{th}(q_k^h)^2 + b_k^h q_k^h + c_k^h \quad (11)$$

where, q_k^h - only heat unit.

$$F^{chp} = \sum_{i\in\Omega chp} a_j^{chp}(P_j^{chp})^2 + b_j^{chp}P_j^{chp} + c_j^{chp} + d_j^{chp}(q_j^{chp})^2 + e_j^{chp}q_j^{chp} + f_j^{chp}P_j^{chp}q_j^{chp} \quad (12)$$

Where, P_j^{chp} – cogeneration unit's heat production, q_j^{chp} - cogeneration unit

$$P_i^{th,min} \leq P_i^{th} \leq P_i^{th,max}, \ i \in \Omega_{th} \quad (13)$$

Cogeneration's function/operation limit

$$Q_k^{h,min} \le q_k^h \le Q_k^{h,max}, \quad k \in \Omega_h \tag{14}$$

Only heat productions operation limit

$$P_j^{chp,min}\left(q_j^{chp}\right) \le P_j^{chp} \le P_j^{chp,max}\left(q_j^{chp}\right), j \in \Omega_{chp} \tag{15}$$

$$Q_j^{chp,min}\left(P_j^{chp}\right) \le q_j^{chp} \le Q_j^{chp,max}\left(P_j^{chp}\right), j \in \Omega_{chp} \tag{16}$$

$$\sum_{i \in \Omega th} P_i^{th} + \sum_{j \in \Omega chp} P_i^{chp} \ge L_e \tag{17}$$

$$\sum_{k \in \Omega h} q_k^h + \sum_{j \in \Omega chp} q_j^{chp} \ge L_{th} \tag{18}$$

c) ***Ramp rate constraints***. In this computation, we can determine TPPs manoeuvre limits; therefore, the result could be used in the intraday market as an initial data.

3. OPTIMIZATION RESULTS OF UC IN TTP AND EPS

Optimising "Thermal Power Plant-2" block selection: "TPP-2" is a power plant with 3 boilers of 35 ton/h, 2 boilers of 75 ton/h, 2 turbine generators of 6MW, 1 turbine generator of 12MW with a total installed capacity of 24MW (Table 1, 2).

Table 1. Technical parameters of boilers

№	Generators	Installed capacity Ton/h	Pressure kgc/sм^2	Steam temperature
1	TS-35/39	35	39	440
2	TS-35/39	35	39	440
3	TS-35/39	35	39	440
4	BKZ-75/39	75	39	440
5	BKZ -75/39	75	39	440
	Total capacity 255 ton/h			

Table 2. Technical parameters of generators

Generator	a /mw2/	b /mw/	c /mw/	Pmin	Pmax
g1	4.3	24	118	3.5	6
g2	4.05	18.07	98.87	3.5	6
g3	3.14	15.55	100	3.5	12

In order to optimization of the plant block selection process, the Unit commitment (UC) model was used to select the generators and boilers for the system with the lowest unit power generation costs depending on the block capacity that can be loaded on the market by the companies as shown in Table 3.

The generators are selected with the minimum steam and water consumption and ramp rate to produce the given daily planning from the dispatcher.

Generators 2 and 3 appear to have supplied their maximum load. However, during peak hours, all generators were operating at full capacity. The amount of steam used by the generator can be calculated. Steam boilers are selected by minimizing fuel consumption.

Table 3. Turbine-Generators supply selected as a result of optimization

Hours	Plan /MW/	G-1 /MW/	G-2 /MW/	G-3 /MW/
t1	18.000	4.641	5.659	7.700
t2	18.000	4.641	5.659	7.700
t3	18.000	4.641	5.659	7.700
t4	18.000	4.641	5.659	7.700
t5	18.500	4.786	5.814	7.900
t6	18.500	4.786	5.814	7.900
t7	19.000	4.932	5.969	8.100
t8	20.000	5.341	6.000	8.659
t9	20.000	5.341	6.000	8.659
t10	20.000	5.341	6.000	8.659
t11	20.000	5.341	6.000	8.659
t12	19.000	4.932	5.969	8.100
t13	19.000	4.932	5.969	8.100
t14	20.000	5.341	6.000	8.659
t15	20.000	5.341	6.000	8.659
t16	21.000	5.763	6.000	9.237
t17	21.000	5.763	6.000	9.237
t18	22.000	6.000	6.000	10.000
t19	23.000	6.000	6.000	11.000
t20	23.000	6.000	6.000	11.000
t21	22.000	6.000	6.000	10.000
t22	21.000	5.763	6.000	9.237
t23	24.000	6.000	6.000	12.000
t24	19.000	4.932	5.969	8.100

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In Fig.1. shows the GAMS code of the combined heat and power productions model.

```
set t 'hour' /t1*t24/
    i 'boiler' /k1*k5/;
Table boilerData(i,*) 'Stantsiin une harakteristek bolon hyazgaaruud'
           fuel  d     e     f     Fmax   Fmin
    k1     0.16  1.45  0.03  3.89  35     20
    k2     0.16  1.45  0.03  3.89  35     20
    k3     0.16  1.45  0.03  3.89  35     20
    k4     0.077 5.53  0.13  5.72  75     35
    k5     0.077 5.53  0.13  5.72  75     35;

scalar sumDemand /0/,sumZuuh/0/,diff /0/;
Parameter demand(t)
/t1 146, t2 146, t3 146, t4 146, t5 149, t6 149,
 t7 151, t8 157, t9 157, t10 157, t11 157,t12 151,
 t13 151, t14 154, t15 154, t16 154.8, t17 154.8,
 t18 169, t19 168, t20 168, t21 163, t22 158,
 t23 174, t24 146/;
Variables
em 'hort bodis ylgaruulalt'
fuel '1 tonn uur uuildwerleh jishmel tulsh'
f(i,t)  'odoo uildwerlej baigaa zuuhnii uuriin zartsuulalt';

binary variable U(i);
  sumZuuh=sum((i),boilerData(i,'Fmax'));
  sumDemand=sum((t),demand(t));
  sumZuuh=sumZuuh*24;
  diff= (sumZuuh-sumDemand)/24;
if(diff GT 90,
 boilerData('k4','Fmax')=0;
 boilerData('k4','Fmin')=0;
elseif diff GT 50,
 boilerData('k3','Fmax')=0;
```

```
);
  f.up(i,t)=boilerData(i,"Fmax");
  f.lo(i,t)=boilerData(i,"Fmin");
Equation coefThermalcalc, balance,emission;

coefThermalcalc.. fuel =e=sum((t,i),boilerData(i,'fuel'));
emission.. em=e=sum((i,t),boilerData(i,'d')*f(i,t)*f(i,t)+boilerData(i,'e')

*f(i,t)+boilerData(i,'f'));

balance(t).. sum(i,f(i,t))=g=demand(t);
Model DEDfuelbased /all/;
solve DEDfuelbased using miqcp min fuel;
```

Figure 1 TPP#2 block selection optimization code in GAMS by combined technology (with emission).

Table 4. Result of optimization Fig. 1.

Hours	Plan from NCD /MW/	Total production ton/h	K-1 ton/h	K-2 ton/h	K-3 ton/h	K-4 ton/h	K-5 ton/h
1	18.000	146	31	20	20	0	75
2	18.000	146	31	20	20	0	75
3	18.000	146	31	20	20	0	75
4	18.000	146	31	20	20	0	75
5	18.500	149	34	20	20	0	75
6	18.500	149	34	20	20	0	75
7	19.000	151	21	20	35	0	75
8	20.000	157	27	20	35	0	75
9	20.000	157	27	20	35	0	75
10	20.000	157	27	20	35	0	75
11	20.000	157	27	20	35	0	75
12	19.000	151	21	20	35	0	75
13	19.000	151	21	20	35	0	75
14	20.000	154	24	20	35	0	75
15	20.000	154.8	24	20	35	0	75
16	21.000	154.8	24	20	35	0	75
17	21.000	154.8	24	20	35	0	75
18	22.000	169	35	35	24	0	75
19	23.000	168	35	23	35	0	75
20	23.000	168	35	35	23	0	75
21	22.000	163	31	20	35	0	75
22	21.000	158	28	20	35	0	75
23	24.000	174	35	35	29	0	75
24	19.000	146	31	20	20	0	75

As shown in the table of the results, the dispatcher optimized the steam required for the production of the daily schedule by the generators with the lowest benchmark fuel, the lowest emission of air pollutants and manoeuvrability.

K-1, 2, 3, 5 boilers are selected and loaded, but K-4 is put into cold reservation without load. This block selection optimization shows that TPP-2 can produce a given mode with minimum cost.

Optimizing the generation of central electric system's power plants to participate in the electricity market using the Unit commitment model: TPPs have been selected by the Unit commitment model to be the minimum price, including TPP#2, TPP#3 and TPP#4 in the Central Power System of Mongolia, as well as Russian power import sources.

Here given by Table 5 is the technical parameters of TPP's, cost and ramp rate for each TTP.

Table 5. Technical parameters of generators for TPP's.

№	Generators type, mark	Year of commissioning	Capacity MW	Voltage кV
TPP#2				
1	TQC-5466/2	1961	6	6.3
2	TQC-5466/2	2015	6	6.3
3	T2-12-2	1969	12	6.3
	Installed capacity P =24MW			
TPP#4				
1	ТВФ-120-2У3	1983	110	10.5
2	ТВФ-120-2У3	1984	120	10.5
3	ТВФ-120-2У3	1985	120	10.5
4	ТВФ-120-2У3	1986	120	10.5
5	ТВФ-110-2У3	1990	100	10.5
6	ТВФ-110-2У3	1991	100	10.5
7	ТВФ-125-2У3	2015	123	10.5
5	T2-12-2	1969	12	6.3
	Installed capacity P =793MW			
TPP#3				
1	T2-12-2	1973	12	6.3
2	T2-12-2	1973	12	6.3
3	T2-12-2	1974	12	6.3
4	T2-12-2	1975	12	6.3
5	ТВС-32	1977	25	6.3
6	ТВС-32	1977	25	6.3
7	ТВС-32	1978	25	6.3
8	ТВС-32	1979	25	6.3
9	QF-50/60-2	2014	50	6.3
	Installed capacity P =198MW			

When calculating the price of imported electricity, we divided the amount of the total energy import contract for the current year by the day of the year to find the daily Pmax load of imported energy. Also, when choosing the manoeuvrability, the maximum load of the station's generators is calculated minus the minimum load that the generator can take.

Entering manoeuvrability as a limits in the GAMS, the amount of power produced at this time is determined so that the difference in the amount of power produced next time is less than or equal to the manoeuvrability specified in the table above.

Table 6. Economical and ramp rate parameters of stations

Stations	Cost (tugrug)	Pmin (MW)	Pmax (MW)	Ramp rate increasing (MW/h)	Ramp rate decreasing (MW/h)
TPP#2	78.29	14	23	13	13
TPP#3	42.81	130	198	30	30
TPP#4	37.68	365	793	50	50
Import	106.2	100	254	50	50

Using these parameters we computed optimal scheduling of Mongolian CES which includes Import.

Table 7 shows the results of TPP#2, which was 40% less than its full capacity during the day, which means that the cost of generating electricity at the plant is 20%-40% higher than the cost of other plants. TPP#3 was loaded at 67% -97% of its installed capacity.

TPP#4 has been optimized to have a minimum load of 483 MW and a maximum load of 793 MW, which is higher than other thermal units which has a ramp-rate of 60% higher than other units. The result of optimization potentially can support of preplanning process the system.

Table 7. Result of unit commitment model into Mongolian central electric system

Plan		Thermal units			
Hours	Plan /MW/	TPP#2 /MW/	TPP#3 /MW/	TPP#4 /MW/	Import /MW/
1	888	14	130	644	100
2	855	14	130	611	100
3	833	14	130	589	100
4	827	14	130	583	100
5	827	14	160	533	120
6	727	14	130	483	100
7	852	14	160	533	**145**
8	901	14	189	583	115
9	955	14	189	633	119
10	**1013**	14	189	683	127
11	987.04	14	156	717.04	100
12	997.49	14	130	**753.49**	100
13	1052	14	147.11	**790.89**	100
14	984.89	14	130	740.89	100
15	**1012**	14	130	768	100
16	**1008**	14	130	764	100
17	**1010**	14	130	766	100
18	**1030**	14	148	768	100
19	**1085**	14	**178**	**793**	100
20	**1115**	14	158	**793**	**150**
21	**1088**	14	131	**793**	**150**
22	**1058**	14	151	**793**	100
23	**1024**	14	130	**780**	100
24	**1023**	14	130	**779**	100

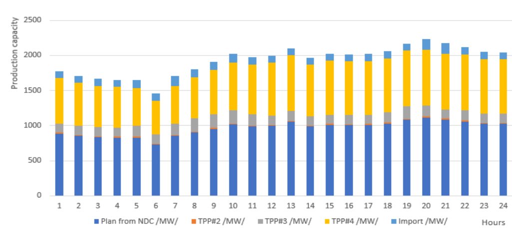

Figure 2 Unit commitment models result.

From Table 8, we can define capacity (deficit/surplus) changes in the TPPs; these results allow us to develop the day-ahead market and an intraday market. These results make it possible to predict the emergence of new entrants into the market, such as wind or solar power plants.

Table 8. Capacity changes (deficit/surplus) of TPPs.

Hours	Stations maneuver/capacity changes (deficit/surplus). (MW)			
	TPP2 /MW/	TPP3 /MW/	TPP4 /MW/	Import /MW/
1	0	0	0	0
2	0	0	33	0
3	0	0	22	0
4	0	0	6	0
5	0	30	50	**-20**
6	0	**-30**	50	20
7	0	30	**-50**	**-45**
8	0	29	**-50**	30
9	0	0	**-50**	**-4**
10	0	0	**-50**	**-8**
11	0	33	**-34.04**	27
12	0	26	**-36.45**	0
13	0	**-17.11**	**-37.4**	0
14	0	17.11	50	0
15	0	0	**-27.11**	0
16	0	0	4	0
17	0	0	**-2**	0
18	0	**-18**	**-2**	0
19	0	**-30**	**-25**	0
20	0	20	0	**-50**
21	0	27	0	0
22	0	**-20**	0	50
23	0	21	13	0
24	0	0	1	0

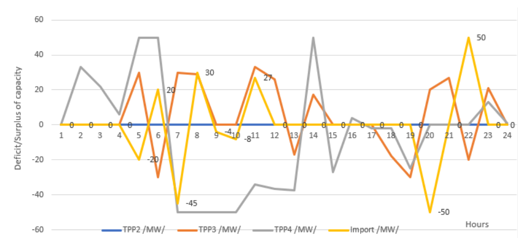

Figure 3 Stations manoeuvre and import from Russia.

Capacity changes are connected with the frequency regulation of the electric systems and ancillary services [5-7]. Also, it is essential to reduce imports from Russia and increase to flexibility of system.

4. THE OPTIMAL PLACEMENT OF PMU

PMU (Phasor unit of measurement) is used in power systems to measure voltage, current, frequency and phase angle at various points in the system. Placing optimal PMUs in power systems is critical for effective system control, monitoring and protection. The placement of PMUs should be based on a number of factors, including the size and complexity of the power system, the critique of the various components, and the expected response time of PMUs. PMUs should generally be placed at strategic points in the system to capture the most significant voltage and current changes and provide the fastest response time.

The optimal placement of PMUs depends on the specific goals and requirements of the power system. Here are some factors to consider when deciding where to place PMUs:

Critical nodes: PMUs should be placed at the critical nodes of the power system, such as the points where power flows change direction or where there is a high voltage drop. This helps to identify and address issues quickly.

Redundancy: It is important to have redundant PMUs in case of failures or outages. Placing PMUs in multiple locations can provide redundancy and ensure that the power system is always monitored.

Coverage: PMUs should be placed to ensure complete coverage of the power system. This means there should be enough PMUs to monitor all the critical components of the power system.

Communication: PMUs rely on communication networks to transmit data, so their placement should consider the power system's communication infrastructure.
Cost: The cost of PMUs and their installation should also be considered. Placing too many PMUs can be expensive while placing too few can leave the power system vulnerable.
Some key places of PMUs:

- *At key substations*: PMUs should be placed at key substations in the power system, such as the points of interconnection with other power systems or large generation facilities. This allows for monitoring of the power flow in and out of the system and provides an early warning of potential problems.
- *At key transmission lines*: PMUs should also be placed at critical transmission lines, such as those that carry a significant portion of the power in the system or connect key substations. This allows for monitoring the flow of power on these lines and enables the detection of any congestion or overloading issues.
- *At key generation facilities*: PMUs should be placed at key generation facilities, such as power plants and wind farms, to monitor their performance and ensure their stability. This allows for early detection of any problems and enables quick responses to prevent cascading failures.
- *At distribution substations*: PMUs should also be placed at distribution substations to monitor the power flow and voltage levels in the distribution network. This allows for the early detection of any issues that may affect the distribution system's reliability.

The optimal placement of PMUs in a power system can be determined through a mathematical optimization model that seeks to minimize the overall cost of placing the PMUs while satisfying certain constraints. The cost can be measured in terms of the number of PMUs required to monitor the system adequately.

The problem can be formulated as follows:
Minimize the number of PMUs subject to the following constraints:

- The power flow equations must be satisfied at all nodes in the system. This ensures that the power flows can be accurately calculated and monitored.
- All nodes' voltage magnitude and phase angle must be within acceptable limits. This ensures that the system remains stable and does not experience any voltage collapses.
- The time required to detect and respond to any fault or disturbance in the system must be within a specified limit. This ensures that any problems can be quickly identified and addressed.
- The PMUs must be placed at strategic points in the system, such as key substations, transmission lines, generation facilities, and distribution substations.

The optimization problem can be solved using mathematical programming techniques like linear or integer programming. The decision variables in the problem are the placement of PMUs at various nodes in the system.
Nowadays in Mongolian central electric system located 41 PMUs [10] and these PMUs supplies of WAMS (Wide Area Monitoring System) by National Dispatching Center. Using the model we computed optimal placement of PMUs. Figure 4 shows GAMS code for optimal placing PMUs and results illustrated at EPS's scheme (Fig 5).
The solution provides the minimum cost of installing the PMUs while ensuring that the system is fully monitored and meets all constraints.

```
Sets bus /1*28/;
Alias(bus,node);

set conex
/1 . 2  1 . 3  1 . 16  2 . 4  3 . 2  4 . 5  4 . 6  5 . 6   7 . 8   7 . 9
 7 . 20  7 . 10  8 . 9  10. 11  10. 12  10. 13  11. 12  13. 14  13. 15
 14. 15  16. 17  16. 18  16. 20 17. 19  17. 26  18. 17  19. 25  20. 21
 21. 22  22. 23  22. 27  23. 24  24. 28/;
conex(bus,node)$(conex(node,bus))=1;
Variables OF;
Binary variable PMU(bus);
Equations const1, const2;
const1 .. OF=g=sum(bus,PMU(bus));
const2(bus) .. PMU(bus)+sum(node$conex(bus,node),PMU(node))=g=1;
Model placement /All/;
Solve placement minimizing OF using mip;
```

Figure 4 GAMS code for optimal placing PMUs

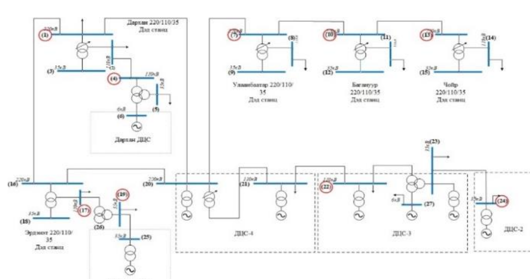

Figure 5 Result of optimal placement (key nodes)

CONCLUSIONS

The mathematical models of Unit Commitment (UC) for the Mongolian Energy System are designed to support optimal scheduling in electricity markets. The models are based on mathematical equations considering various parameters such as fuel costs, generation capacity, transmission constraints, and demand variability. By optimizing the scheduling of electricity generation and demand resources over a specific time, the models aim to reduce the dependence on imported energy from Russia and increase the reliability of the Mongolian Energy System. The computed results from these models can provide a set of optimal schedules for each generator and demand resource. Implementing these models can lead to significant benefits for the Mongolian Energy System. By reducing the dependence on imported energy from Russia, the system can become more self-sufficient and less vulnerable to external shocks. The system's increased reliability can provide more stable and predictable energy prices, benefiting both consumers and producers in the electricity market. The proposed mathematical models of UC for the Mongolian Energy System represent an essential step towards a more efficient, reliable, and sustainable energy system in Mongolia. By supporting optimal scheduling in electricity markets, these models can reduce energy imports, increase energy security, and promote the development of renewable energy sources.

In addition to the mathematical models of Unit Commitment (UC) for the Mongolian Energy System, optimal placement of Phasor Measurement Units (PMUs) has also been computed. The computed results from the optimal placement of PMUs can provide a set of locations where the PMUs can be installed to achieve maximum observability of the power system. This can help to improve the system's reliability by providing real-time information about the state of the power system and allowing operators to quickly detect and respond to potential problems. The combination of mathematical models of UC and optimal placement of PMUs can provide a comprehensive solution for supporting optimal scheduling in electricity markets and improving the reliability of the Mongolian Energy System.

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