Qisqa muddatli rejalashtirishda aktiv quvvat yo‘qotishlarini minimallashtirish orqali taqsimlovchi elektr tarmoqlari rejimini optimallashtirish

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Dolzarbligi: Qayta tiklanadigan energiya manbalarining ishlab chiqarishdagi ulushining global o'sishi tufayli butun dunyo bo'ylab taqsimlovchi elektr tarmoqlarida energiya tebranishlari muammosi keskinlashdi. Batareyalarga asoslangan energiya saqlash tizimlari eng yuqori yuklamalarni yumshatish, qayta tiklanadigan energiya ishlab chiqarishning beqarorligini qoplash, zaxira quvvatni ta'minlash va tarmoq ishlashini optimallashtirish, shu jumladan tarmoqdagi umumiy aktiv quvvat yo'qotishlarini kamaytirish kontekstida imkon beradi. Biroq, ularni amalga oshirish integratsiya va boshqaruvga kompleks yondashuvni talab qiladigan bir qator texnik, iqtisodiy va rostlash muammolari bilan bog'liq.

Maqsad: Aktiv quvvat yo‘qotishlarini minimallashtirish nuqtai nazaridan taqsimlovchi elektr tarmog‘ida akkumulyatorli energiya saqlash tizimini ulash tugunini va quvvatini tanlash.

Usullar: Ushbu tadqiqotda taqsimlovchi elektr tarmog‘ida barqarorlashgan rejimlarni hisoblash va umumiy aktiv quvvat yo‘qotishlarini aniqlash uchun Nyuton-Rafson usuli qo‘llanildi. Akkumulyatorli energiya saqlash tizimi quvvatlarini aniqlashda zaryad-razryad siklining muvozanatiga oid cheklovlar hisobga olindi. Aktiv quvvat yo‘qotishlarini minimallashtirish maqsadida akkumulyatorli energiya saqlash tizimi quvvatlarini ketma-ket o‘zgartirish asosidagi yondashuv qo‘llandi.

Natijalar: Aktiv quvvat yo‘qotishlarini minimallashtirish nuqtai nazaridan energiya saqlash tizimini ulash tugunini tanlashga imkon beruvchi algoritm ishlab chiqildi. Taqsimlovchi elektr tarmog‘ining test sxemasi misolida akkumulyatorli energiya saqlash tizimini ulash bo‘yicha modellashtirish ishlari olib borildi, bunda aktiv quvvat yo‘qotishlari va akkumulyatorli energiya saqlash tizimining sig‘imi qiymatlari aniqlandi.

Kalit so'zlar: taqsimlovchi elektr tarmoq; akkumulyator batareyalariga asoslangan energiya saqlash tizimi; quvvat yo'qotishlari; sutkalik yuklama gragigi.

Оптимизация режима распределительных электрических сетей путем минимизации потерь активной мощности при краткосрочном планировании

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Актуальность: В связи с глобальным ростом доли возобновляемых источников энергии в генерации в распределительных электрических сетях по всему миру остро возникла проблема колебаний мощности. Системы накопления энергии на основе аккумуляторных батарей позволяют сглаживать пиковые нагрузки, компенсировать нестабильность генерации возобновляемой энергии, обеспечивать резервное питание и оптимизировать работу сети, в том числе в контексте снижения суммарных потерь активной мощности в сети. Однако их внедрение сопряжено с рядом технических, экономических и нормативных задач, требующих комплексного подхода к интеграции и управлению.

Цель: Выбор узла подключения и мощности системы накопления энергии на основе аккумуляторных батарей в распределительной электрической сети с точки зрения минимизации потерь активной мощности в сети.

Методы: В исследовании использован метод Ньютона-Рафсона для расчетов установившегося режима и суммарных потерь активной мощности в распределительной сети. При определении мощностей аккумуляторной накопительной системы учитывались ограничения, связанные с балансом циклов заряда-разряда. Применен подход, связанный с последовательным изменением мощностей накопительной системы с целью определения минимума потерь акутивной мощности.

Результаты: Представлен алгоритм, позволяющий выбрать узел подключения системы накопления энергии с точки зрения минимизации потерь активной мощности. На примере тестовой схемы распределительной электрической сети проведено моделирование подключения системы накопления

энергии на основе аккумуляторных батарей, получены значения потерь активной мощности и емкости системы накопления энергии на основе аккумуляторных батарей.
Ключевые слова: распределительная электрическая сеть; система накопления энергии на основе аккумуляторных батарей; потери мощности; суточный график нагрузки.

Optimisation of the distribution network mode by minimising active power losses in short-term planning

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Relevance: Due to the global increase in the share of renewable energy sources in the share of generation in distribution electric networks around the world, an acute problem of power fluctuations has arisen. Battery energy storage systems make it possible to smooth out peak loads, compensate for the instability of renewable energy generation, provide backup power and optimize network operation, including in the context of reducing total active power losses in the network. However, their implementation is associated with a number of technical, economic and regulatory challenges that require an integrated approach to integration and management.
Aim: Selection of the connection node and power of the battery-based energy storage system in the distribution electrical network with a view to minimising active power losses in the network.
Methods: The study used the Newton-Raphson method to calculate the steady state and total active power losses in the distribution network. When determining the capacities of the battery storage system, restrictions related to the balance of charge-discharge cycles were taken into account. An approach was applied involving a sequential change in the capacities of the storage system in order to determine the minimum active power losses.
Results: An algorithm is presented that allows selecting the connection node of an energy storage system in terms of minimising active power losses. Using a test diagram of a distribution electrical network, the connection of a battery-based energy storage system was simulated, and the values of active power losses and the capacity of the battery-based energy storage system were obtained.
Keywords: power distribution network; battery energy storage system; power losses; daily load schedule.

1. Introduction

Battery energy storage systems (BESS) are becoming a critical component of modern distribution grids. Their ability to store and distribute energy at optimal times can help reduce active power losses, improve voltage stability, and enhance overall grid efficiency [1-3].Modern distribution grids face a number of challenges related to increasing loads, variability in electricity consumption, and the growing share of renewable energy sources (RES) [4-6]. One of the key tasks is to reduce active power losses and ensure a uniform load schedule, which is especially important in the context of the introduction of smart grids [7-9]. One of the most effective solutions is the use of energy storage systems that optimize grid operation by managing energy flows, increasing reliability, and improving the quality of power supply [10-12]. The amount of losses in distribution grids is affected by many factors, including the resistance of grid elements and the amount of current flowing through them; low power factor; uneven loads throughout the day; an increase in the share of RES due to additional fluctuations in grid voltage and frequency [4]. The article [5] discusses the possibility of using heuristic approaches and artificial neural networks when selecting the location for connecting battery storage units. The paper [6] proposes a method for selecting installation locations and parameters of battery storage systems in distribution electric networks, based on, on the one hand, minimizing the capacity of the BESS itself, while maintaining the overall reliability of the network, on the other. In [7], it is proposed to use storage systems to smooth out daily schedules when forecasting the load level for the day ahead. In the article [8], planning for changing the BESS capacity is implemented by taking into account the minimum cost of electricity, taking into account the parameters of the BESS itself - the state of charge (SOC) and capacity (SOH). The study [9] proposes a method aimed at minimizing the cost of purchasing electricity, taking into account the cost of active losses in the network, as well as the cost of a penalty for voltage deviation. Optimization of the operating mode of the distribution network is possible through the use of energy storage systems that allow managing the consumption and generation of electricity, reducing the load on the network and minimizing losses [13-15]. This paper proposes the use of lithium-ion batteries (Li-Ion), due to their widespread use, high energy density and fast response time, which are necessary to smooth out load peaks and reduce losses [16-18]. Management of energy storage systems should include aspects such as: load forecasting using artificial intelligence and machine learning; dynamic charge and discharge management taking into account electricity tariffs [19-20].

2. Methods and materials

As an example, we will consider the test circuit of the distribution electrical network shown in Fig. 1. Here, node 1 was taken as the head node.

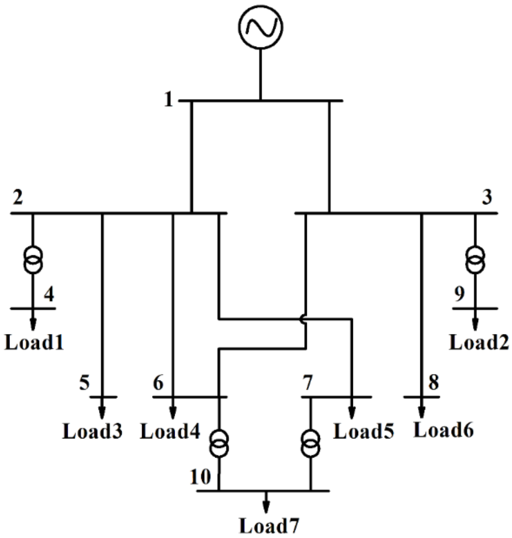

Fig 1. Test circuit of the electrical distribution network

The schematic information of the circuit by nodes and branches is given in Tables 1 and 2.

Table 1. Node data

Node No.	U_{nom}, kV
1	10
2	10
3	10
4	0,4
5	10
6	10
7	10
8	10
9	0,4
10	0,4

Table 2. Branch data

Begin	End	R, Ohm	X, Ohm
1	2	0.3	0.41
1	3	0.504	0.603
2	5	0.215	0.28
2	7	0.24	0.16
3	6	0.2	0.28
3	8	0.09	0.126

Table 3 shows data on the resistances and transformation ratios of power transformers.

Table 3. Transformer data

HV Node	LV Node	R, Ohm	X, Ohm	K
2	4	1,84	8,73	25
3	9	1,84	8,73	25
6	10	1,84	8,73	25
7	10	1,84	8,73	25

The load powers (kW) for a time interval equal to 15 minutes are given in Table 4. Thus, for each load node there are 96 values of active power.

Table 4. Change in load power during 24 hours

Time	P_{Load1}, kW	P_{Load2}, kW	P_{Load3}, kW	P_{Load4}, kW	P_{Load5}, kW	P_{Load6}, kW	P_{Load7}, kW
0:00	18,6	16,8	132	138	227,4	150	32,88
0:15	18,6	16,8	132	138	227,4	150	32,88
0:30	18,6	16,8	132	138	227,4	150	32,88
0:45	18,6	16,8	132	138	227,4	150	32,88
1:00	18,6	16,8	132	138	227,4	150	32,88
1:15	21,7	19,6	154	161	265,3	175	38,36
1:30	21,7	19,6	154	161	265,3	175	38,36
1:45	21,7	19,6	154	161	265,3	175	38,36
2:00	24,8	22,4	176	184	303,2	200	43,84
2:15	24,8	22,4	176	184	303,2	200	43,84
2:30	27,9	25,2	198	207	341,1	225	49,32
2:45	24,8	22,4	176	184	303,2	200	43,84
3:00	21,7	19,6	154	161	265,3	175	38,36
3:15	18,6	16,8	132	138	227,4	150	32,88
3:30	24,8	22,4	176	184	303,2	200	43,84
3:45	21,7	19,6	154	161	265,3	175	38,36
4:00	21,7	19,6	154	161	265,3	175	38,36
4:15	27,9	25,2	198	207	341,1	225	49,32
4:30	27,9	25,2	198	207	341,1	225	49,32
4:45	27,9	25,2	198	207	341,1	225	49,32
5:00	27,9	25,2	198	207	341,1	225	49,32
5:15	46,5	42,0	330	345	568,49	375	82,2
5:30	52,7	47,6	374	391	644,3	425	93,16
5:45	62	56	440	460	758	500	109,6
6:00	77,5	70,0	550	575	947,49	625	137,0
6:15	83,7	75,6	594	621	1023,3	675	147,96
6:30	83,7	75,6	594	621	1023,3	675	147,96
6:45	86,8	78,4	616	643,9	1061,2	699,9	153,44
7:00	114,7	103,6	814	851	1402,3	925	202,76
7:15	127,1	114,8	902,0	942,99	1553,89	1024,99	224,68
7:30	151,9	137,	1078	1126,99	1857,09	1224,99	268,52
7:45	170,5	154,0	1210	1264,99	2084,49	1374,99	301,40
8:00	176,7	159,6	1254	1310,99	2160,29	1424,99	312,36
8:15	186,0	168,0	1320	1379,99	2273,99	1499,99	328,8
8:30	201,5	182,0	1430	1494,99	2463,49	1624,99	356,2
8:45	235,6	212,8	1672	1748	2880,4	1900	416,48
9:00	257,3	232,4	1825,99	1908,98	3145,68	2074,98	454,84
9:15	266,6	240,8	1892	1977,99	3259,39	2149,99	471,28
9:30	272,8	246,4	1936	2023,99	3335,19	2199,99	482,24
9:45	279,0	252,02	1980	2069,99	3410,99	2249,99	493,2
10:00	294,5	266,0	2089,99	2184,99	3600,49	2374,99	520,6

10:15	297,6	268,8	2112	2208	3638,4	2400	526,08
10:30	291,4	263,2	2068	2161,99	3562,59	2349,99	515,12
10:45	294,5	266,0	2090	2185	3600,49	2375	520,60
11:00	288,3	260,4	2046	2138,99	3524,69	2324,99	509,64
11:15	285,2	257,6	2024	2116	3486,8	2300	504,16
11:30	279,0	252,0	1980	2069,99	3410,99	2249,99	493,20
11:45	285,2	257,6	2024	2115,999	3486,79	2299,99	504,16
12:00	288,3	260,4	2046	2139	3524,7	2325	509,64
12:15	279,0	252,0	1979,99	2069,99	3410,99	2249,99	493,2
12:30	266,6	240,8	1891,99	1977,99	3259,39	2149,99	471,28
12:45	260,4	235,2	1848	1931,99	3183,59	2099,99	460,32
13:00	248,0	224,0	1759,99	1839,99	3031,99	1999,99	438,4
13:15	232,5	210,0	1649,99	1724,99	2842,49	1874,99	411,0
13:30	223,2	201,6	1584	1655,99	2728,79	1799,99	394,56
13:45	217,0	196,0	1540	1609,99	2652,99	1749,99	383,6
14:00	220,1	198,8	1562	1633	2690,9	1775	389,08
14:15	229,4	207,2	1627,99	1701,99	2804,59	1849,99	405,51
14:30	235,59	212,79	1671,99	1747,99	2880,39	1899,99	416,47
14:45	241,8	218,4	1716	1793,99	2956,19	1949,99	427,44
15:00	248,0	224,0	1760	1839,99	3031,99	1999,99	438,4
15:15	257,3	232,4	1826,0	1909,0	3145,7	2075,0	454,84
15:30	272,8	246,4	1935,99	2023,99	3335,19	2199,99	482,24
15:45	254,2	229,6	1803,98	1885,99	3107,78	2049,99	449,36
16:00	272,8	246,4	1935,99	2023,99	3335,18	2199,99	482,24
16:15	279,0	252,0	1980	2069,99	3410,99	2249,99	493,2
16:30	263,5	238,0	1869,99	1954,99	3221,49	2124,99	465,8
16:45	272,8	246,4	1935,99	2023,99	3335,19	2199,99	482,24
17:00	275,9	249,2	1958	2047	3373,1	2225	487,72
17:15	279,0	252,0	1980	2070	3411	2250	493,2
17:30	279	252	1980	2070	3411	2250	493,2
17:45	288,3	260,4	2045,99	2138,99	3524,69	2324,99	509,64
18:00	297,6	268,8	2111,99	2207,99	3638,39	2399,99	526,08
18:15	297,6	268,8	2112	2208	3638,4	2400	526,08
18:30	263,5	238	1870	1955	3221,5	2125	465,8
18:45	248,0	224,0	1759,99	1839,99	3031,99	1999,99	438,4
19:00	226,3	204,4	1605,99	1678,98	2766,68	1824,98	400,04
19:15	198,4	179,2	1408	1472	2425,6	1600	350,72
19:30	155	140	1100	1150	1895	1250	274
19:45	130,2	117,6	924	966	1591,8	1050	230,16
20:00	124,0	112,0	879,99	919,99	1516	999,99	219,2
20:15	96,1	86,8	682	713	1174,9	775	169,88
20:30	93,0	84,0	660	689,99	1137	749,99	164,4
20:45	99,2	89,6	703,99	735,99	1212,8	799,99	175,36
21:00	108,5	98,0	769,99	804,99	1326,49	874,99	191,8
21:15	86,8	78,4	615,99	643,99	1061,19	699,99	153,44
21:30	62,0	56,0	439,99	459,99	757,99	499,99	109,6

21:45	31	28	220	230	379	250	54,8
22:00	24,8	22,4	176	183,99	303,19	199,99	43,84
22:15	21,7	19,6	154	161	265,3	175	38,36
22:30	21,7	19,6	154	161	265,3	175	38,36
22:45	18,6	16,8	132	138	227,4	150	32,88
23:00	18,6	16,8	132	138	227,4	150	32,88
23:15	24,8	22,4	176	183,99	303,19	200	43,84
23:30	18,6	16,8	132	137,99	227,39	150	32,88
23:45	21,7	19,6	154	161	265,3	175	38,36

Fig. 2 shows an algorithm that searches for a connection node, as well as changes in the output/consumption of power of the battery storage system from the point of view of the minimum loss of active power in the network during the day.

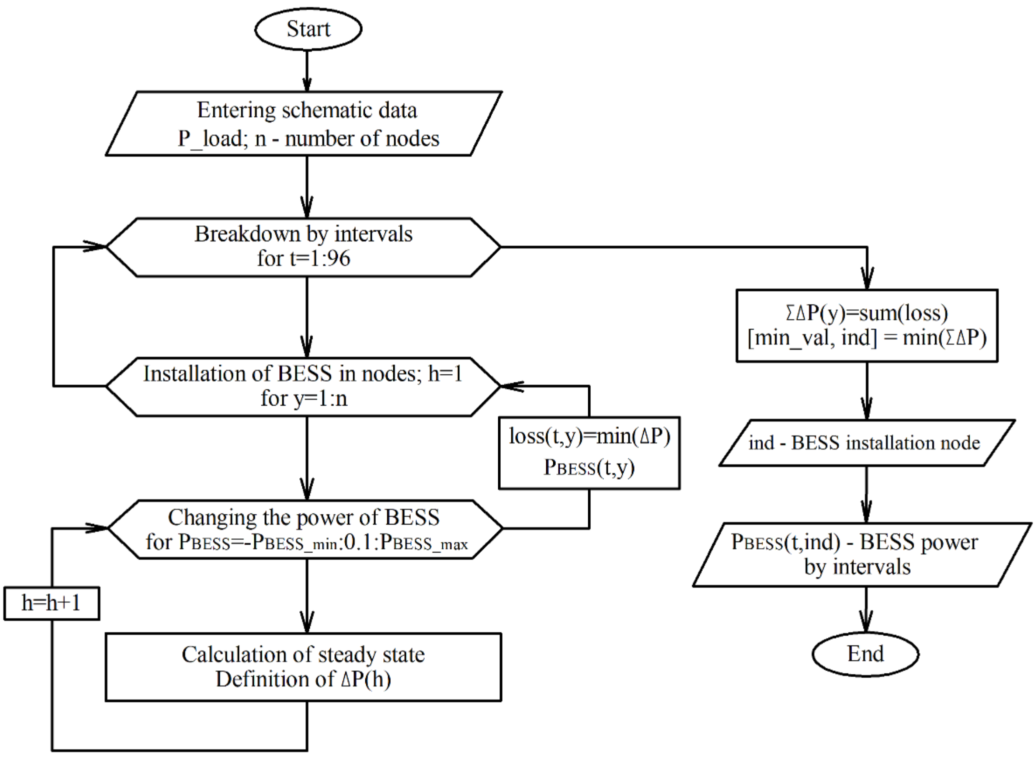

Fig. 2. Algorithm for selecting a connection node for a storage battery system

The algorithm functions as follows: the initial circuit information is entered data on nodes, branches, transformers, changes in load powers during the day. Then the cycle with sorting through time intervals begins. Let us consider the operation of the algorithm for the 1st time interval in more detail. BESS is installed in each of the network nodes in turn, while the BESS power is changed within PBESS_min to PBESS_max in order to determine the active power losses ΔP in the network based on the results of calculating the steady-state mode using the backward-forward sweep method. In this study, the value of PBESS_min = -3000 kW, and PBESS_max = 3000 kW. In this case, the "-" sign in front of PBESS_min means that the BESS is in the discharge mode, i.e. it gives power to the network. After completing the cycle with sorting through BESS powers, the algorithm returns to the cycle of selecting the next BESS installation node. Thus, upon completion of the cycles associated with the selection of plant nodes and determination of BESS capacities, the algorithm returns to the next time interval. Upon completion of the enumeration of all time intervals, the loss and PBESS variables are formed, the contents of which are shown in Tables 5-6. The loss variable contains the values of the minimum active power losses when changing the BESS capacity.

3. Results and discussion

The cells of Table 5 contain the values of active power losses in the network when installing BESS in different nodes at different time intervals.

Table 5. Values of active power losses (kW) in the network

Time	BESS installation nodes									
	1	2	3	4	5	6	7	8	9	10
0:00	27,62	58,59	76,57	222,02	82,84	68,71	75,23	74,21	291,11	74,63
0:15	27,63	58,59	76,57	222,06	82,84	68,71	75,23	74,21	291,11	74,63
0:30	27,63	58,59	76,57	222,06	82,84	68,718	75,23	74,21	291,11	74,63
0:45	27,63	58,59	76,57	222,06	82,84	68,71	75,23	74,21	291,11	74,63
1:00	27,63	58,59	76,57	222,06	82,84	68,71	75,23	74,21	291,11	74,63
1:15	28,19	59,54	76,65	159,27	80,49	91,07	82,08	78,47	283,69	80,91
1:30	28,19	59,54	76,65	159,28	80,49	91,07	82,09	78,47	283,73	80,92
1:45	28,19	59,54	76,65	159,28	80,49	91,07	82,09	78,47	283,73	80,92
2:00	28,83	61,73	81,2	220,37	80,58	75,34	85,88	81,52	291,78	85,63
2:15	28,83	61,73	81,2	220,38	80,59	75,34	85,88	81,52	291,8	85,63
2:30	29,56	65,47	84,3	245,78	83,44	73,42	89,47	85,05	293,37	86,12
2:45	28,83	61,73	81,2	220,38	80,58	75,34	85,88	81,52	291,8	85,63
3:00	28,19	59,54	76,65	159,28	80,49	91,079	82,09	78,47	283,71	80,92
3:15	27,63	58,59	76,57	222,05	82,84	68,71	75,22	74,21	291,07	74,62
3:30	28,83	61,73	81,2	220,37	80,58	75,33	85,86	81,51	291,79	85,61
3:45	28,19	59,54	76,65	159,28	80,49	91,07	82,09	78,47	283,71	80,92
4:00	28,19	59,54	76,65	159,28	80,49	91,07	82,09	78,47	283,73	80,92
4:15	29,56	63,22	79,77	208,31	80,07	81,45	86,28	78,66	295,56	78,85
4:30	29,56	63,22	79,77	208,31	80,08	81,47	86,29	78,66	295,6	78,85
4:45	29,56	63,22	79,77	208,31	80,08	81,47	86,29	78,66	295,6	78,85
5:00	29,56	63,22	79,77	208,31	80,08	81,47	86,29	78,66	295,6	78,85
5:15	35,67	61,55	75,82	177,48	93,21	102,64	95,11	90,36	313,44	102,6
5:30	38,41	66,01	86,74	184,61	98,4	101,71	98,53	110,5	339,37	106,7
5:45	43,14	73,16	95,7	193,97	106,97	112,4	105,77	120,24	336,68	122,9
6:00	52,74	86,47	108,02	212,85	124,46	132,08	119,62	121,11	372,85	133,5
6:15	57,22	92,71	115,22	222,05	131,4	139,21	127,61	131,45	376,27	152,7
6:30	57,22	92,71	115,22	222,06	131,41	139,21	127,62	131,46	376,28	152,8
6:45	59,58	91,35	111,54	236,76	131,38	132,6	131,54	133,15	382,01	149,4
7:00	84,85	143,71	165,69	294,85	165,57	177,3	171,5	169,84	441,31	198,1
7:15	98,41	146,35	180,6	301,63	185,12	199,45	192,0	196,95	481,06	190,4
7:30	129,89	100,02	89,3	173,85	100,7	86,11	87,9	88,38	212,67	98,23
7:45	157,58	120,7	107,86	203,64	120,94	104,41	104,99	106,26	233,13	115,3
8:00	167,64	128,5	114,76	213,62	128,27	112,34	111,59	112,88	242,02	120,1
8:15	183,32	140,85	125,52	235,54	139,94	122,31	122,11	123,7	253,06	129,8
8:30	211,38	163,47	145,69	264,02	160,68	136,46	140,76	143,06	276,10	146,6
8:45	282,05	221,52	198,68	321,15	215,12	187,77	191,77	193,56	330,83	197,4
9:00	333,21	263,65	237,5	355,47	255,62	227,82	230,83	230,88	371,23	235,6
9:15	356,95	283,05	253,74	382,77	276,3	249,2	250,68	248,18	390,74	253,4
9:30	373,22	296,72	267,64	397,94	288,94	261,21	262,52	259,56	403,58	265,7
9:45	389,89	310,98	280,56	412,85	301,71	272,91	277,41	271,78	417,68	278,4

10:00	433,35	347,43	313,98	450,8	339,86	308,58	304,33	303,51	454,15	311,2
10:15	442,51	355,32	321,31	448,73	347,77	311,26	311,14	310,89	461,53	316,8
10:30	424,52	339,82	306,59	433,12	334,51	298,91	299,44	297,28	446,21	304,0
10:45	433,47	347,53	314,06	450,92	339,99	308,68	304,4	303,59	454,26	311,3
11:00	415,70	332,01	298,63	438,37	325,81	294,69	294,26	292,85	440,03	298,9
11:15	407,01	325,22	291,43	432,34	318,78	286,87	287,18	285,52	432,20	292,3
11:30	389,89	310,98	280,56	412,84	301,69	272,91	277,42	271,78	417,68	278,4
11:45	406,99	325,21	291,43	432,31	318,75	286,86	287,17	285,5	432,18	292,3
12:00	415,72	332,02	298,64	438,39	325,82	294,7	294,27	292,85	440,04	298,9
12:15	389,87	310,96	280,55	412,82	301,67	272,88	277,4	271,76	417,66	278,3
12:30	356,92	283,02	253,7	382,7	276,29	249,2	250,66	248,16	390,72	253,3
12:45	341,15	270,2	237,9	372,83	259,09	235,15	235,3	239,4	380,16	237,5
13:00	310,71	244,61	214,5	346,52	235,32	211,20	220,18	219,47	354,67	215,0
13:15	275,04	214,69	187,77	316,06	207,43	184,22	193,1	192,79	325,47	190,0
13:30	254,94	198,43	173,12	300,98	192,07	172,25	179,53	178,77	308,42	173,5
13:45	242,02	187,74	164,16	272,18	182,8	162,11	161,65	168,44	297,82	165,2
14:00	248,45	193,05	168,85	277,51	187,45	164,18	169,08	174,24	304,48	170,9
14:15	269,48	210,54	184,45	296,01	203,55	182,0	191,8	186,41	322,72	183,8
14:30	287,10	226,46	203,52	326,65	220,04	192,61	196,69	198,41	336,87	202,3
14:45	301,42	237,18	208,57	297,53	230,63	211,31	219,88	217,7	350,65	213,3
15:00	316,14	249,92	219,69	352,36	240,6	216,4	225,43	224,67	361,1	220,2
15:15	333,38	263,8	237,59	355,47	255,74	227,98	230,98	231,01	371,38	235,7
15:30	373,12	296,64	267,57	397,96	288,85	261,11	262,44	259,5	403,5	265,6
15:45	325,61	257,4	227,63	328,89	247,14	227,86	232,55	233,95	366,22	230,9
16:00	373,07	296,6	267,5	397,96	288,77	261,12	262,44	259,49	403,46	265,6
16:15	389,89	310,98	280,56	412,85	301,71	272,91	277,41	271,78	417,68	278,4
16:30	348,91	276,41	245,62	341,2	264,36	248,93	258,55	252,63	383,53	250,5
16:45	373,19	296,7	267,6	397,96	288,95	261,2	262,54	259,57	403,56	265,7
17:00	381,51	298,26	264,09	390,69	304,09	275,68	283,25	278,64	371,69	277,9
17:15	389,90	310,98	280,52	412,87	301,72	272,9	277,39	271,79	417,69	278,4
17:30	389,91	311,0	280,57	412,87	301,72	272,93	277,43	271,79	417,7	278,4
17:45	415,68	331,99	298,62	438,35	325,77	294,66	294,24	292,82	440,0	298,8
18:00	442,47	355,29	321,27	448,73	347,74	311,24	311,12	310,87	461,49	316,8
18:15	442,51	355,33	321,31	448,73	347,77	311,27	311,14	310,9	461,53	316,8
18:30	349,02	276,5	245,72	341,2	264,36	248,99	258,63	252,7	383,63	250,6
18:45	310,68	244,58	214,45	346,57	235,30	211,26	220,23	219,4	354,65	215,0
19:00	261,41	204,4	177,02	284,2	202,18	190,62	189,41	198,47	315,14	176,6
19:15	205,64	158,56	136,65	240,86	158,37	142,13	143,04	158,35	266,34	138,8
19:30	134,40	102,78	90,16	184,79	103,92	90,72	93,11	96,31	172,37	94,01
19:45	101,94	173,21	211,25	291,79	180,56	197,56	206,93	203,49	431,77	202,2
20:00	94,90	163,61	200,44	281,22	171,77	188,15	201,65	200,82	462,21	192,9
20:15	67,20	128,08	161,25	249,56	123,14	134,49	161,19	162,61	405,24	153,2
20:30	64,57	125,7	159,13	251,67	124,76	136,67	159,66	158,64	383,32	152,0
20:45	69,91	130,52	163,42	262,19	126,98	138,66	161,79	178,01	425,4	169,3
21:00	78,59	144,41	180,04	364,55	148,6	162,96	156,4	179,82	408,86	190,3
21:15	59,53	91,35	111,54	236,79	131,33	132,51	131,47	133,15	381,91	149,2

21:30	43,09	73,11	95,67	193,99	106,9	112,36	105,71	120,21	336,44	122,8
21:45	30,37	66,02	86,85	279,56	88,17	94,44	82,3	84,29	304,05	85,88
22:00	28,83	61,73	81,19	220,37	80,58	75,34	85,88	81,52	291,76	85,63
22:15	28,19	59,54	76,65	159,28	80,49	91,08	82,09	78,47	283,71	80,92
22:30	28,19	59,54	76,65	159,28	80,49	91,08	82,09	78,47	283,73	80,92
22:45	27,63	58,59	76,57	222,05	82,84	68,71	75,22	74,21	291,07	74,62
23:00	27,63	58,59	76,57	222,06	82,84	68,71	75,23	74,21	291,11	74,63
23:15	28,83	61,73	81,2	220,37	80,58	75,33	85,86	81,51	291,79	85,61
23:30	27,63	58,59	76,57	222,04	82,84	68,71	75,21	74,2	291,11	74,61
23:45	28,19	59,54	76,65	159,27	80,49	91,07	82,08	78,47	283,69	80,91
$\Sigma\Delta P$	18148,77	16522,42	16153,3	27726,23	17234,45	16085,32	16309,31	16261,67	33430,39	16527,64

The variable P_{BESS} contains the BESS power values (MW) by nodes at different time intervals.

Table 6. BESS power values

Time	BESS installation nodes									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0:00	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
0:15	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
0:30	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
0:45	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
1:00	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
1:15	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
1:30	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
1:45	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
2:00	3	2,88	2,88	2,61	2,81	2,48	2,92	2,64	2,84	2,58
2:15	3	2,88	2,88	2,61	2,81	2,48	2,92	2,64	2,84	2,58
2:30	3	2,97	2,9	2,74	2,83	2,35	2,95	2,67	2,83	2,53
2:45	3	2,88	2,88	2,61	2,81	2,48	2,92	2,64	2,84	2,58
3:00	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
3:15	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
3:30	3	2,88	2,88	2,61	2,81	2,48	2,92	2,64	2,84	2,58
3:45	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
4:00	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
4:15	3	2,86	2,76	2,52	2,73	2,59	2,86	2,49	2,84	2,34
4:30	3	2,86	2,76	2,52	2,73	2,59	2,86	2,49	2,84	2,34
4:45	3	2,86	2,76	2,52	2,73	2,59	2,86	2,49	2,84	2,34
5:00	3	2,86	2,76	2,52	2,73	2,59	2,86	2,49	2,84	2,34
5:15	3	2,14	2,14	2,2	2,69	2,71	2,65	2,38	2,81	2,53
5:30	3	2,14	2,32	2,21	2,68	2,53	2,58	2,73	2,88	2,48
5:45	3	2,13	2,32	2,21	2,67	2,55	2,52	2,72	2,81	2,61
6:00	3	2,1	2,2	2,22	2,69	2,58	2,43	2,33	2,85	2,45
6:15	3	2,1	2,2	2,23	2,68	2,56	2,44	2,39	2,82	2,66
6:30	3	2,1	2,2	2,23	2,68	2,56	2,44	2,39	2,82	2,66
6:45	3	1,9	2	2,3	2,59	2,33	2,44	2,34	2,82	2,52
7:00	3	2,6	2,4	2,4	2,51	2,42	2,45	2,28	2,83	2,63
7:15	3	2,1	2,3	2,32	2,52	2,45	2,46	2,41	2,87	2,16
7:30	-2,88	-2,3	-2,28	-2,1	-2,32	-2,48	-2,68	-2,41	-2,64	-1,35

7:45	-2,88	-2,43	-2,34	-2,22	-2,35	-2,39	-2,78	-2,43	-2,66	-1,64
8:00	-2,88	-2,45	-2,36	-2,25	-2,41	-2,28	-2,77	-2,45	-2,68	-1,84
8:15	-2,88	-2,47	-2,4	-2,38	-2,45	-2,36	-2,76	-2,44	-2,68	-1,99
8:30	-2,88	-2,48	-2,42	-2,46	-2,57	-2,8	-2,82	-2,47	-2,71	-2,27
8:45	-2,88	-2,52	-2,44	-2,45	-2,65	-2,67	-2,79	-2,53	-2,73	-2,36
9:00	-2,88	-2,58	-2,48	-2,32	-2,68	-2,57	-2,75	-2,58	-2,74	-2,39
9:15	-2,88	-2,62	-2,57	-2,43	-2,59	-2,45	-2,68	-2,61	-2,75	-2,41
9:30	-2,88	-2,63	-2,53	-2,45	-2,63	-2,47	-2,71	-2,65	-2,75	-2,42
9:45	-2,88	-2,63	-2,54	-2,46	-2,68	-2,51	-2,64	-2,67	-2,76	-2,43
10:00	-2,88	-2,67	-2,58	-2,47	-2,57	-2,46	-2,89	-2,73	-2,78	-2,47
10:15	-2,88	-2,67	-2,58	-2,31	-2,56	-2,59	-2,9	-2,72	-2,78	-2,52
10:30	-2,88	-2,67	-2,59	-2,31	-2,48	-2,54	-2,82	-2,71	-2,77	-2,48
10:45	-2,88	-2,67	-2,58	-2,47	-2,57	-2,46	-2,89	-2,73	-2,78	-2,47
11:00	-2,99	-2,68	-2,62	-2,51	-2,54	-2,46	-2,76	-2,63	-2,78	-2,42
11:15	-2,99	-2,65	-2,63	-2,53	-2,53	-2,49	-2,77	-2,65	-2,77	-2,41
11:30	-2,88	-2,63	-2,54	-2,46	-2,68	-2,51	-2,64	-2,67	-2,76	-2,43
11:45	-2,99	-2,65	-2,63	-2,53	-2,53	-2,49	-2,77	-2,65	-2,77	-2,41
12:00	-2,99	-2,68	-2,62	-2,51	-2,54	-2,46	-2,76	-2,63	-2,78	-2,42
12:15	-2,88	-2,63	-2,54	-2,46	-2,68	-2,51	-2,64	-2,67	-2,76	-2,43
12:30	-2,88	-2,62	-2,57	-2,43	-2,59	-2,45	-2,68	-2,61	-2,75	-2,41
12:45	-2,99	-2,59	-2,71	-2,48	-2,89	-2,52	-2,82	-2,48	-2,77	-2,57
13:00	-2,99	-2,58	-2,72	-2,47	-2,87	-2,56	-2,46	-2,34	-2,75	-2,56
13:15	-2,99	-2,58	-2,72	-2,46	-2,88	-2,59	-2,44	-2,31	-2,73	-2,48
13:30	-2,99	-2,55	-2,71	-2,48	-2,87	-2,45	-2,35	-2,25	-2,71	-2,61
13:45	-2,99	-2,55	-2,68	-2,22	-2,78	-2,49	-2,87	-2,28	-2,7	-2,54
14:00	-2,99	-2,55	-2,68	-2,22	-2,82	-2,64	-2,67	-2,23	-2,72	-2,46
14:15	-2,99	-2,56	-2,69	-2,23	-2,86	-2,51	-2,31	-2,43	-2,74	-2,64
14:30	-2,88	-2,52	-2,44	-2,45	-2,65	-2,67	-2,79	-2,53	-2,73	-2,36
14:45	-2,99	-2,6	-2,72	-1,7	-2,72	-2,31	-2,21	-2,16	-2,76	-2,35
15:00	-2,99	-2,58	-2,72	-2,47	-2,87	-2,56	-2,46	-2,34	-2,75	-2,56
15:15	-2,88	-2,58	-2,48	-2,32	-2,68	-2,57	-2,75	-2,58	-2,74	-2,39
15:30	-2,88	-2,63	-2,53	-2,45	-2,63	-2,47	-2,71	-2,65	-2,75	-2,42
15:45	-2,99	-2,57	-2,64	-1,96	-2,86	-2,35	-2,43	-2,23	-2,75	-2,34
16:00	-2,88	-2,63	-2,53	-2,45	-2,63	-2,47	-2,71	-2,65	-2,75	-2,42
16:15	-2,88	-2,63	-2,54	-2,46	-2,68	-2,51	-2,64	-2,67	-2,76	-2,43
16:30	-2,99	-2,61	-2,64	-1,77	-2,97	-2,25	-2,16	-2,22	-2,74	-2,28
16:45	-2,88	-2,63	-2,53	-2,45	-2,63	-2,47	-2,71	-2,65	-2,75	-2,42
17:00	-2,22	-2,9	-2,9	-2,22	-2,22	-2,22	-2,22	-2,22	-2,22	-2,22
17:15	-2,88	-2,63	-2,54	-2,46	-2,68	-2,51	-2,64	-2,67	-2,76	-2,43
17:30	-2,88	-2,63	-2,54	-2,46	-2,68	-2,51	-2,64	-2,67	-2,76	-2,43
17:45	-2,99	-2,68	-2,62	-2,51	-2,54	-2,46	-2,76	-2,63	-2,78	-2,42
18:00	-2,88	-2,67	-2,58	-2,31	-2,56	-2,59	-2,9	-2,72	-2,78	-2,52
18:15	-2,88	-2,67	-2,58	-2,31	-2,56	-2,59	-2,9	-2,72	-2,78	-2,52
18:30	-2,99	-2,61	-2,64	-1,77	-2,97	-2,25	-2,16	-2,22	-2,74	-2,28
18:45	-2,99	-2,58	-2,72	-2,47	-2,87	-2,56	-2,46	-2,34	-2,75	-2,56
19:00	-2,73	-2,51	-2,76	-2,15	-2,36	-1,87	-2,12	-1,65	-2,73	-2,73

19:15	-2,65	-2,5	-2,8	-2,2	-2,28	-2,11	-2,31	-1,42	-2,65	-2,65
19:30	-2,12	-2,4	-2,65	-2,21	-2,29	-2,17	-2,19	-1,75	-2,12	-2,12
19:45	3	2,8	2,8	2,23	2,32	2,32	2,64	2,43	2,67	2,27
20:00	3	2,8	2,8	2,23	2,34	2,34	2,74	2,57	2,83	2,29
20:15	3	2,9	2,9	2,3	2,1	2,1	2,81	2,68	2,84	2,35
20:30	3	2,95	2,95	2,34	2,24	2,24	2,87	2,69	2,78	2,41
20:45	3	2,85	2,85	2,35	2,1	2,1	2,73	2,88	2,89	2,56
21:00	3	2,9	2,9	2,8	2,33	2,33	2,33	2,65	2,76	2,67
21:15	3	1,9	2	2,3	2,59	2,33	2,44	2,34	2,82	2,52
21:30	3	2,13	2,32	2,21	2,67	2,55	2,52	2,72	2,81	2,61
21:45	3	2,9	2,9	2,9	2,9	2,87	2,67	2,58	2,86	2,46
22:00	3	2,88	2,88	2,61	2,81	2,48	2,92	2,64	2,84	2,58
22:15	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
22:30	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52
22:45	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
23:00	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
23:15	3	2,88	2,88	2,61	2,81	2,48	2,92	2,64	2,84	2,58
23:30	3	2,9	2,88	2,65	3	2,41	2,74	2,56	2,87	2,41
23:45	3	2,86	2,81	2,21	2,87	2,99	2,88	2,62	2,82	2,52

At the end of the algorithm, the ΣΔP variable is calculated to determine the minimum value of active power losses by nodes during the day. Based on this, the ind variable is determined the BESS installation node number, and the BESS power values during the day for the selected installation node are derived from Table 6. This paper proposes to forcibly switch the batteries to the charging mode during the time intervals when the load values are relatively small – from 0:00 to 7:30 and from 19:45 to 23:45. During these periods, the BESS power can vary from 0 to 3 MW. Taking this into account, the BESS is charged for 11 hours 45 minutes during the day, in which case the balance of charge and discharge modes is ensured.

Discission. It is obvious from Table 5 that when installing the BESS system in the 6th node of the distribution electric network, the active power losses during the day are minimal and amount to 16085.32 kW, while installing the BESS in the 9th node, the active power losses per day will be the highest - 33430.39 kW. Installing the BESS in the 1st node does not make sense if the goal is to study the effect of batteries on active power losses in the distribution network.

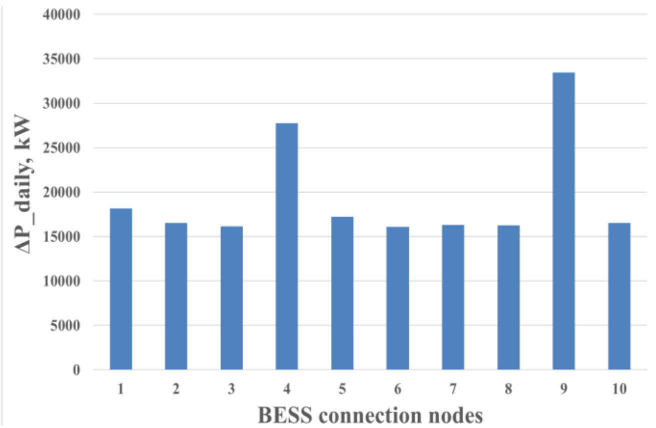

Fig. 3. Diagram of daily total losses of active power by nodes

However, installing batteries in the 1st node could help unload the feeder lines, as well as reduce the cost of payment for electricity in the case of using a multi-tariff payment system, i.e. during hours of relatively cheap electricity, the batteries will be switched to charging mode, and during hours of increased electricity costs, the batteries will supply power to the network.

Fig. 3 shows a comparative diagram of the levels of daily total losses of active power in the distribution network depending on the BESS system installation node.

A more detailed review of Table 6, namely the 6th node of the BESS installation, which, when installed, ensures the minimum value of active power loss per day, gives us the values of the BESS active power supplied to the network for 96 (each for 15 minutes) time intervals.

Fig. 4 shows the daily load schedule of the distribution electrical network with and without taking into account the installation of the BESS system.

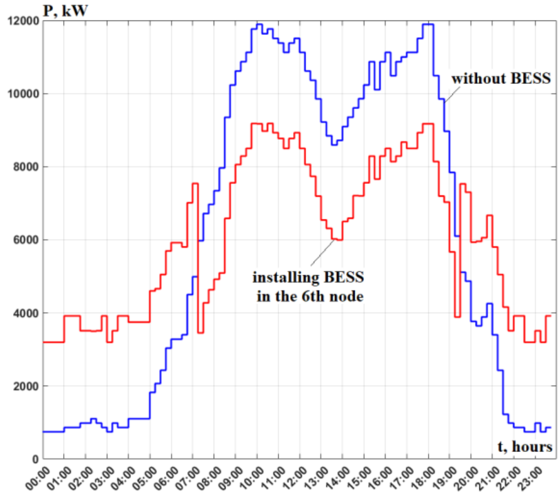

Fig. 4. Daily load schedule of the distribution network

As can be seen from Fig. 4, the use of the BESS system made it possible to smooth out periods of peak consumption of active power, thereby contributing to the reduction of active power losses in network elements - transformers and transmission lines.

Also, Fig. 5 shows comparative graphs of active power losses in the distribution electrical network without and with the installation of BESS.

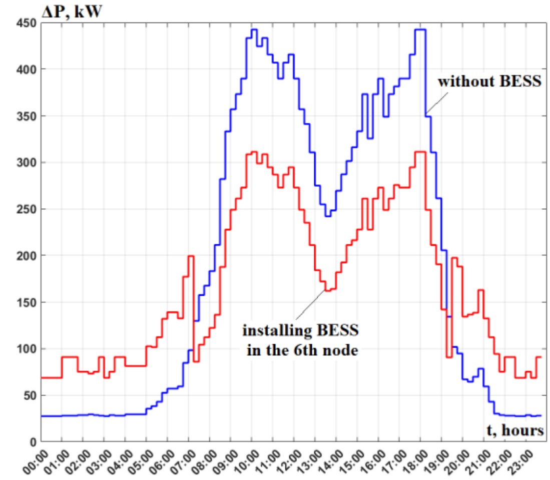

Fig. 5. Curves of changes in active power losses with and without taking into account the installation of the BESS system

It should be noted that in the time intervals from 0:00 to 7:30, as well as from 19:30 to 23:45, the active power losses when installing BESS exceed the level of losses in the case without BESS. This is due to the fact that it is during these time intervals that the BESS system is in the charging mode, that is, the network elements are additionally loaded, which leads to an increase in the level of active power losses. However, if we consider the time intervals from 7:30 to 19:30, the values of active power losses when installing BESS are significantly lower, which is explained by the transition of BESS to the discharge mode, that is, BESS, due to its generation, partially compensates for the losses in the distribution network elements, due to which the flow of active power from the 1st node will decrease.

4. Conclusion

The use of energy storage systems in distribution electric networks allows to significantly reduce active power losses, optimize network operation and smooth out load peaks [21]. In the future, the introduction of storage devices will become an integral part of the modernization of distribution networks, which will increase their reliability, reduce operating costs and improve the quality of electricity supply to consumers. However, the successful implementation of energy storage systems requires a comprehensive approach, including: development of methods for the optimal placement of storage systems in the network, taking into account power losses, load profiles and the presence of renewable energy sources; the use of intelligent control systems capable of adaptively regulating the charging and discharging processes depending on the current conditions in the network; economic analysis of the effectiveness of implementation, including an assessment of the payback period and potential reduction in network operating costs; improvement of the regulatory framework stimulating the development of energy storage technologies and their integration into the existing energy system.

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