1. Satriani Said AKHMAD[1], 2. Ansar SUYUTI[2], 3. Indar Chaerah GUNADIN[2], 4.Sri Mawar SAID[2], 5. Andi Muhammad ILYAS[3], 6. Muhammad Natsir RAHMAN[3], 7. Agus SISWANTO[4], 8. Yuli Asmi RAHMAN[5]

State Polytechnic of Ujung Pandang (1), Hasanuddin University of Makassar (2), Khairun University of Ternate (3), Universitas 17 Agustus 1945 of Cirebon, (4), Universitas of Tadulako (5).
ORCID: 1. 0009-0009-4680-7399; 2. 0000-0002-7742-9986; 3. 0000-0001-9516-0282; 4. 0000-0002-4879-4001; 5. 0000-0001-6001-2298; 6. 0000-0002-3482-9672; 7. 0000-0002-5852-8161; 8. 0000-0001-9332-1345

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Voltage Stability Assessment at Integrated Electric Power System with Wind Power Generation in South Sulawesi Indonesia

***Abstract**. Today the use of renewable energy is being encouraged to overcome the limitations of fossil energy. One of the renewable energies utilized in South Sulawesi Indonesia is wind energy. The weakness of wind power plants is that the energy produced is not constant so that it can affect the stability of integrated conventional systems. This research discusses the stability of systems integrated with renewable energy generators. The method used is the New Voltage Stability Index. The results showed that the highest stability index occurred in the Sidera to Sidera 70 kV networks of 0.157433. The second stability index value on the network from Tello to 30 kV Tello is 0.153720. The third stability index value occurs in the network from 150 kV Powatu to Powatu 70 kV of 0.149948. The value of the simulation results of the system stability index below 1 or in a stable state.*

Streszczenie.** Obecnie zachęca się do korzystania z energii odnawialnej w celu przezwyciężenia ograniczeń energii kopalnej. Jedną z odnawialnych źródeł energii wykorzystywanych w południowym Sulawesi w Indonezji jest energia wiatrowa. Słabością elektrowni wiatrowych jest to, że wytwarzana energia nie jest stała, przez co może wpływać na stabilność zintegrowanych systemów konwencjonalnych. W pracy omówiono stabilność systemów zintegrowanych z generatorami energii odnawialnej. Stosowaną metodą jest nowy wskaźnik stabilności napięcia. Wyniki wykazały, że najwyższy wskaźnik stabilności wystąpił w sieciach Sidera-Sidera 70 kV wynoszący 0,157433. Druga wartość wskaźnika stabilności w sieci od Tello do 30 kV Tello wynosi 0,153720. Trzecia wartość wskaźnika stabilności występuje w sieci od 150 kV Powatu do Powatu 70 kV wynoszącej 0,149948. Wartość wyników symulacji wskaźnika stabilności systemu poniżej 1 lub w stanie stabilnym.* (Ocena stabilności napięcia w zintegrowanym systemie elektroenergetycznym z wytwarzaniem energii wiatrowej w południowym Sulawesi w Indonezji***)

Keywords: new voltage stability index, wind power plant, South Sulawesi power system.
Słowa kluczowe: indeks stabilności napięcia, energetyka wiatrowa

Introduction

Power system analysis is of particular concern to electricity engineers, especially with regard to voltage stability. Voltage stability is currently a serious concern regarding the design, planning and operation of systems integrated with wind energy systems that produce intermittent power. Globally, the power system network develops due to the integration of several private power companies to the national electricity network (PT. PLN). This leads to the violation of stability limits of the system. As a results, voltage instability occurs and incurs high cost for both consumers and companies.

Increasing demand for electricity must be supported by the quality and reliability of the electric power system [1]. PT. PLN is a sole power company which constructs, manages, and maintains the whole Indonesian electric power system on one side and should guarantees the quality of electricity to the consumers on another side [2,3].

Voltage stability as defined by P. Kundur is the ability of a power system to maintain a stable and acceptable voltage on all buses in the system under normal operating conditions and after experiencing a disturbance [4]. It is desired that the power system remains in a state of equilibrium under normal conditions and is expected to react to return the system state to an acceptable state after the disturbance.

The causes of voltage instability are sudden load increase, external factors, and improper operation of the voltage control device. More importantly, voltage instability can arise where there is a mismatch between the reactive power supply and demand, i.e., the inability of the system to meet the reactive power requirements. Voltage instability due to overload on the power network can cause a decrease in system voltage and eventually a voltage collapse occurs. This has severe consequences on system security and jeopardizes essential services to provide customers with reliable and continuous power supply [5].

There are various methods to assess whether a voltage system is stable or not and how close the system is to instability by evaluating voltage stability index. The stability index should be simple and easy to implement in computing to help system planners and operators to examine the condition of voltage stability in the whole electric power system. The stability index can indicate the critical bus of the power system connected between one bus to another. In general, analysis of voltage stability problems in power systems is used to: 1) determine the voltage drop indicator, 2) determine when voltage instability occurs, 3) determine weak buses in the network, and 4) identify areas subjected to unstable systems [6].

Material dan Method

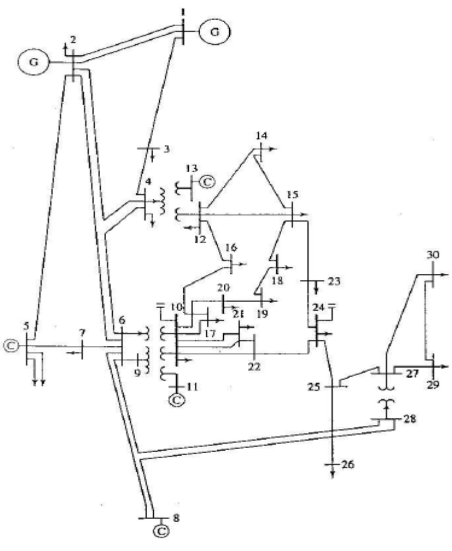


Figure 1. Single line diagram of the IEEE 30-Bus system
Source: Hadi Saadat book

Material

Transmission System

Electrical power systems consist of three main parts: power station, transmission line, and distribution system. Line transmission connects power stations to the distribution system or to the other power system. Distribution system integrates all dispersed loads to the transmission line [7].

IEEE 30-Bus Test System

The IEEE 30-bus test system has 6 generator (PV) buses, 24 load buses (PQ) and 41 interconnected lines or branches. From the generator buses, bus 1 is selected as the slack bus. The following image shows a single line diagram of the system.

The data bus and network or line, the IEEE 30 bus system used as a test method can be seen as follows.

South Sulawesi Power System

PT. PLN (Persero) 2019-2028 in the RUPTL (Business Plan for the Supply of Electricity) contains plans for developing the electricity system in South Sulawesi Province, constructing electricity infrastructure until 2028. More precisely as follows: 1) 2702.3 MW Power Plants, 2) Transmission Networks 2,149 kms, 3) Substation 3,760 MVA, 4) Distribution network 526,391 kms, 4) Distribution station 50,214 MVA.

Table 1. IEEE 30-bus system test data

Bus No.	Bus Code	Volt.Magn	Angle Dee.	Load		Generator		Ijected		
				MW	MVar	MW	Mvar	Qmin	Qmax	Mvar
1	1	1.06	0	0.0	0.0	0.0	0.0	0	0	0
2	2	1.043	0	21.7	12.7	40.0	0.0	-40	50	0
3	0	1	0	2.4	1.2	0.0	0.0	0	0	0
4	0	1.06	0	7.6	1.6	0.0	0.0	0	0	0
5	2	1.01	0	94.2	19.0	0.0	0.0	-40	40	0
6	0	1	0	0.0	0.0	0.0	0.0	0	0	0
7	0	1	0	22.8	10.9	0.0	0.0	0	0	0
8	2	1.01	0	30.0	30.0	0.0	0.0	-10	40	0
9	0	1	0	0.0	0.0	0.0	0.0	0	0	0
10	0	1	0	5.8	2.0	0.0	0.0	-6	24	19
11	2	1.082	0	0.0	0.0	0.0	0.0	0	0	0
12	0	1	0	11.2	7.5	0.0	0.0	0	0	0
13	2	1.071	0	0.0	0.0	0.0	0.0	-6	24	0
14	0	1	0	6.2	1.6	0.0	0.0	0	0	0
15	0	1	0	8.2	2.5	0.0	0.0	0	0	0
16	0	1	0	3.5	1.8	0.0	0.0	0	0	0
17	0	1	0	9.0	5.8	0.0	0.0	0	0	0
18	0	1	0	3.2	0.9	0.0	0.0	0	0	0
19	0	1	0	9.5	3.4	0.0	0.0	0	0	0
20	0	1	0	2.2	0.7	0.0	0.0	0	0	0
21	0	1	0	17.5	11.2	0.0	0.0	0	0	0
22	0	1	0	0.0	0.0	0.0	0.0	0	0	0
23	0	1	0	3.2	1.6	0.0	0.0	0	0	0
24	0	1	0	8.7	6.7	0.0	0.0	0	0	4.3
25	0	1	0	0.0	0.0	0.0	0.0	0	0	0
26	0	1	0	3.5	2.3	0.0	0.0	0	0	0
27	0	1	0	0.0	0.0	0.0	0.0	0	0	0
28	0	1	0	0.0	0.0	0.0	0.0	0	0	0
29	0	1	0	2.4	0.9	0.0	0.0	0	0	0
30	0	1	0	10.6	1.9	0.0	0.0	0	0	0

Source: Hadi Saadat Book.

Table 2. IEEE 30 bus system test line data

No	Bus from	Bus to	R(pu)	X(pu)	1/B(pu)	No	Bus from	Bus to	R(pu)	X(pu)	1/B(pu)
1	1	2	0.0192	0.0575	0.0264	22	15	18	0.1073	0.2185	0
2	1	3	0.0452	0.1852	0.0204	23	18	19	0.0639	0.1292	0
3	2	4	0.057	0.1737	0.0184	24	19	20	0.034	0.068	0
4	3	4	0.0132	0.0379	0.0042	25	10	20	0.0936	0.209	0
5	2	5	0.0472	0.1983	0.0209	26	10	17	0.0324	0.0845	0
6	2	6	0.0581	0.1763	0.0187	27	10	21	0.0348	0.0749	0
7	4	6	0.0119	0.0414	0.0045	28	10	22	0.0727	0.1499	0
8	5	7	0.046	0.116	0.0102	29	21	22	0.0116	0.0236	0
9	6	7	0.0267	0.082	0.0085	30	15	23	0.1	0.202	0
10	6	8	0.012	0.042	0.0045	31	22	24	0.115	0.179	0
11	6	9	0	0.208	0	32	23	24	0.132	0.27	0
12	6	10	0	0.556	0	33	24	25	0.1885	0.3292	0
13	9	11	0	0.208	0	34	25	26	0.2544	0.38	0
14	9	10	0	0.11	0	35	25	27	0.1093	0.2087	0
15	4	12	0	0.256	0	36	28	27	0	0.396	0
16	12	13	0	0.14	0	37	27	29	0.2198	0.4153	0
17	12	14	0.1231	0.2559	0	38	27	30	0.3202	0.6027	0
18	12	15	0.0662	0.1304	0	39	29	30	0.2399	0.4533	0
19	12	16	0.0945	0.1987	0	40	8	28	0.0636	0.2	0.0214
20	14	15	0.221	0.1997	0	41	6	28	0.0169	0.0599	0.065
21	16	17	0.0824	0.1923	0						

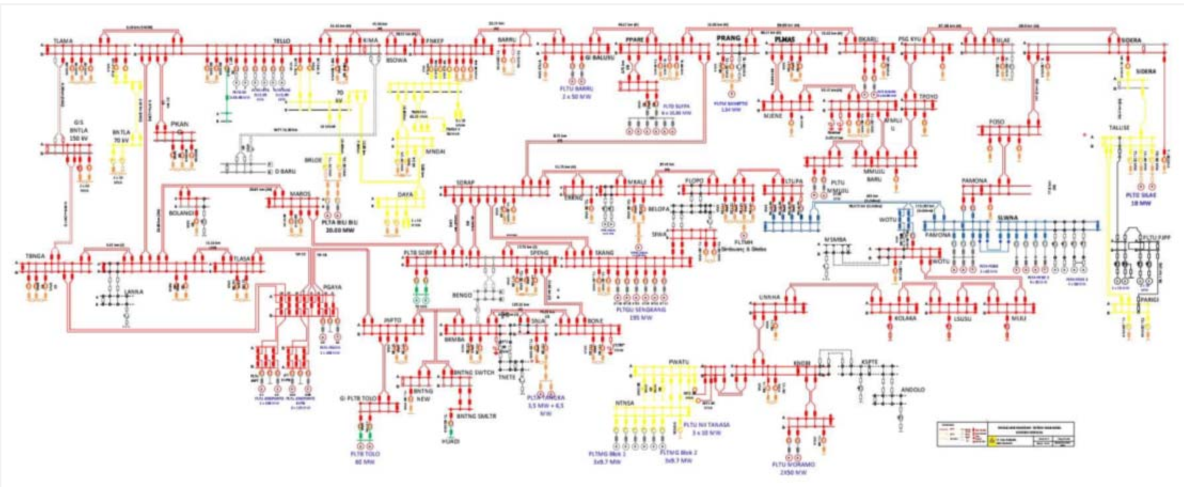
Source: Hadi Saadat Book.

Teble 3. Sulbagsel data bus system

Bus			Volt.	Ang.	Load		Generator		Injected		
No.	Name	Code	Mag.	Deg.	MW	MVAR	MW	MVAR	Qmin	Qmax	MVAR
1	Sengkang	1	1.00	0	26.7	0.1	189.0	141.8	-20.0	60.0	0.0
2	Sidrap	0	0.99	0	33.9	4.2	0.0	0.0	0.0	0.0	0.0
3	Soppeng	0	1.00	0	17.2	3.3	0.0	0.0	0.0	0.0	0.0
4	Enrekang	0	1.00	0	10.2	2.0	0.0	0.0	0.0	0.0	0.0
5	Makale	2	1.02	0	11.2	2.4	7.1	5.3	-100.0	100.0	0.0
6	Palopo	2	1.00	0	43.7	14.1	5.5	4.2	-30.0	60.0	0.0
7	Siwa	0	1.01	0	10.0	1.6	0.0	0.0	0.0	0.0	0.0
8	PLTB Sidrap	2	0.99	0	0.0	0.0	18.7	14.2	-100.0	100.0	0.0
9	Bone	0	0.99	0	35.8	7.1	0.0	0.0	0.0	0.0	-0.2
10	Sinjai	2	1.00	0	22.1	2.5	2.0	1.5	-20.0	60.0	0.0
11	Bulukumba	0	0.98	0	34.9	8.5	0.0	0.0	0.0	0.0	-0.2
12	Bantaeng Switch	0	0.98	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	Bantaeng Smelter	0	0.98	0	28.7	0.0	0.0	0.0	0.0	0.0	0.0
14	Bantaeng New	0	0.99	0	11.2	8.0	0.0	0.0	0.0	0.0	0.0
15	Jeneponto	0	0.99	0	21.9	3.8	0.0	0.0	0.0	0.0	0.0
16	PLTB Tolo	2	1.00	0	0.0	0.0	0.0	0.0	-100.0	100.0	0.0
17	PLTU Jeneponto EXP	2	1.00	0	0.0	0.0	162.1	121.5	-30.0	60.0	0.0
18	PLTU Jeneponto	2	1.00	0	0.0	0.0	180.5	135.4	-20.0	60.0	0.0
19	Punagaya	2	1.00	0	3.9	0.0	180.6	135.4	-30.0	60.0	0.0
20	Tallasa	0	1.00	0	23.7	3.7	0.0	0.0	0.0	0.0	0.0
21	Sungguminasa	0	1.00	0	39.1	8.0	0.0	0.0	0.0	0.0	0.0
22	Bolangi	0	1.00	0	24.2	6.0	0.0	0.0	0.0	0.0	0.0
23	Maros	0	1.00	0	22.2	4.3	0.0	0.0	0.0	0.0	0.0
24	Tanjung Bunga	0	1.00	0	58.4	14.5	0.0	0.0	0.0	0.0	0.0
25	Bontoala	0	1.00	0	44.8	12.5	0.0	0.0	0.0	0.0	0.0
26	Tallo Lama	0	1.01	0	36.1	8.5	0.0	0.0	0.0	0.0	0.0
27	Tallo Lama 70 KV	0	1.01	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	Bontoala 70 KV	0	1.01	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	Tello	2	1.02	0	50.9	10.4	0.0	0.0	-30.0	60.0	0.0
30	Panakukang	0	1.01	0	68.4	13.8	0.0	0.0	0.0	0.0	0.0
31	Tello 30 KV	0	1.02	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	Barawaja	0	1.02	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	Tello 70 KV	0	1.03	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
34	Borongloe	2	0.99	0	1.9	9.4	14.9	11.2	-100.0	100.0	0.0
35	Daya	0	1.03	0	20.1	2.4	0.0	0.0	0.0	0.0	0.1
36	Mandai	0	1.03	0	23.4	5.1	0.0	0.0	0.0	0.0	0.0
37	Tonasa	0	1.04	0	2.5	0.0	0.0	0.0	0.0	0.0	0.0
38	Kima	0	1.01	0	32.0	10.1	0.0	0.0	0.0	0.0	0.0
39	Bosowa	0	1.01	0	18.9	0.0	0.0	0.0	0.0	0.0	0.0
40	Pangkep	0	1.00	0	24.2	5.2	0.0	0.0	0.0	0.0	0.0
41	Pangkep 70 KV	0	1.04	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
42	Barru	0	1.00	0	10.6	2.6	0.0	0.0	0.0	0.0	0.0
43	GI Balusu	2	1.00	0	1.0	0.1	33.9	25.4	-30.0	60.0	0.0
44	Pare-pare	0	1.00	0	24.0	5.7	0.0	0.0	0.0	0.0	0.0
45	PLTD Suppa	2	1.00	0	0.0	0.0	0.0	0.0	-20.0	60.0	0.0
46	Pinrang	2	1.00	0	33.2	11.0	0.4	0.0	-30.0	60.0	0.0
47	Polmas	0	1.02	0	18.3	2.4	0.0	0.0	0.0	0.0	0.0
48	Majene	0	1.02	0	16.1	1.7	0.0	0.0	0.0	0.0	0.0
49	Bakaru	2	1.05	0	0.1	0.0	122.0	91.5	-20.0	60.0	0.0
50	Mamuju	0	1.02	0	11.8	1.6	0.0	0.0	0.0	0.0	-0.3
51	Mamuju Baru	0	1.02	0	6.2	0.1	0.0	0.0	0.0	0.0	0.0
52	PLTU Mamuju	2	1.05	0	0.0	0.0	40.2	30.2	-30.0	60.0	0.0
53	Topoyo	0	0.98	0	7.4	1.0	0.0	0.0	0.0	0.0	0.0
54	Pasang Kayu	0	0.95	0	10.8	1.6	0.0	0.0	0.0	0.0	0.0
55	Silae	0	0.96	0	12.6	0.2	0.0	0.0	0.0	0.0	0.0
56	Sidera	0	0.96	0	15.4	5.1	0.0	0.0	0.0	0.0	0.0
57	Sidera 70 KV	0	0.97	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
58	Poso	0	0.95	0	11.9	2.3	0.0	0.0	0.0	0.0	0.0
59	Pamona 150 KV	0	0.98	0	0.2	0.7	0.0	0.0	0.0	0.0	0.0
60	Tallise	2	1.00	0	4.2	8.0	0.0	0.0	-100.0	100.0	0.0
61	Parigi	0	0.97	0	16.9	5.5	0.0	0.0	0.0	0.0	0.0
62	Pamona 275 KV	2	1.00	0	0.0	0.0	144.0	108.0	-30.0	60.0	0.0
63	Slwna	2	1.00	0	0.0	0.0	30.6	23.0	-30.0	60.0	0.0
64	Latupa 275 KV	0	0.99	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
65	Latupa 150 KV	0	1.01	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	Wotu 275 KV	0	0.99	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
67	Wotu 150 KV	0	0.98	0	17.1	3.4	0.0	0.0	0.0	0.0	0.0
68	Malili	0	0.97	0	4.7	0.8	0.0	0.0	0.0	0.0	0.0
69	Lasusua	0	0.95	0	7.2	1.3	0.0	0.0	0.0	0.0	0.0
70	Kolaka	0	0.96	0	20.8	5.5	0.0	0.0	0.0	0.0	0.0
71	UNNHA	0	0.95	0	20.8	6.0	0.0	0.0	0.0	0.0	0.0
72	Kendari	0	0.95	0	40.7	10.4	0.0	0.0	0.0	0.0	0.0
73	Pwatu 150 KV	0	0.95	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
74	Pwatu 70 KV	0	0.98	0	31.7	8.1	0.0	0.0	0.0	0.0	0.0
75	NTNSA	2	1.00	0	6.9	2.5	13.5	10.1	-100.0	100.0	0.0
76	PLTU Maramo	2	1.00	0	9.5	2.4	90.5	67.9	-100.0	100.0	0.0

Table 4. South Sulawesi transmission line data

No.	Bus from	Bus to	R (pu)	X (pu)	1/B (pu)	No.	Bus from	Bus to	R (pu)	X (pu)	1/B (pu)
1	1	2	0.009550	0.079640	0.011490	46	33	36	0.058280	0.106990	0.000320
2	1	3	0.011350	0.058520	0.004040	47	35	36	0.024480	0.082910	0.000190
3	1	7	0.031310	0.112490	0.008850	48	36	41	0.187890	0.319400	0.000500
4	2	3	0.028820	0.095640	0.004820	49	37	41	0.018120	0.061360	0.000050
5	2	4	0.016770	0.090370	0.008500	50	38	40	0.019870	0.064350	0.003800
6	2	5	0.034310	0.182840	0.012030	51	39	40	0.011360	0.036780	0.004930
7	2	8	0.002030	0.016160	0.000340	52	40	41	0.000000	0.394900	0.000000
8	2	44	0.010390	0.033900	0.001420	53	40	42	0.024190	0.086670	0.011670
9	3	9	0.022840	0.074200	0.008040	54	40	43	0.023680	0.080130	0.006700
10	4	5	0.017370	0.093600	0.009640	55	42	43	0.013880	0.049740	0.006700
11	5	6	0.010530	0.063350	0.008070	56	43	44	0.023890	0.080720	0.003960
12	6	65	0.060690	0.111410	0.000340	57	44	45	0.003900	0.013630	0.000560
13	8	23	0.017950	0.146400	0.003990	58	44	46	0.014380	0.047440	0.000670
14	9	10	0.040070	0.134730	0.011490	59	44	47	0.047860	0.171640	0.018190
15	9	11	0.073170	0.247750	0.008820	60	46	49	0.030760	0.110230	0.010120
16	10	11	0.035490	0.116280	0.008820	61	47	48	0.026300	0.094510	0.007440
17	11	12	0.003890	0.013180	0.001110	62	47	49	0.026270	0.094400	0.007430
18	11	15	0.025130	0.084140	0.003440	63	48	50	0.071950	0.258510	0.020350
19	12	13	0.020230	0.037140	0.000110	64	50	51	0.030760	0.110230	0.010120
20	14	15	0.012480	0.042250	0.006700	65	51	52	0.031050	0.127910	0.011490
21	15	16	0.017860	0.058660	0.003140	66	51	53	0.048400	0.161330	0.018190
22	15	19	0.016130	0.054660	0.003140	67	53	54	0.048400	0.161330	0.018190
23	17	19	0.013880	0.049740	0.006700	68	54	55	0.048400	0.161330	0.018190
24	18	19	0.013880	0.049740	0.006700	69	55	56	0.015410	0.051370	0.006270
25	19	20	0.003910	0.032880	0.002170	70	56	57	0.000000	0.500000	0.000000
26	19	24	0.003850	0.026350	0.001240	71	56	58	0.048400	0.161330	0.020350
27	20	21	0.004340	0.028920	0.003140	72	57	60	0.048400	0.161330	0.020350
28	21	22	0.001530	0.012770	0.001110	73	58	59	0.048400	0.161330	0.018190
29	21	23	0.007370	0.059910	0.017560	74	59	62	0.000000	0.138900	0.000000
30	21	24	0.003610	0.021030	0.001360	75	60	61	0.094460	0.107750	0.001420
31	21	29	0.001780	0.013600	0.001240	76	62	63	0.019140	0.063560	0.000180
32	22	23	0.005980	0.046950	0.008070	77	62	64	0.009670	0.080590	0.020350
33	24	25	0.001450	0.006250	0.001110	78	62	66	0.005240	0.043710	0.020350
34	25	26	0.020230	0.037140	0.001110	79	64	65	0.000000	0.138900	0.000000
35	26	27	0.000000	0.415900	0.000000	80	64	66	0.010770	0.036870	0.008070
36	26	29	0.002570	0.010610	0.000880	81	66	67	0.000000	0.138900	0.000000
37	27	28	0.020570	0.069650	0.000060	82	67	68	0.017370	0.071570	0.020350
38	29	30	0.001730	0.006920	0.000060	83	68	69	0.025650	0.116100	0.020350
39	29	31	0.000000	0.553500	0.000000	84	69	70	0.024180	0.109440	0.020350
40	29	33	0.000000	0.415900	0.000000	85	70	71	0.020930	0.092510	0.011490
41	29	38	0.004240	0.014110	0.003800	86	71	72	0.014300	0.064250	0.007440
42	29	39	0.016870	0.060480	0.005750	87	72	73	0.003840	0.017860	0.000340
43	31	32	0.090660	0.307000	0.000020	88	72	76	0.025650	0.116100	0.006270
44	33	34	0.060730	0.205630	0.000340	89	73	74	0.000000	0.500000	0.000000
45	33	35	0.026810	0.054060	0.000130	90	74	75	0.046260	0.095100	0.000340



Source : PT. PLN (Persero) UIKL Sulawesi

Figure 2. Single Line Diagram of South Sulawesi Power System

PT PLN (Persero) tries to achieve this goal through several efforts. For example, in South Sulawesi, the Southern Sulawesi I Main Unit Development (MUD) is building two underground transmission networks or high voltage cable lines (HVCL) with a voltage of 150 kV. Second, the 150 kV HVCL network from Kima to Daya Baru, and from Tanjung Bunga to Bontoala. The total length of the two HVCLs is 27.57 kms, passing through Makassar and Maros. The purpose of constructing the Tanjung Bunga Bontoala 150 kV HVCL is to increase the reliability of the electricity supply for Makassar City and its surroundings. At the same time, Kima was also built to Daya Baru 150 kV

HVCL to ensure reliable electricity supply in the Makassar industrial area [8]. South Sulawesi data bus system, transmission line data and single-line diagrams are shown in Table 3, Table 4, and Figure 1 below, respectively

Methods

L-Index

Kessel and Glavitsch, (1986) developed the L-index based on the power flow solution. Assessment of instability based on the type of load that is constant. The stability index value ranges from 0 to 1. A value 0 means stable and a value of 1 is unstable. The lower of the index value the more stable the voltage and vice versa [9]. The L-Index is formulated as follows.

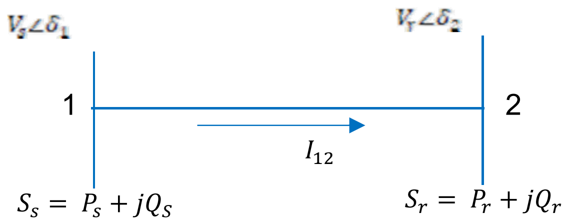
(1) $$L = \max_{j \in \alpha_L}\{L_j\} = \max_{j \in \alpha_L}\left\{\left|1 - \frac{\sum_{i \in \alpha_G} F_{ji} * V_i}{V_j}\right|\right\}$$

$$F_{ji} = |F_{ji}| < \theta_{ji}$$

L is the system on the consumer side and *G* is the system on the generator, *[Lj]* a local indicator that determines the busbar from which the instability occurs. *[F]* is calculated by $[[F] = [Y_{LL}]^{-1}[Y_{LG}]$ where $[Y_{LL}]$ and $[Y_{LG}]$ are *Y*-bus matrices. The voltages V_i and V_j represent the voltages on buses *i* and *j* [10, 11].

Line Stability Index (Lmn)

Lmn derived based on the concept of power transmission lines in one channel [12]. Lmn Index can be described and formulated as follows.



Fig/ 3: Typical one-line diagram of transmission line

Where, V_s, P_s, and Q_s are the sending / generating voltage, real power and reactive power, respectively. V_r, P_r and Q_r are the receiver/load tip voltage, real power, and reactive power, respectively. δ_1 is the phase voltage of the generator, and δ_2 is the phase angle of the load at the load, I_{12} is the line current and θ is the angle of the transmission line, and formulated as follows:

(2) $$Lmn = \frac{4\,X\,Q_r}{|V_s|^2\,sin^2\,(\theta - \delta)} \leq 1$$

The lmn-index is also directly related to reactive power, and not directly related to active power through the voltage phase angle δ. Networks in the system are said to be close to instability when the Lmn-index is close to one (1). On the other hand, if the Lmn-index value is less than 1, the system is said to be stable.

Fast Voltage Stability Index (FVSI)

FVSI equation is given below.

(3) $$FVSI = \frac{4Z^2Q_r}{V_s^2X} \leq 1$$

where *Z* is the line impedance, *X* is line reactance, Q_r is reactive power in the receiving end, V_s is voltage in the sending end.

New voltage stability index (NVSI)

NVSI is a combination of the line stability index (Lmn) and fast voltage stability index (FVSI) which aims to increase the accuracy and speed of computation. A figure of one-line diagram of a two-bus power system model whose parameters and variables in per unit can be seen as follows.

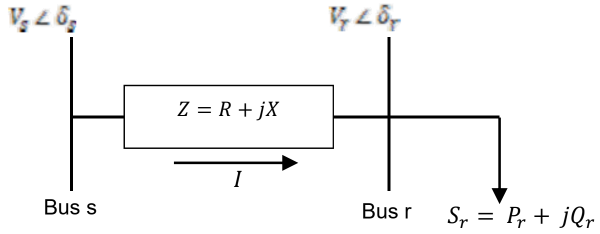


Fig 4. One-line diagram of a two-bus power system model.

The expression of new voltage stability index is given below.

(4) $$NVSI = \frac{4Q_r}{|V_s|^2}\left[\frac{|Z|^2}{X}\sigma - \frac{X}{sin^2(\theta - \delta)}(\sigma - 1)\right] \leq 1 \quad \sigma = \begin{cases} 1 & \delta < \delta c \\ 0 & \delta \geq \delta c \end{cases}$$

$$\sigma = \begin{cases} 1 & \delta < \delta c \\ 0 & \delta \geq \delta c \end{cases}$$

where δ is a variable, If is switching function whose value depends on the angle difference, the value of δ is very small [13].

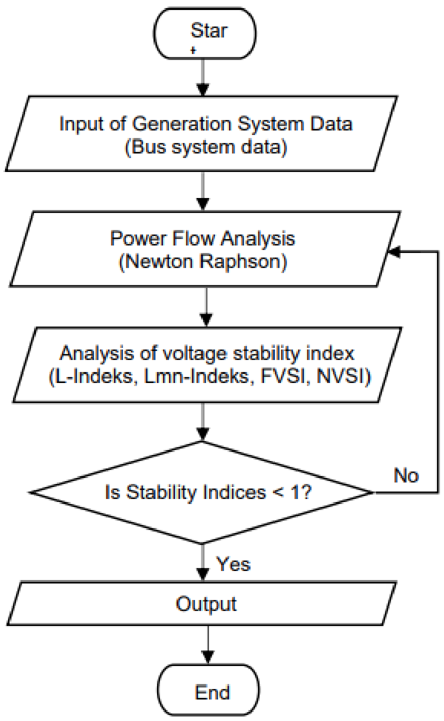


Fig. 5. Research flowchart

In this study the Line Stability Index (Lmn), Fast Voltage Stability Index (FVSI) and New Voltage Stability Index (NVSI) methods were used to determine the stability index of the Southern Sulawesi electricity system (SULBAGSEL) which is integrated with wind power plants. SULBAGSEL has a transmission network of 7,092.42 Kms, and has various types of energy sources, both conventional and renewable, which are interconnected. This situation can lead to system instability [14, 15]. Therefore, the

SULBAGSEL network system must be monitored to predict and create warnings of possible instability incidents. The research flowchart can be seen in the following figure.

Results and Discussion

Stability index testing in this study was carried out twice. The first method used was tested with IEEE 30 bus data. The second uses the Sulbagsel data system which is integrated with the Sidrap and Jeneponto wind power generators.

IEEE 30 bus system data stability index results.

For more details about the stability index using IEEE 30 bus data, see the following table.

Table 5. The results of the IEEE 30 bus data stability index

No. Bus	Bus From	Bus To	Lmn	Fvsi	Nvsi
1	1	2	0.00015	0.00014	0.00015
2	1	3	0.00048	0.00044	0.00048
3	2	4	0.00047	0.00045	0.00047
4	3	4	0.00010	0.00010	0.00010
5	2	5	0.00054	0.00049	0.00054
6	2	6	0.00049	0.00045	0.00049
7	4	6	0.00011	0.00011	0.00011
8	5	7	0.00033	0.00033	0.00033
9	6	7	0.00023	0.00022	0.00022
10	6	8	0.00011	0.00011	0.00011
11	6	9	0.00051	0.00051	0.00051
12	6	10	0.00138	0.00137	0.00138
13	9	11	0.00048	0.00048	0.00048
14	9	10	0.00025	0.00025	0.00025
15	4	12	0.00064	0.00063	0.00064
16	12	13	0.00032	0.00032	0.00032
17	12	14	0.00072	0.00071	0.00071
18	12	15	0.00038	0.00037	0.00037
19	12	16	0.00056	0.00055	0.00055
20	14	15	0.00104	0.00103	0.00103
21	16	17	0.00053	0.00053	0.00053
22	15	18	0.00064	0.00064	0.00064
23	18	19	0.00039	0.00038	0.00038
24	19	20	0.00020	0.00020	0.00020
25	10	20	0.00059	0.00058	0.00058
26	10	17	0.00022	0.00022	0.00022
27	10	21	0.00021	0.00021	0.00021
28	10	22	0.00043	0.00043	0.00043
29	21	22	0.00007	0.00007	0.00007
30	15	23	0.00059	0.00059	0.00059
31	22	24	0.00060	0.00060	0.00060
32	23	24	0.00080	0.00080	0.00080
33	24	25	0.00105	0.00106	0.00106
34	25	26	0.00135	0.00134	0.00134
35	25	27	0.00064	0.00065	0.00065
36	28	27	0.00098	0.00098	0.00098
37	27	29	0.00130	0.00128	0.00128
38	27	30	0.00193	0.00185	0.00185
39	29	30	0.00147	0.00145	0.00145
40	8	28	0.00054	0.00054	0.00054
41	6	28	0.00016	0.00016	0.00016

Stability index value with IEEE 30 bus test data < 1 (under one or the system is in a stable state). The stability index testing graph using IEEE 30 bus data can be seen as follows.

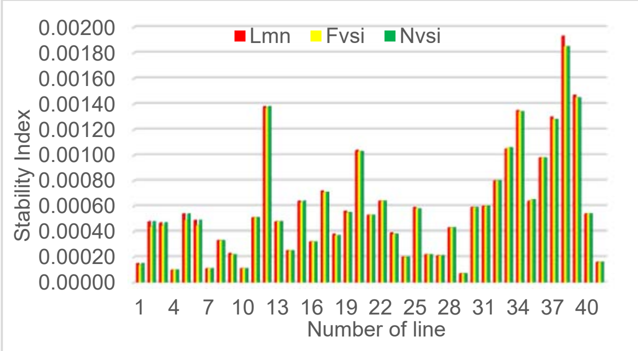


Fig 6. Graph of IEEE 30 Bus System Data Stability Index

The results of testing the method using IEEE 30 bus data show that the method used can work well. This can be used as an assumption that the method can be used in the Sulbagsel system.

Sulbagsel System Stability Index Results

The stability index simulation results using the Lmn-index (Lmn), Fast voltage stability index (FVSI), and New voltage stability index (NVSI) can be seen in Table 6 and Figure 7 below.

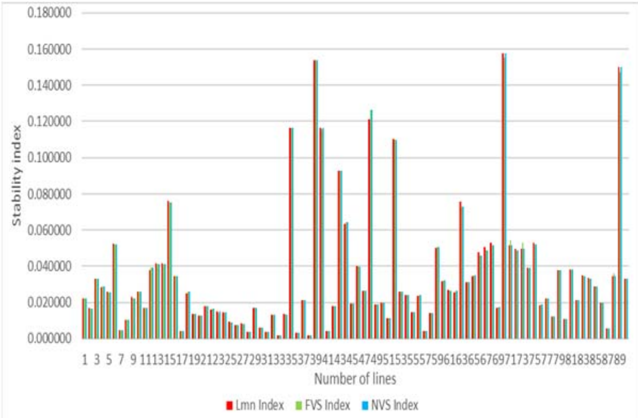


Fig. 7. Voltage stability graph

Table 6. Voltage stability indices

No.	Bus from		Bus to		Lmn Index	FVS Index	NVS Index
1	1	Sengkang	2	Sidrap	0.022376	0.021990	0.021990
2	1	Sengkang	3	Soppeng	0.016897	0.016529	0.016529
3	1	Sengkang	7	Siwa	0.033201	0.032993	0.032993
4	2	Sidrap	3	Soppeng	0.028497	0.028633	0.028633
5	2	Sidrap	4	Enrekang	0.025792	0.025657	0.025657
6	2	Sidrap	5	Makale	0.052320	0.051950	0.051950
7	2	Sidrap	8	PLTB Sidrap	0.004505	0.004505	0.004505
8	2	Sidrap	44	Pare-pare	0.010238	0.010178	0.010178
9	3	Soppeng	9	Bone	0.023061	0.022362	0.022362
10	4	Enrekang	5	Makale	0.026048	0.026004	0.026004
11	5	Makale	6	Palopo	0.017033	0.017033	0.017033
12	6	Palopo	65	Latupa 275 kV	0.037638	0.039326	0.039326
13	8	PLTB Sidrap	23	Maros	0.041655	0.041271	0.041271
14	9	Bone	10	Sinjai	0.041698	0.040987	0.040987
15	9	Bone	11	Bulukumba	0.076030	0.075285	0.075285
16	10	Sinjai	11	Bulukumba	0.034367	0.034601	0.034601
17	11	Bulukumba	12	Bantaeng Switch	0.004057	0.004048	0.004048

18	11	Bulukumba	15	Jeneponto	0.025121	0.025890	0.025890
19	12	Bantaeng Switch	13	Bantaeng Smelter	0.013807	0.013638	0.013638
20	14	Bantaeng New	15	Jeneponto	0.012840	0.012869	0.012869
21	15	Jeneponto	16	PLTB Tolo	0.017824	0.017792	0.017792
22	15	Jeneponto	19	Punagaya	0.016017	0.016493	0.016493
23	17	PLTU Jeneponto EXP	19	Punagaya	0.015091	0.014306	0.015091
24	18	PLTU Jeneponto	19	Punagaya	0.014863	0.014027	0.014863
25	19	Punagaya	20	Tallasa	0.009210	0.009077	0.009077
26	19	Punagaya	24	Tanjung Bunga	0.007512	0.007326	0.007326
27	20	Tallasa	21	Sungguminasa	0.008277	0.008171	0.008171
28	21	Sungguminasa	22	Bolangi	0.003612	0.003610	0.003610
29	21	Sungguminasa	23	Maros	0.016953	0.016947	0.016947
30	21	Sungguminasa	24	Tanjung Bunga	0.005995	0.006033	0.006033
31	21	Sungguminasa	29	Tello	0.003879	0.003855	0.003855
32	22	Bolangi	23	Maros	0.013320	0.013325	0.013325
33	24	Tanjung Bunga	25	Bontoala	0.001836	0.001830	0.001830
34	25	Bontoala	26	Tallo Lama	0.013866	0.013400	0.013400
35	26	Tallo Lama	27	Tallo Lama 70 kV	0.116293	0.116293	0.116293
36	26	Tallo Lama	29	Tello	0.003147	0.003141	0.003141
37	27	Tallo Lama 70 kV	28	Bontoala 70 kV	0.021172	0.021172	0.021172
38	29	Tello	30	Panakukang	0.002047	0.002042	0.002042
39	29	Tello	31	Tello 30 kV	0.153725	0.153725	0.153725
40	29	Tello	33	Tello 70 kV	0.116356	0.115509	0.116356
41	29	Tello	38	Kima	0.004283	0.004273	0.004273
42	29	Tello	39	Bosowa	0.018174	0.018104	0.018104
43	31	Tello 30 kV	32	Barawaja	0.092696	0.092696	0.092696
44	33	Tello 70 kV	34	Borongloe	0.063402	0.064297	0.064297
45	33	Tello 70 kV	35	Daya	0.019585	0.019371	0.019371
46	33	Tello 70 kV	36	Mandai	0.040398	0.039900	0.039900
47	35	Daya	36	Mandai	0.026374	0.026369	0.026369
48	36	Mandai	41	Pangkep 70 kV	0.121125	0.126267	0.126267
49	37	Tonasa	41	Pangkep 70 kV	0.018689	0.018706	0.018706
50	38	Kima	40	Pangkep	0.019666	0.019670	0.019670
51	39	Bosowa	40	Pangkep	0.011203	0.011224	0.011224
52	40	Pangkep	41	Pangkep 70 kV	0.110194	0.109848	0.109848
53	40	Pangkep	42	Barru	0.025806	0.025987	0.025987
54	40	Pangkep	43	GI Balusu	0.023894	0.024236	0.024236
55	42	Barru	43	GI Balusu	0.014647	0.014747	0.014747
56	43	GI Balusu	44	Pare-pare	0.023593	0.023897	0.023897
57	44	Pare-pare	45	PLTD Suppa	0.004019	0.004019	0.004019
58	44	Pare-pare	46	Pinrang	0.014026	0.014117	0.014117
59	44	Pare-pare	47	Polmas	0.050308	0.050416	0.050416
60	46	Pinrang	49	Bakaru	0.031557	0.032342	0.032342
61	47	Polmas	48	Majene	0.026988	0.026375	0.026375
62	47	Polmas	49	Bakaru	0.025626	0.026345	0.026345
63	48	Majene	50	Mamuju	0.075813	0.072800	0.072800
64	50	Mamuju	51	Mamuju Baru	0.031323	0.031061	0.031061
65	51	Mamuju Baru	52	PLTU Mamuju	0.034521	0.035197	0.035197
66	51	Mamuju Baru	53	Topoyo	0.047861	0.045695	0.045695
67	53	Topoyo	54	Pasang Kayu	0.050715	0.048759	0.048759
68	54	Pasang Kayu	55	Silae	0.053188	0.051758	0.051758
69	55	Silae	56	Sidera	0.017221	0.017338	0.017338
70	56	Sidera	57	Sidera 70 kV	0.157433	0.155288	0.157433
71	56	Sidera	58	Poso	0.051527	0.054615	0.051527
72	57	Sidera 70 kV	60	Tallise	0.049853	0.048572	0.048572
73	58	Poso	59	Pamona 150 kV	0.049555	0.052768	0.049555
74	59	Pamona 150 kV	62	Pamona 275 kV	0.039137	0.038615	0.039137
75	60	Tallise	61	Parigi	0.053126	0.051871	0.051871
76	62	Pamona 275 kV	63	Slwna	0.018641	0.018870	0.018870
77	62	Pamona 275 kV	64	Latupa 275 kV	0.022414	0.022253	0.022253
78	62	Pamona 275 kV	66	Wotu 275 kV	0.012153	0.012069	0.012069
79	64	Latupa 275 kV	65	Latupa 150 kV	0.037938	0.037856	0.037856
80	64	Latupa 275 KV	66	Wotu 275 kV	0.010900	0.010906	0.010906
81	66	Wotu 275 kV	67	Wotu 150 kV	0.038274	0.038019	0.038274
82	67	Wotu 150 kV	68	Malili	0.021363	0.021034	0.021034
83	68	Malili	69	Lasusua	0.035048	0.034321	0.034321
84	69	Lasusua	70	Kolaka	0.033685	0.033169	0.033169
85	70	Kolaka	71	Unaha	0.028859	0.028760	0.028760
86	71	Unaha	72	Kendari	0.019956	0.020032	0.020032
87	72	Kendari	73	Pwatu 150 kV	0.005510	0.005498	0.005498
88	72	Kendari	76	PLTU Maramo	0.034697	0.035830	0.034697
89	73	Powatu 150 kV	74	Powatu 70 kV	0.149948	0.147288	0.149948
90	74	Powatu 70 kV	75	NTNSA	0.033118	0.033107	0.033107

The results showed that the Lmn-Index (Lmn) method with an average stability index of 0.034536. Fast Voltage Stability Index (NVSI) with an average stability index of 0.034449. The average New Voltage Stability Index (NVSI) value is 0.034455.

The simulation results show that the highest stability index value for the Lmn and NVSI methods is 0.157433, while the FVSI is 0.155288. This situation occurs on network number 70, from the Sidera bus to the 70 KV Sidera bus.

The second stability index for each method is 0.153720, occurring in network number 39, from the Tello bus to the 30 KV Tello bus.

The stability index values of the three Lmn and NVSI methods were 0.149948, while the FVSI was 0.147288. This situation occurs on network number 89, from the 150 KV Powatu bus to the 70 KV Powatu bus.

Conclusion

The simulation results of the stability index of the Sulbagsel electricity system show that the stability index value is <1 (below one), which means that the system is in a stable state.

Authors: *Dr. Satriani Said AKHMAD, ST., MT Department of Electrical Engineering, Faculty of Engineering, Ujung Pandang State Polytechnic, Indonesia; Prof. Dr. Ir. Ansar SUYUTI, MT, IPU, ASEAN.Eng, Department of Electrical Engineering, Faculty of Engineering University of Hasanuddin Makassar Indonesia; Dr. Indar Chaerah GUNADIN, ST., MT Department of Electrical Engineering, Faculty of Engineering University of Hasanuddin Makassar Indonesia; Dr. Ir. Sri Mawar SAID, MT, Department of Electrical Engineering, Faculty of Engineering University of Hasanuddin Makassar Indonesia; Dr. Andi Muhammad ILYAS, ST., MT, Department of Electrical Engineering, Faculty of Engineering, Khairun University, Ternate, North Moluccas, Indonesia; Muhammad Natsir RAHMAN, ST., MT, Department of Electrical Engineering, Faculty of Engineering, Khairun University, Ternate, North Moluccas, Indonesia; Dr. Agus SISWANTO, ST., MT, Department of Electrical Engineering, Faculty of Engineering, Universitas 17 Agustus 1945 Cirebon, Indonesia; Dr. Yuli Asmi RAHMAN, ST., MT, Department of Electrical Engineering, Faculty of Engineering, Universitas Tadulako, Indonesia.*
E-mail: satriani_said@poliupg.ac.id

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