Vol. 03, Iss. 1 (2026) 1-12, DOI: 10.61552/JSI.2026.01.001

JSDI

Journal of Sustainable Development Innovations

www.jsi.aspur.rs

Research article

Voltage Security Assessment of Power Grid Network

Manish Parihar[a,*], M.K. Bhaskar[a]

[a]M.B.M. University, Jodhpur, Rajasthan, India.

Keywords:

Blackout, Voltage stability, PV curve, effect of single, Multiple load variation.

* Corresponding author:

Manish Parihar
E-mail: manish.pariharee@gmail.com

Received: 7 January 2025
Revised: 2 February 2025
Accepted: 3 March 2025

A B S T R A C T

A blackout, also known as a power outage, represents a significant failure within an electrical power system, where large-scale loss of power occurs due to system instability. One of the methods used to predict and analyze such blackouts is PV curve analysis. This method focuses on understanding the relationship between power (P) and voltage (V) within a power system. In this article, we will explore the theoretical background of blackouts, PV curve analysis, and how it helps in predicting system collapse by examining voltage stability under increasing load conditions. Single load variation and multiple load variation scenario is considered for detailed analysis.

1. INTRODUCTION

Electric power systems are being run nearer to their limits due to the emergence of organized competitive power markets and the lack of necessary transmission grid investment. From voltage stability point of view, maximum permissible loading limits must not be exceeded in the operation of power systems. A variety of factors, including the loss of generating units, breaker failures, common tower and common right-of-way circuit outages, and a combination of system circumstances and events, can result in cascading outages in power systems. Control measures must be implemented when a power system is exposed to significant disturbances in order to steer the system clear of dangerous situations and to reduce the disturbance's scope. The primary source of these unsatisfactory voltage transients is the distribution system's incapacity to supply reactive power at the required rate [1, 2].

A precise evaluation of the underlying causes of low voltage is the main area of research in handling the issues of voltage collapse. These disruptions frequently lead to the system's voltage collapsing, which results in significant losses for the system as well as monetary losses. Every year, thousands of disruptions occur worldwide in the contemporary power systems. Blackouts resulted from a few of them [3, 4]. Large scale blackouts rarely happened in power systems, but they caused enormous economic and social damages. In order to prevent future blackouts, it is very important to review the previous large scale incidents and to draw their common characteristics [5, 6].

The stability, reliability and security of power system are the concerned issues in any developing country like India due to the lessons from the blackout [7, 8]. Stability of a power system is affected by three factors: Characteristics of the physical system, Business structures of owning and operating entities, The regulatory framework (CERC in India) [9].

A blackout refers to the total loss of power to an area and is the most severe form of power outage that can occur in a power system [10]. The blackout situation does not arise all of a sudden but is a result of series of events. The power system transits from normal operating condition to critical condition and then to emergency condition before entering into a state of total blackout. Outages may last from a few minutes to a few weeks depending on: The nature of the blackout, and the configuration of the electrical network [11].

The cascade events move slowly throughout the steady-state phase, allowing the system to maintain a balance between supply and demand. The cascading overflow is the main incident that occurs during this time. The system operator may want to take action to halt the cascade overload from spreading and subsequently avert a blackout because of the gradual deterioration of the situation during the steady-state progression phase. Voltage collapse and cascading overloads are significant incidents in the progression of blackouts [12].

There is a number of different analysis tools used to analyze the security of the power system [13-15]. The methods differ in the time-frame they take into consideration for analysis or analyze different aspects of the system. For example, some methods just monitor the transient phenomenon of the system compared to other methods which do a steady state system analysis. All these methods generate different report which can be used by the operators to take appropriate actions [16-18].

In this paper Voltage Security Assessment method is utilized. This method usually employs regular power flow programs to solve for steady state voltage levels in the system. Typically, it uses Newton-Raphson power flow solution method. Blackouts are catastrophic failures in power systems, resulting in the complete loss of power in an area or grid. This may occur due to natural disasters, equipment failures, or operational issues.

Understanding the dynamics that lead to a blackout is crucial for the prevention of future outages. One of the prominent methods for analyzing the causes of blackouts and predicting future instabilities is through PV curve analysis. PV curves depict the relationship between active power demand (P) and bus voltage (V) at different loading conditions. These curves help in assessing the voltage stability limits of a power system and identifying the points where the system becomes unstable [19].

2. VOLTAGE STABILITY AND BLACKOUTS

The ability of a power system to sustain appropriate voltage levels both during regular operation and following a disruption is known as voltage stability. The loss of voltage stability can lead to voltage collapse, which may eventually cause a blackout. Voltage instability typically occurs in heavily loaded systems where the demand for reactive power increases. Blackouts may occur due to several mechanisms, including voltage collapse: In this scenario, the inability of the system to supply adequate reactive power leads to a drop in voltage levels across the grid [20, 21]. As demand continues to rise, voltage levels drop further, eventually causing a system-wide collapse. Excessive load on transmission lines or power generation facilities can cause cascading failures [22, 23]. The system's protection mechanisms disconnect parts of the grid to protect the equipment, which may lead to larger outages. Oscillations or instability in the rotor angle of generators can propagate through the system, leading to synchronism loss and wide-scale outages [24].

PV curve analysis is widely used in power system planning and operation to assess the limits of voltage stability. The "P" in the PV curve stands for active power, and the "V" stands for bus voltage. The curve is plotted by varying the load at a bus while observing the resulting bus voltage. The PV curve typically has a characteristic "nose" shape. Initially, as the load increases, the voltage decreases gradually. However, beyond a certain point—known as the voltage collapse point or critical point—the voltage drops rapidly with only a small increase in load. This critical point marks the maximum loading condition before voltage instability occurs, leading to a blackout if not addressed [25, 26].

The key components of a PV curve are: Stable Region: The region before the critical point, where the system can handle an increase in load without a significant drop in voltage, Critical Point: The point at which the system reaches its maximum voltage stability. Any increase in load beyond this point causes voltage to drop rapidly, and Unstable Region: The region after the critical point, where the system becomes highly unstable, and any further load increase may lead to voltage collapse.

PV curve analysis is crucial for understanding when a system is nearing voltage collapse. By plotting the PV curve for different load levels, operators can identify the critical point of the system and adjust the loading conditions or dispatch reactive power resources to prevent the system from reaching this point. The analysis also helps in determining system margins, i.e., how close the system is to its voltage stability limit [27]. The loadability margin is the difference between the current operating point and the critical point on the PV curve. A small loadability margin indicates that the system is operating close to its voltage stability limit and is at high risk of voltage collapse. Conversely, a large margin indicates that the system is operating safely within its stability limits. To demonstrate the practical application of PV curve analysis, 5 bus system model is considered. The load is increased gradually, and the corresponding voltage at the bus is monitored. The PV curve is plotted to observe the system's behaviour under different loading conditions. To examine voltage stability under different loading pattern such as base case loading, single load change, multiple load change is considered.

3. SIMULATION & RESULTS

Power system analysis is an essential component of any transmission or distribution system. Figure 1 illustrates the network of five bus power systems, while tables 1, 2, and 3 provide relevant data on the five bus systems.

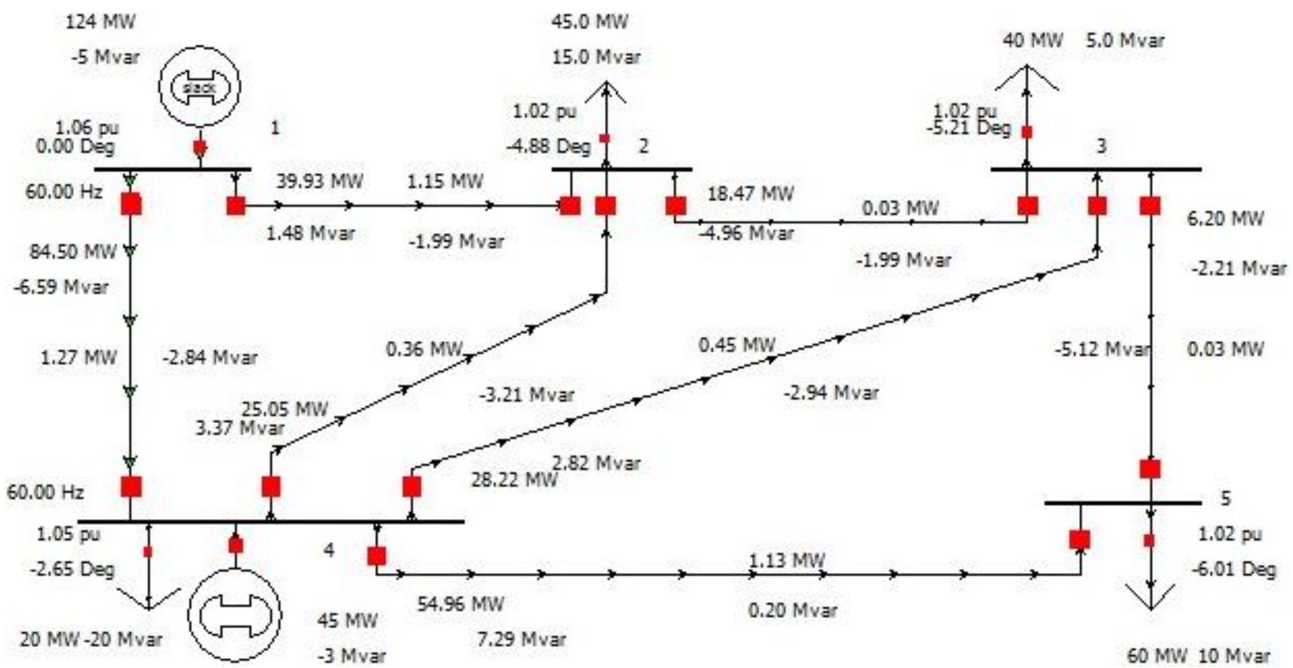

Fig. 1. Five bus system line diagra.

Table 1. Five Bus System Base Operating Condition.

Bus. no.	***Voltage p.u.***	***Angle (δ) degree***	***Generation Active power MW***	***Load***	
				MW	***MVar***
1	1.06	0	0	0	0
2	1.00	0	0	45	15
3	1.00	0	0	40	5
4	1.047	0	45.00	20	-20
5	1.00	0	0	60	10

Table 2. Voltage Regulated Bus 4 Base Case Operating Condition.

Bus. No.	***Voltage p.u.***	***MVar capability***	
		min	***max***
4	1.047	-40	50

Table 3. 5 Bus System Base Case Line Data.

Send Bus	***End Bus***	***Resistance***	***Reactance***	***Line charging (B/2)***
1	4	.0600	.0600	.0300
1	2	.0800	.2400	.025
4	2	.0600	.1800	.0200
4	3	.0600	.1800	.0200
4	5	.0400	.1200	.0150
2	3	.0100	.0300	.0100
3	5	.0800	.2400	.0250

In an actual electric power system, the real and reactive load changes simultaneously. In single load variation case the real and reactive load at a particular node are varied. The loads at all other nodes are fixed at base value.

Case study 1: By varying load power at load bus 2, constant generator real power P_4=45 MW, Q_ (Mvar limit) = -40 & 50 at generator bus 4. The results are shown in table 4, 5, 6.

Table 4. Real & Reactive Load Variation At Node 2 & Power Factor $\phi = 45°$ *lag*.

P_2 ***MW***	V_2 ***p.u.***	V_3 ***p.u.***	V_4 ***p.u.***	V_5 ***p.u.***
0	1.04	1.04	1.05	1.05
100	.94	.95	1.03	.98
150	.84	.87	.99	.92
200	.70	.73	.92	.83
210	.63	.68	.89	.79
215	.56	.61	.86	.74

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
77	0	-30
187	52	50
251	147	50
336	306	50
364	373	50
395	456	50

Table 5. Real & Reactive Load Variation At Node 2 And Power Factor $\phi = 0°$.

P_2 ***MW***	V_2 ***p.u.***	V_3 ***p.u.***	V_4 ***p.u.***	V_5 ***p.u.***
0	1.04	1.04	1.05	1.05
100	1.02	1.02	1.05	1.02
200	.99	.99	1.04	1
300	.92	.93	1.01	.95
400	.79	.80	.94	.86
420	.72	.74	.90	.81
430	.67	.69	.87	.77

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
77	0	-30
184	-18	8
297	-19	50
422	57	50
575	221	50
622	305	50
658	383	50

Table 6. Real & Reactive Load Variation At Node 2 And Power Factor $\phi = 45°$ *lead*.

P_2 ***MW***	V_2 ***p.u.***	V_3 ***p.u.***	V_4 ***p.u.***	V_5 ***p.u.***
0	1.04	1.04	1.05	1.05
100	1.09	1.07	1.06	1.04
200	1.12	1.10	1.07	1.06
300	1.14	1.12	1.07	1.06
400	1.15	1.12	1.06	1.05
600	1.15	1.11	1.05	1.04
650	1.13	1.09	1.03	1.01
690	1.09	1.05	1	.97
700	1.08	1.03	.98	.96
750	1.03	.98	.93	.90

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
77	0	-30
185	-67	-40
302	-117	-40
428	-142	-40
562	-139	-40
865	-103	35
954	-52	50
1037	41	50
1063	78	50
1176	221	50

Here curve is drawn between real load power and bus voltage of candidate bus 2 for different power factor from lagging to leading conditions as shown in figure 2.

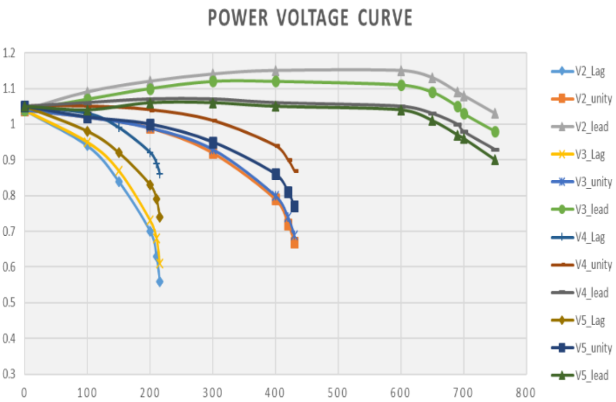

Fig. 2. PV curve for single load variation at bus 2 from lagging to leading condition.

Case study 2: By varying load power at load bus 3, constant generator real power $P_4 = 45\ MW$, $Q_{Mvar\ limit} = -40\ \&\ 50$ at generator bus 4, at different operating conditions. The results are shown in table 7, 8, 9.

Table 7. Real & Reactive Load Variation At Node 3 And Power Factor $\phi = 45°\ lag$.

P_3 MW	V_2 $p.u.$	V_3 $p.u.$	V_4 $p.u.$	V_5 $p.u.$
0	1.03	1.04	1.05	1.02
100	.93	.91	1.02	.96
150	.84	.80	.97	.89
170	.79	.74	.94	.85
190	.70	.64	.90	.78
200	.63	.56	.86	.72

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
82	2	-22
194	69	50
262	175	50
295	237	50
342	340	50
378	430	50

Table 8. Real & Reactive Load Variation At Node 3 And Power Factor $\phi = 0°\ lead$.

P_3 MW	V_2 $p.u.$	V_3 $p.u.$	V_4 $p.u.$	V_5 $p.u.$
0	1.03	1.04	1.05	1.02
100	1.01	1.01	1.05	1.01
200	.98	.97	1.03	.99
300	.90	.88	.99	.92
350	.83	.81	.95	.87
370	.79	.77	.93	.84
390	.70	.66	.87	.75

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
82	2	-22
190	-17	20
305	0	50
434	90	50
511	174	50
549	230	50
613	364	50

Table 9. Real & Reactive Load Variation At Node 3 And Power Factor $\phi = 45°\ lead$.

P_3 MW	V_2 $p.u.$	V_3 $p.u.$	V_4 $p.u.$	V_5 $p.u.$
0	1.03	1.04	1.05	1.02
100	1.07	1.08	1.06	1.04
300	1.10	1.13	1.06	1.06
400	1.10	1.13	1.05	1.05
450	1.09	1.14	1.05	1.04
550	1.09	1.14	1.05	1.04
600	1.06	1.12	1.02	1.01
620	1.04	1.10	1.01	.99
640	1.01	1.07	.98	.96
660	.93	1	.93	.89

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
82	2	-22
191	-55	-40
436	-120	-40
574	-106	-40
648	-103	-23
805	-94	40
894	-36	50
934	7	50
981	68	50
1057	220	50

Here curve is drawn between real load power and bus voltage of candidate bus 3 for different power factor from lagging to leading conditions as shown in figure 3.

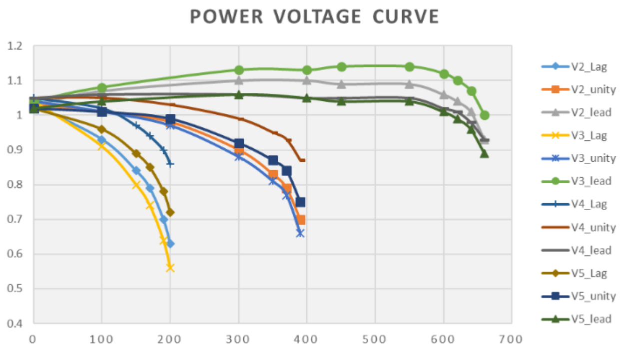

Fig. 3. PV curve for single load variation at bus 3 from lagging to leading condition.

Case study 3: By varying load power at nus 4,constant generator real power $P_4 = 45\ MW$, $Q_{Mvar\ limit} = -40\ \&\ 50$ at generator bus 4. The results are shown in table 10, 11, 12.

Table 10. Real & Reactive Load Variation At Node 4 And Power Factor $\phi = 45°\ lag$.

P_4 MW	V_2 $p.u.$	V_3 $p.u.$	V_4 $p.u.$	V_5 $p.u.$
0	1.02	1.02	1.05	1.02
100	.98	.98	1	.97
200	.92	.91	.91	.88
300	.82	.81	.79	.77
350	.74	.73	.70	.67
370	.69	.67	.63	.60
390	.63	.60	.57	.53

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
104	1	10
209	79	50
325	229	50
462	445	50
554	623	50
610	754	50
665	890	50

Table 11. Real & Reactive Load Variation At Node 4 And Power Factor $\phi = 0°$.

P_4 MW	V_2 $p.u.$	V_3 $p.u.$	V_4 $p.u.$	V_5 $p.u.$
0	1.02	1.02	1.05	1.02
100	1.02	1.02	1.05	1.02
300	.98	.98	1	.97
400	.95	.95	.97	.94
450	.94	.93	.95	.92
500	.92	.91	.93	.90
550	.90	.89	.90	.87
600	.87	.86	.87	.84
650	.84	.83	.84	.81
700	.79	.78	.79	.75
740	.72	.71	.71	.67
750	.68	.67	.67	.63

Slack bus		***Generator bus***
P_{GEN}	Q_{GEN}	Q_4
104	1	10
208	-26	49
428	34	50
545	88	50
606	122	50
670	164	50
736	213	50
806	275	50
882	355	50
970	470	50
1069	651	50
1114	755	50

Table 12. Real & Reactive Load Variation At Node 4 And Power Factor $\phi = 45° \ lead$.

P_4 MW	V_2 p.u.	V_3 p.u.	V_4 p.u.	V_5 p.u.
0	1.02	1.02	1.05	1.02
100	1.03	1.03	1.05	1.02
400	1.07	1.07	1.11	1.08
500	1.08	1.08	1.13	1.09
700	1.08	1.08	1.14	1.10
900	1.06	1.07	1.13	1.09
1000	1.04	1.05	1.12	1.08
1100	1	1.02	1.10	1.05
1200	.94	.96	1.05	.99
1250	.89	.90	1	.94

Slack bus		Generator bus
P_{GEN}	Q_{GEN}	Q_4
104	1	10
208	-37	-40
551	-210	-40
675	-238	-40
939	-249	-40
1227	-184	-40
1385	-109	-40
1559	16	-40
1775	241	-17
1939	470	50

The bus voltage at node 4 decreases when the generator reaches its Mvar limit, as can be seen by looking at the PV table for candidate bus 4. Generators' reactive output rises as a result of the system's increasing demand for reactive power. The generator's terminal voltage drops as it approaches the maximum reactive power. It transfers its portion of the reactive power demand to a different generator located farther from the critical area.

Here curve is drawn between real load power and bus voltage of candidate bus 4 for different power factor from lagging to leading conditions as shown in figure 4.

It is observed from the case study 1, 2, 3 results that the power factor significantly affect loadability of the system. Using same data simulation is done with Power world simulator and using above given data load flow analysis is done using Newton Raphson method. Line power flows, voltage magnitude and angle at each bus and losses in line are shown for Base case loading level in table 13 & 14.

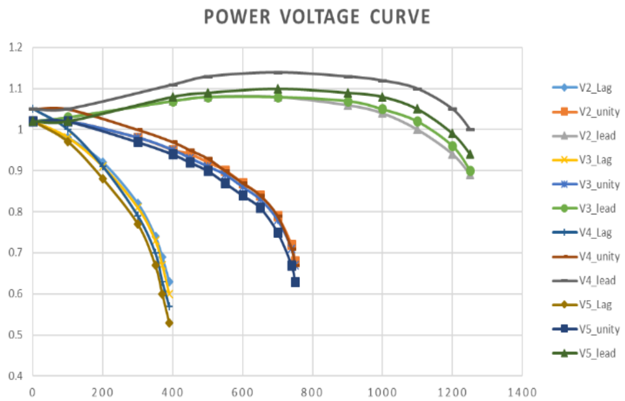

Fig. 4. PV curve for single load variation at bus 4 from lagging to leading condition.

Table 13. Base Case Loading Level LL=1.

Bus . no.	Load	
	MW	MVar
1	0	0
2	45	15
3	40	5
4	20	-20
5	60	10

Table 14. Line Flows And Losses At Loading Level LL=1.

Send Bus	End Bus	Real power MW	Reactive Power MVar	Real power losses	Reactive power losses
1	2	39.93	1.48	1.15	-1.99
1	4	84.5	-6.59	1.27	-2.84
2	3	18.47	-4.96	.03	-1.99
3	5	6.20	-2.21	-5.12	.03
4	2	25.05	3.37	.36	-3.21
4	3	28.22	2.82	.45	-2.94
4	5	54.96	7.29	1.13	.20

A practical power system consists of hundreds of buses and load changes simultaneously at several nodes. For analysis the loads are varied uniformly at all buses up to the level of voltage instability. For the load level of 3.5 times of system base load, the line 1-4 is the most stressed line. Now for different loading conditions (multiple load variation), results were obtained and are presented in tables 15, 16, 17.

Table 15. Loading Level At Different Loading Conditions.

Load Level (LL)	*LL= .6*		*LL= .8*		*LL= 1.2*	
Bus . no.	**MW**	**MVar**	**MW**	**MVar**	**MW**	**MVar**
1	0	0	0	0	0	0
2	27	9	36	12	54	18
3	24	3	32	4	48	6
4	12	-12	16	-16	24	-24
5	36	6	48	8	72	12

Table 16. Line Flows For Loading Level At Different Loading Conditions.

Load Level		*LL= .6*		*LL= .8*	
Send Bus	***End Bus***	***Real power MW***	***Reactive Power MVar***	***Real power MW***	***Reactive Power MVar***
1	2	20.89	.36	30.36	.77
1	4	34.40	8.38	59.21	.76
2	3	9.61	-2.33	14.05	-3.63
3	5	3.23	-1.71	4.72	-1.96
4	2	16.18	-2.16	20.59	.52
4	3	17.81	-2.33	22.98	.16
4	5	33.18	.34	44.01	3.66
Load Level		*LL= 1.2*			
Send Bus	***End Bus***	***Real power MW***		***Reactive Power MVar***	
1	2	49.57		2.50	
1	4	110.3		-13.67	
2	3	22.85		-6.32	
3	5	7.66		-2.45	
4	2	29.56		6.39	
4	3	33.52		5.66	
4	5	66.04		11.24	

Table 17. Line Losses For Loading Level At Different Loading Conditions.

Load Level		*LL=.6*		*LL=.8*	
Send Bus	***End Bus***	***Real power losses***	***Reactive Power losses***	***Real power losses***	***Reactive Power losses***
1	2	.32	-4.55	.67	-3.47
1	4	.24	-5.95	.63	-4.78
2	3	.01	-2.13	.02	-2.07
3	5	.01	-5.33	.02	-5.23
4	2	.14	-3.92	.24	-3.61
4	3	.17	-3.82	.29	-3.44
4	5	.40	-2.03	.72	-1.07
Load Level		*LL=1.2*			
Send Bus	***Send Bus***	***Real power losses***		***Reactive Power losses***	
1	1	1.77		-.08	
1	1	2.18		-.11	
2	2	.05		-1.90	
3	3	.05		-4.99	
4	4	.52		-2.70	
4	4	.65		-2.31	
4	4	1.65		1.78	

Again increase loading level at all buses simultaneously till system becomes vulnerable, thus reactive & active power loading was shown in table 18. Line power flows and line losses are shown in table 19 for loading level 1.4, table 20 for loading level 1.6, table 21 for loading level 2, table 22 for loading level 3, table 23 for loading level 3.

Table 18. Multiple Load Change At Different Load Buses.

Load Level (LL)	*LL= 1.4*		*L= 1.6*		*L= 2*	
Bus . no.	***MW***	***MVar***	***MW***	***MVar***	***M W***	***MVar***
1	0	0	0	0	0	0
2	63	21	72	24	90	30
3	56	7	64	8	80	10
4	28	-28	32	-32	40	-40
5	84	14	96	16	120	20
Load Level (LL)	*LL= 3*		*LL= 3.5*			
Bus . no.	***MW***	***MVar***	***MW***	***MVar***		
1	0	0	0	0		
2	135	45	157.5	52.5		
3	120	15	140	17.5		
4	60	-60	70	-70		
5	180	30	210	35		

Table 19. Line Flows and Losses at Loading Level LL=1.4.

Send Bus	*End Bus*	*Real power MW*	*Reactive Power MVar*	*Real power losses*	*Reactive power losses*
1	2	59.30	3.85	2.53	2.25
1	4	136.58	-20.45	3.37	3.46
2	3	27.18	-7.72	.08	-1.80
3	5	9.11	-2.68	.07	-4.85
4	2	34.13	9.61	.71	-2.09
4	3	38.89	8.69	.89	-1.55
4	5	77.24	15.53	2.28	3.71

Table 20: Line Flows and Losses at Loading Level LL=1.6.

Send Bus	*End Bus*	*Real power MW*	*Reactive Power MVar*	*Real power losses*	*Reactive power losses*
1	2	69.13	5.53	3.45	5.05
1	4	163.55	-29.96	4.86	7.92
2	3	31.49	-9.15	.11	-1.68
3	5	10.54	-2.90	.09	-4.69
4	2	38.77	13.03	.95	-1.35
4	3	44.34	11.93	1.18	-.64
4	5	88.59	20.20	3.04	5.99

Table 21. Line Flows And Losses At Loading Level LL= 2.

Send Bus	*End Bus*	*Real power MW*	*Reactive Power MVar*	*Real power losses*	*Reactive power losses*
1	2	89.76	16.71	6.01	12.88
1	4	218.7	-5.31	8.52	19.01
2	3	40.33	-8.77	.18	-1.32
3	5	13.55	-2.12	.16	-4.13
4	2	48.13	18.06	1.55	.66
4	3	55.35	17.22	1.95	1.89
4	5	111.7	30.30	5.12	12.41

Table 22: Line Flows and Losses at Loading Level LL=3.

Send Bus	*End Bus*	*Real power MW*	*Reactive Power MVar*	*Real power losses*	*Reactive power losses*
1	2	148.3	69.04	19.34	-19.73
1	4	376.4	111.06	27.56	76.63
2	3	62.85	-4.51	.57	.33
3	5	21.67	2.07	.56	-1.62
4	2	73.44	35.42	4.57	10.52
4	3	85.28	36.37	5.88	14.48
4	5	175.1	72.64	16.23	46.41

Table 23. Line Flows And Losses At Loading Level LL= 3.5.

Send Bus	*End Bus*	*Real power MW*	*Reactive Power MVar*	*Real power losses*	*Reactive power losses*
1	2	189.6	135.34	39.18	113.56
1	4	488.5	267.82	55.57	161.19
2	3	74.22	.25	1.17	2.59
3	5	26.90	6.26	1.36	1.92
4	2	89.05	51.51	9.02	24.69
4	3	103.8	55.03	11.75	32.90
4	5	215.6	119.51	34.21`	100.97

Table 24. Voltage Regulated Bus Operating Condition for Multiple Load Change Condition.

Load Level (LL)	*Slack Bus (bus 1)*		*Bus 4*
	P_{gen}	Q_{gen}	Q_{gen}
.6	55	9	-30
.8	90	2	-17
1	124	-5	-3
1.2	160	-11	13
1.4	196	-17	30
1.6	233	-21	48
2	308	50	11
3	525	180	50
3.5	678	403	50

Table 24 depicts slack bus real - reactive generation power and bus 4 reactive power generation. Voltage magnitude and angle at all buses shown in table 25.

Table 25. Voltage & Load Angle Values.

Load Level (LL)	*L= 1.6*		*L= 2*	
Bus no.	$\|V\|$	δ	$\|V\|$	δ
1	1.06	0	1.06	0
2	1.00	-8.64	.97	-11.25
3	1.00	-9.23	.96	-12.04
4	1.05	-5.32	1.03	-6.94
5	.99	-10.70	.95	-14.05
Load Level (LL)	*LL= 3*		*L= 3.5*	
Bus no.	$\|V\|$	δ	$\|V\|$	δ
1	1.06	0	1.06	0
2	.83	-19.73	.69	-28.28
3	.83	-21.32	.68	-31.02
4	.94	-11.71	.84	-15.47
5	.80	-25.57	.62	-39.03

A blackout occurs at this load level. It was noted that the maximum load flow happened between buses 1 and 4. Since buses 1 and 4 are the system's primary generators of power, the majority of electricity is distributed between them. Figure 5 shows power voltage curve for multiple load change condition at all nodes of the system. The reason for the significant power transfer from bus 4 to bus 5 is that bus 5 has the greatest power demand of all the buses. it is observed that as the load on the system increases for both single and multiple load variation, correspondingly bus voltage decreases. When the buses with the highest power flow between their tie lines were eliminated, then the largest losses happened.

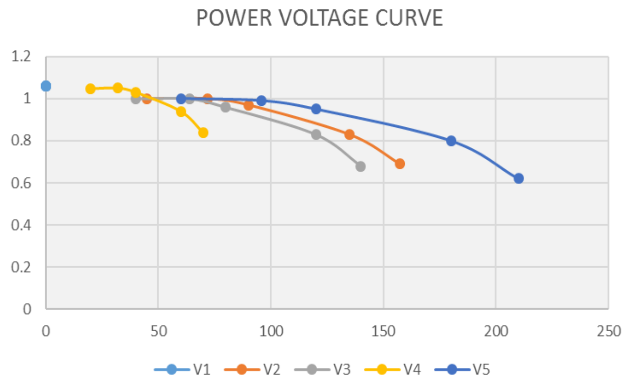

Fig. 5. Multiple load variation PV curve.

In other words, removing a line from an interconnected power system causes the remaining lines in the system to overload. Consider 5 bus system and transmission line between bus 1 and bus 4 is removed (single line outage case/contingency case). Table 26 displays the line flows and losses for this scenario.

Table 26. Line Flows and Losses When Line 1-4 Removed.

Send Bus	***End Bus***	***Real power MW***	***Reactive Power MVar***	***Real power losses***	***Reactive power losses***
1	2	135.25	.5	13.03	33.72
1	4	X	X	X	X
2	3	63.82	-27.31	.47	-.65
3	5	21.01	-9.55	.38	-3.99
4	2	12.96	23.51	.45	-2.88
4	3	2.12	18.57	.24	-3.53
4	5	40.04	14.40	.68	-1.15

Line removal		***Slack Bus (bus 1)***		***Bus 4***
Send Bus	***End Bus***	P_{gen}	Q_{gen}	Q_{gen}
1	4	135	-5	36

Since the connection between buses 1 and 4 is the primary tie line that transmits power between the two buses, disconnecting it would result in the highest active power loss ever recorded. Bus 5's high power consumption is one factor contributing to this substantial power loss. Because bus 5 is not directly connected to bus 1 (power must pass through bus 2 and then through buses 3 or 4), the power path becomes longer, resulting in increased power loss on the lines due to line impedances.

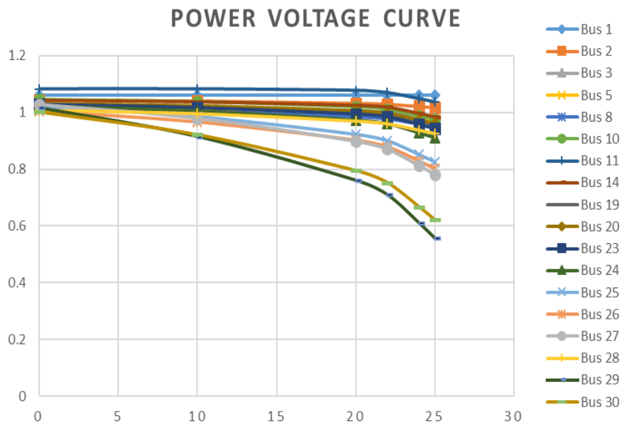

Fig. 6. PV curve for single load variation at bus 29 for lagging load condition.

Finally, another critical side effect of this line removal can be seen on bus 2: all of the power generated by bus 1 must now be routed through bus 2 to the entire grid, which could cause issues if bus 2 is not rated high enough for this power.

For further examination IEEE 30 bus system is also utilized. It is observed that as the load on bus 29 is increased till maximum loading point, then voltage at bus 29 drops from 1.015 p.u. to 0.558 p.u., for bus 30 from 1.001 p.u. to 0.62 p.u. , for bus 2 from 1.04 p.u. to 1.01 p.u.. It is observed from figure 6 that bus 29 & bus 30 are weak buses in the network, whereas bus1 & bus 2 are stable buses. PV curve for bus 1 & bus 2 depicts flat voltage profile as shown in figure 6 that means there is no effect of load variation on these buses.

4. CONCLUSION

There is a continuously varying load and demand, so by interconnection exchange of peak loads is possible. The arrangement of load sharing among the stations can guarantee economical operation by allowing the more efficient plants to operate year-round at a high load factor, while the less efficient plants only operate during peak load hours. Because of the interconnected grid, the majority of the electricity market today benefits from power pooling and wholesale electricity markets, which enable them to sell electricity to one another when needed.

However, as mentioned above, caution should be exercised in an interconnected system because if one line is removed, other lines that are connected to it will overload and the system may eventually collapse. Same reason is seen in Indian blackout which occurs on 30 and 31 July 2012. The 400 kV Bina-Gwalior-Agra-2 was under planned shutdown since 28th July 2012 for up-gradation work to 765 kV. Thereafter outages started from the afternoon of 29th July 2012, 220 kV Kota – Badod, 220 kV Binmal(PG) – Sirohi, 400 kV Bhinmal – Kankroli , 400 kV Zerda – Kankroli. It is observed that the 400 kV network between Western Region and Northern Region got depleted progressively over the night starting with a planned outage on a high capacity corridor followed by two forced outages in quick succession. The 400(kV) Bina-Gwalior-Agra was the only main AC circuit remaining which connected NR to WR. Thus the flow of power from WR to NR region via Bina-Gwalior-Agra link increased which led to overloading of the tie-line. As a consequence, cascading effect initiated tripping other connected lines and system collapses leading to Northern Grid Blackout on 30 July 2012. Although interconnected system has greater advantage but Blackout condition is serious issue. Therefore, corrective action should be taken and record of each bus and transmission line in an interconnected system should be maintained.

REFERENCES

[1] P. Kundur, *Power System Stability and Control*, 1994. [Online]. Available: http://ci.nii.ac.jp/ncid/BA21960468.

[2] K. P. Basu, “Power transfer capability of transmission line limited by voltage stability: Simple analytical expressions,” *IEEE Power Eng. Rev.*, vol. 20, no. 9, pp. 46–47, 2000.

[3] S. D. Kulkarniirlekar, “Blackouts in the power system,” *Int. J. Electr. Electron. Res.*, vol. 3, no. 4, pp. 1–7, 2015.

[4] H. Saadat, *Power System Analysis*, McGraw-Hill, 1999.

[5] M. Moghavvemi and F. M. Omar, “Technique for contingency monitoring and voltage collapse prediction,” *IEE Proc. Gener. Transm. Distrib.*, vol. 145, no. 6, pp. 634–640, 1998.

[6] N. S. Raviprakasha and K. Ramar, “Maximum power transfer in AC transmission lines is limited by voltage stability,” in *Proc. Int. Conf. Power Electron., Drives Energy Syst. for Ind. Growth*, vol. 2, pp. 776–781, 1996.

[7] M. Abrar, “Power cut and power blackout in India: A major threat overview,” *Int. J. Adv. Res. Technol.*, vol. 5, no. 7, pp. 8–15, 2016.

[8] S. Shivashimpiger, V. Parthasarathy, Siridevi, and D. H. M. Ravikumar, “A qualitative analysis of power system blackouts—Northern Grid case study,” *IJETER*, vol. 3, pp. 373–379, 2015.

[9] Central Electricity Regulatory Commission, “Report on the Grid Disturbances of 30th July and 31st July 2012,” New Delhi: Central Electricity Regulatory Commission, 2012.

[10] S. Matthewman and H. Byrd, “Blackouts: A sociology of electrical power failure,” *Social Space*, pp. 1–25, 2014.

[11] M. Parihar and M. K. Bhaskar, “Review of power system blackout,” *Int. J. Res. Innov. Appl. Sci.*, vol. 3, no. 6, pp. 8–12, 2018.

[12] A. Atputharajah and T. K. Saha, “Power system blackouts—Literature review,” in *Proc. Int. Conf. Ind. Inf. Syst. (ICIIS)*, Dec. 28, 2009, pp. 460–465.

[13] H. S. Salama and I. Vokony, “Voltage stability indices–A comparison and a review,” *Computers & Electrical Engineering*, vol. 98, p. 107743, 2022, doi: 10.1016/j.compeleceng.2022.107743.

[14] R. Gadal, A. Oukennou, F. El Mariami, A. Belfqih, and N. Agouzoul, “Voltage Stability Assessment and Control Using Indices and FACTS: A Comparative Review,” *J. Electr. Comput. Eng.*, 2023, doi: 10.1155/2023/5419372.

[15] S. Mokred, Y. Wang, and T. Chen, “A novel collapse prediction index for voltage stability analysis and contingency ranking in power systems,” *Prot. Control Modern Power Syst.*, vol. 8, no. 1, p. 7, 2023.

[16] W. M. Villa-Acevedo, J. López-Lezama, and D. G. Colomé, "Voltage stability margin index estimation using a hybrid kernel extreme learning machine approach," *Energies*, vol. 13, no. 4, p. 857, 2020.

[17] A. A. Elemary, M. M. Ahmed, E. M. Saied, and M. A. Hamdy, "Power System Voltage Stability Index," *Int. J. Eng. Res. Technol.* (IJERT), vol. 11, pp. 8–24, 2022.

[18] R. Maharjan and S. Kamalasadan, "Voltage stability index for online voltage stability assessment," in *Proc. North Am. Power Symp. (NAPS)*, 2015, pp. 1–6.

[19] B. Aydin, "Voltage security assessment using PV and QV curves," Master's Thesis, TC Bahçeşehir Üniversitesi, Istanbul, 2008.

[20] C. M. Reddy, "Power system voltage stability analysis," Ph.D. dissertation, Dept. of Electrical Engineering, IIT Hyderabad, 2011. [Online]. Available: https://raiithold.iith.ac.in/662/

[21] F. A. Althowibi and M. W. Mustafa, "Power system voltage stability: indications, allocations, and voltage collapse predictions," *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.*, vol. 2, no. 7, pp. 3138–3152, 2013.

[22] H. Thakur and A. Agarwal, "Developing algorithms to allocate power thresholds," in *Proc. IEEE 3rd Int. Conf. Smart Technol. Power Energy Control (STPEC)*, 2023, pp. 1–6, Bhubaneswar, India, doi: 10.1109/STPEC59253.2023.10431313.

[23] C. Truden, C. Wankmüller, D. Zehetner, et al., "Location and capacity allocation for emergency contact points in large-scale power outages," *Cent. Eur. J. Oper. Res.*, 2024, doi: 10.1007/s10100-024-00922-3.

[24] A. Chakrabarti, D. P. Kothari, A. K. Mukhopadhyay, and A. De, *An Introduction to Reactive Power Control and Voltage Stability in Power Transmission Systems*. PHI Learning Pvt. Ltd, 2010.

[25] A. A. Khan, "PV Curves for Radial Transmission Line," in *Proc. Natl. Syst. Conf.*, 2007.

[26] S. Mokred, Y. Wang, and T. Chen, "Modern voltage stability index for prediction of voltage collapse and estimation of maximum load-ability for weak buses and critical lines identification," *Int. J. Electr. Power Energy Syst.*, vol. 145, p. 108596, 2023.

[27] M. Parihar and M. K. Bhaskar, "Radial Transmission Line Voltage Stability Analysis," *IJRERD*, vol. 02, pp. 1–7, 2017.

APPENDIX

IEEE 30 Bus System Base Case Values

Bus No.	Name	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar
1	Glen Lyn	1.06	139.92	98.43	-	-
2	Claytor	1.0431	137.69	93.08	21.7	12.7
3	Kumis	1.0207	134.73	90.9	2.4	1.2
4	Hancock	1.0117	133.553	89.15	7.6	1.6
5	Fieldale	1.01	133.32	84.27	94.2	19
6	Roanoke	1.0102	133.354	87.37	-	-
7	Blaine	1.0023	132.314	85.57	22.8	10.9
8	Reusens	1.01	133.32	86.62	30	30
9	Roanoke	1.0509	1.051	84.32	-	-
10	Roanoke	1.0451	34.489	82.73	5.8	2
11	Roanoke	1.082	11.902	84.32	-	-
12	Hancock	1.0571	34.885	83.49	11.2	7.5
13	Hancock	1.071	11.781	83.49	-	-
14	Bus 14	1.0422	34.395	82.6	6.2	1.6
15	Bus 15	1.0376	34.244	82.5	8.2	2.5
16	Bus 16	1.0443	34.465	82.91	3.5	1.8
17	Bus 17	1.0399	34.317	82.57	9	5.8
18	Bus 18	1.0281	33.929	81.89	3.2	0.9
19	Bus 19	1.0256	33.847	81.72	9.5	3.4
20	Bus 20	1.0297	33.981	81.91	2.2	0.7
21	Bus 21	1.0327	34.08	82.29	17.5	11.2
22	Bus 22	1.0332	34.098	82.3	-	-
23	Bus 23	1.0271	33.897	82.11	3.2	1.6
24	Bus 24	1.0215	33.712	81.94	8.7	6.7
25	Bus 25	1.0173	33.572	82.36	-	-
26	Bus 26	0.9996	32.989	81.95	3.5	2.3
27	Cloverdl	1.0232	33.767	82.89	-	-
28	Cloverdl	1.0068	132.9	86.74	-	-
29	Bus 29	1.0034	33.113	81.66	2.4	0.9
30	Bus 30	0.9919	32.734	80.78	10.6	1.9