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Analysis of Maximum Watt Margin in Multi-Bus Systems

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Abstract

The main aim of this study article is to analyze the Maximum Watt Margin (MWM) for different buses in a complicated multi-bus system. This is accomplished by using the potent Newton-Raphson iterative approach to a thorough load flow study. The weakest and strongest buses in the system are determined by using the ∂Qi/∂Vi index, which provides important information about their reactive power sensitivities. Additional research is conducted to examine the relationship between the Maximum Watt Margin (MWM) and the level of vulnerability displayed by each specific bus. Detailed P-V and Q-V profiles are closely examined and displayed in the results to give a more comprehensive picture. The IEEE-57 bus system is subjected to extensive testing and evaluations to validate the suggested technique. As a result, all the crucial observations and outcomes are thoroughly revealed and discussed in this comprehensive paper, shedding light on the crucial aspects of voltage stability and system robustness.

***Major Findings:** 1. In this study, the minimum value of ∂Qi/∂Vi is associated with 31st bus, designating it as the weakest bus. The 19th bus follows as the next weakest, while the 22nd bus, exhibiting the maximum value of ∂Qi/∂Vi, is identified as the strongest. 2. It can be observed from the curve that Maximum Watt Margin (MWM) diminishes as the degree of weakness increases. Specifically, the weakest bus (31st bus) exhibits the lowest MWM, while the strongest bus (22nd bus) showcases the highest MWM.*

Keywords: *Different Bus Voltage, Loadability, MWM, ∂Qi/∂Vi*

1.0 Introduction

The growing demand for electricity poses a significant challenge as the availability of energy sources remains constrained, emphasizing the critical need for system stability. Voltage instability, a key concern in this context, is primarily caused by imbalances in reactive power[1-3]. In interconnected grid systems, the loadability or maximum power transfer capability of a bus is heavily dependent on its ability to absorb reactive power from the network. Inability to manage this effectively can lead to voltage collapse- a severe phenomenon with potentially catastrophic consequences.

Voltage collapse has garnered significant attention within the power industry over the past two decades due to its role in causing widespread blackouts around the world[1,2]. As a result, understanding and predicting voltage stability before a collapse occurs has become an essential focus of research, aiming to prevent such disruptions and enhance grid reliability[1-6].

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Voltage stability refers to the power system's capability to maintain steady and acceptable voltage levels at all buses under both normal operating conditions and during disturbances[7-14]. This stability is essential for ensuring the reliable operation of the grid. It is achieved when system voltages remain close to their nominal or base values, even after being subjected to a disturbance[14-17].

However, if the voltage at any bus falls below a critical threshold- referred to as the voltage collapse point- the system transitions into an unstable state[18-20]. This instability can disrupt power delivery, leading to potential failures across the network. Therefore, maintaining voltage stability is a fundamental requirement for the safe and efficient operation of interconnected power systems.

To ensure voltage stability and effectively transmit active power to connected loads, each bus in a power system operates within a defined maximum limit. This limit, commonly referred to as bus loadability or Maximum Watt Margin (MWM), represents the maximum amount of power that can be reliably transferred without compromising voltage stability.

The MWM serves as a critical indicator of the system's robustness, providing insight into its capacity to withstand varying load conditions and disturbances. By quantifying this limit, operators can assess the resilience of the system and implement measures to prevent voltage instability or collapse, ensuring consistent and reliable power delivery.

Load flow analysis was performed on an IEEE 57-bus system using the Newton-Raphson iterative method, a highly efficient and accurate approach for solving power system equations[17,18]. This analysis incorporates the use of the ∂Qi/∂Vi sensitivity index, derived from the Jacobian matrix, to evaluate the system's reactive power-voltage relationship[2-19]. By employing this index, the weakest and strongest buses in the system are identified, providing valuable insights into the system's stability characteristics.

Furthermore, the Maximum Watt Margins (MWMs) of various load buses are calculated to assess their power transfer capabilities. The study also examines how these MWMs vary with the degree of weakness of the buses, offering a deeper understanding of the correlation between bus vulnerability and loadability. These observations are crucial for enhancing system reliability, optimizing load distribution, and preventing voltage instability in the power network.

Identifying The Strongest Bus, Weakest Load Bus, and Maximum Weight Margins (MWMs)

The Newton-Raphson Load Flow analysis is applied to the IEEE-57 bus system to examine the variations in active power (P) and reactive power (Q) using the following equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (1)$$

The matrix J=[J1 J2; J3 J4] in Equation (1) is referred to as the Jacobian Matrix. The degree of weakness of the i-th bus, or the reactive power sensitivity of the corresponding bus, is ascertained by analyzing the values of the diagonal elements of the J4 matrix. The strongest bus corresponds to the maximum value of ∂Qi/∂|Vi|, while the weakest bus corresponds to the minimum value[1-19].

The voltage level of a bus decreases when there is a variation in its active or reactive power. This behavior is effectively illustrated by the P-V curve, also known as the "Nose" curve, which depicts the relationship between the active power transferred and the bus voltage level (per unit)[1,18,19]. In the P-V curve, as active power transfer

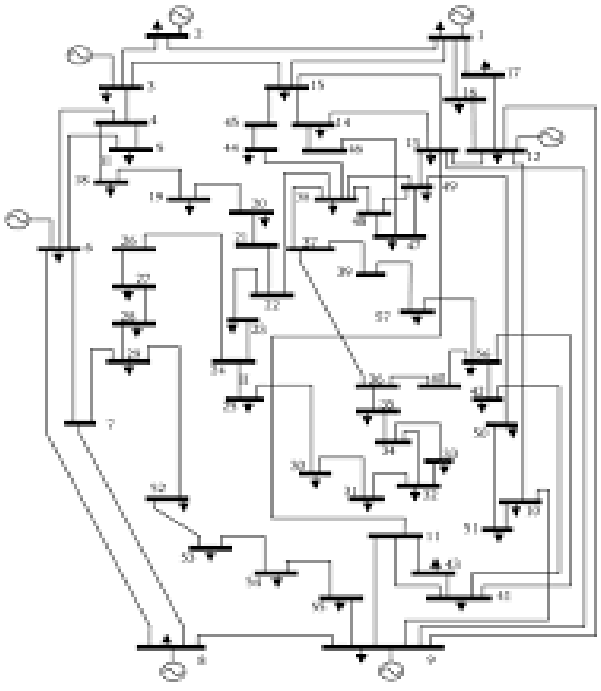


Figure 1. IEEE 57 bus system[17-20].

Table 1. Busdata (ieee 57 bus systems)[17-20]

Bus	Type	V_{sp}	Theta	P_{Gi}	Q_{Gi}	P_{Li}	Q_{Li}	Q_{min}	Q_{max}
1	1	1.040	0	0.0	0.0	0.0	0.0	0.0	0.0
2	2	1.010	0	3.0	88.0	0.0	0.8	50.0	17.0
3	2	0.985	0	41.0	21.0	40.0	1.0	60.0	10.0
4	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
5	3	1.000	0	13.0	4.0	0.0	0.0	0.0	0.0
6	2	0.980	0	75.0	2.0	0.0	0.8	25.0	-8.0
7	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
8	2	1.005	0	150.0	22.0	450.0	62.1	200.0	-140.0
9	2	0.980	0	121.0	26.0	0.0	2.2	9.0	-3.0
10	3	1.000	0	5.0	2.0	0.0	0.0	0.0	0.0
11	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
12	2	1.015	0	377.0	24.0	310.0	120.5	155.0	-150.0
13	3	1.000	0	18.0	2.3	0.0	0.0	0.0	0.0
14	3	1.000	0	10.5	5.3	0.0	0.0	0.0	0.0
15	3	1.000	0	22.0	5.0	0.0	0.0	0.0	0.0
16	3	1.000	0	43.0	3.0	0.0	0.0	0.0	0.0
17	3	1.000	0	42.0	8.0	0.0	0.0	0.0	0.0
18	3	1.000	0	27.2	9.8	0.0	0.0	0.0	0.0
19	3	1.000	0	3.3	0.6	0.0	0.0	0.0	0.0
20	3	1.000	0	2.3	1.0	0.0	0.0	0.0	0.0
21	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
22	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
23	3	1.000	0	8.3	2.1	0.0	0.0	0.0	0.0
24	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
25	3	1.000	0	6.3	3.2	0.0	0.0	0.0	0.0
26	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
27	3	1.000	0	9.3	0.5	0.0	0.0	0.0	0.0
28	3	1.000	0	4.6	2.3	0.0	0.0	0.0	0.0

29	3	1.000	0	17.0	2.6	0.0	0.0	0.0	0.0
30	3	1.000	0	3.6	1.8	0.0	0.0	0.0	0.0
31	3	1.000	0	5.8	2.9	0.0	0.0	0.0	0.0
32	3	1.000	0	1.6	0.8	0.0	0.0	0.0	0.0
33	3	1.000	0	3.8	1.9	0.0	0.0	0.0	0.0
34	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
35	3	1.000	0	6.0	3.0	0.0	0.0	0.0	0.0
36	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
37	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
38	3	1.000	0	14.0	7	0.0	0.0	0.0	0.0
39	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
40	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
41	3	1.000	0	6.3	3.0	0.0	0.0	0.0	0.0
42	3	1.000	0	7.1	4.4	0.0	0.0	0.0	0.0
43	3	1.000	0	2.0	1.0	0.0	0.0	0.0	0.0
44	3	1.000	0	12.0	1.8	0.0	0.0	0.0	0.0
45	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
46	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
47	3	1.000	0	25.7	11.6	0.0	0.0	0.0	0.0
48	3	1.000	0	0.0	0.0	0.0	0.0	0.0	0.0
49	3	1.000	0	18.0	8.5	0.0	0.0	0.0	0.0
50	3	1.000	0	21.0	10.5	0.0	0.0	0.0	0.0
51	3	1.000	0	18.0	5.3	0.0	0.0	0.0	0.0
52	3	1.000	0	4.9	2.2	0.0	0.0	0.0	0.0
53	3	1.000	0	20.0	10.0	0.0	0.0	0.0	0.0
54	3	1.000	0	4.1	1.1	0.0	0.0	0.0	0.0
55	3	1.000	0	6.8	3.1	0.0	0.0	0.0	0.0
56	3	1.000	0	7.6	2.2	0.0	0.0	0.0	0.0
57	3	1.000	0	6.7	2.0	0.0	0.0	0.0	0.0

Table 2. Linedata (IEEE 57 BUS System)[17-20]

From Bus	To Bus	R pu	Xpu	B/2 pu	X'mer Tap (a)
1	2	0.0083	0.0280	0.0645	1
2	3	0.0298	0.0850	0.0409	1
3	4	0.0112	0.0366	0.0190	1
4	5	0.0625	0.1320	0.0129	1
4	6	0.0430	0.1480	0.0174	1
6	7	0.0200	0.1020	0.0138	1
6	8	0.0339	0.1730	0.0235	1
8	9	0.0099	0.0505	0.0274	1
9	10	0.0369	0.1679	0.0220	1
9	11	0.0258	0.0848	0.0109	1
9	12	0.0648	0.2950	0.0386	1
9	13	0.0481	0.1580	0.0203	1
13	14	0.0132	0.0434	0.0055	1
13	15	0.0269	0.0869	0.0155	1
1	15	0.0178	0.0910	0.0494	1
1	16	0.0454	0.2060	0.0273	1
1	17	0.0238	0.1080	0.0143	1
3	15	0.0162	0.0530	0.0272	1
4	18	0.0	0.5550	0.0	0.970
4	18	0.0	0.4300	0.0	0.978
5	6	0.0302	0.0641	0.0062	1
7	8	0.0139	0.0712	0.0097	1
10	12	0.0277	0.1262	0.0164	1
11	13	0.0223	0.0732	0.0094	1
12	13	0.0178	0.0580	0.0302	1
12	16	0.0180	0.0813	0.0108	1

12	17	0.0397	0.1790	0.0238	1
14	15	0.0171	0.0547	0.0074	1
18	19	0.4610	0.6850	0.0	1
19	20	0.2830	0.4340	0.0	1
21	20	0.0	0.7767	0.0	1.043
21	22	0.0736	0.1170	0.0	1
22	23	0.0099	0.0152	0.0	1
23	24	0.1660	0.2560	0.0042	1
24	25	0.0	1.1020	0.0	1
24	25	0.0	1.2300	0.0	1
24	26	0.0	0.0473	0.0	1.043
26	27	0.1650	0.2540	0.0	1
27	28	0.0618	0.0954	0.0	1
28	29	0.0418	0.0567	0.0	1
7	29	0.0	0.0648	0.0	0.967
25	30	0.1350	0.2020	0.0	1
30	31	0.3260	0.4970	0.0	1
31	32	0.5070	0.7550	0.0	1
32	33	0.0392	0.0360	0.0	1
34	32	0.0	0.9530	0.0	0.975
34	35	0.0520	0.0780	0.0016	1
38	36	0.0430	0.0537	0.0008	1
36	37	0.0290	0.0366	0.0	1
37	38	0.0651	0.1009	0.0010	1
37	39	0.0239	0.0379	0.0	1
36	40	0.0300	0.0466	0.0	1
22	28	0.0192	0.0295	0.0	1

Table 3. Diagonal element of J4 matrix

LOAD BUS NO	SYSTEM BUS NO.	DIAGONAL ELEMENT OF J4 MATRIX(∂Qi/∂Vi)
1	4	42.8409
2	5	19.1138
3	7	38.6802
4	10	29.0049
5	11	31.3931
6	13	71.9323
7	14	55.375
8	15	67.1201
9	16	16.2147
10	17	14.4974
11	18	5.6081
12	19	2.8816
13	20	3.2042
14	21	8.3298
15	22	86.6499
16	23	55.7734
17	24	27.2263
18	25	6.0192
19	26	26.1084
20	27	10.742
21	28	19.4389
22	29	30.831
23	30	5.7887
24	31	2.8498
25	32	17.7746
26	33	15.4301
27	34	11.59
28	35	23.4139
29	36	49.7589
30	37	48.8519
31	38	71.7688
32	39	22.5024
33	40	18.4551
34	41	7.345
35	42	4.7472
36	43	9.3584
37	44	22.6369
38	45	17.3636
39	46	30.219
40	47	45.3746
41	48	53.0709
42	49	22.9886
43	50	10.0786
44	51	18.6247
45	52	10.317
46	53	9.7212
47	54	5.6893
48	55	11.3672
49	56	7.4147
50	57	3.938

increases while reactive power (Q) is held constant, the bus voltage progressively declines.

Similarly, a Q-V curve can be constructed by holding the active power (P) constant and gradually increasing the reactive power (Q) of the bus. Both curves reveal critical insights into the system's stability limits. The point at which the Newton-Raphson load flow method fails to converge on these curves is identified as the Voltage Collapse point. This point, often referred to as the "knee" point, marks the onset of voltage instability in the system[1-5,18,19].

The P-V profile is particularly useful for determining the Maximum Watt Margin (MWM) of a bus, which indicates the maximum active power that can be transferred while maintaining voltage stability. These analyses are essential for assessing the operational limits and stability margins of power systems, providing a foundation for preventive measures against voltage collapse.

Figure 1 illustrates the IEEE-57 bus system, a widely used benchmark model in power system studies. This system consists of 57 interconnected buses, each with specific characteristics and roles within the network. The accompanying table provides detailed bus data and line data, essential for performing load flow and stability analyses.

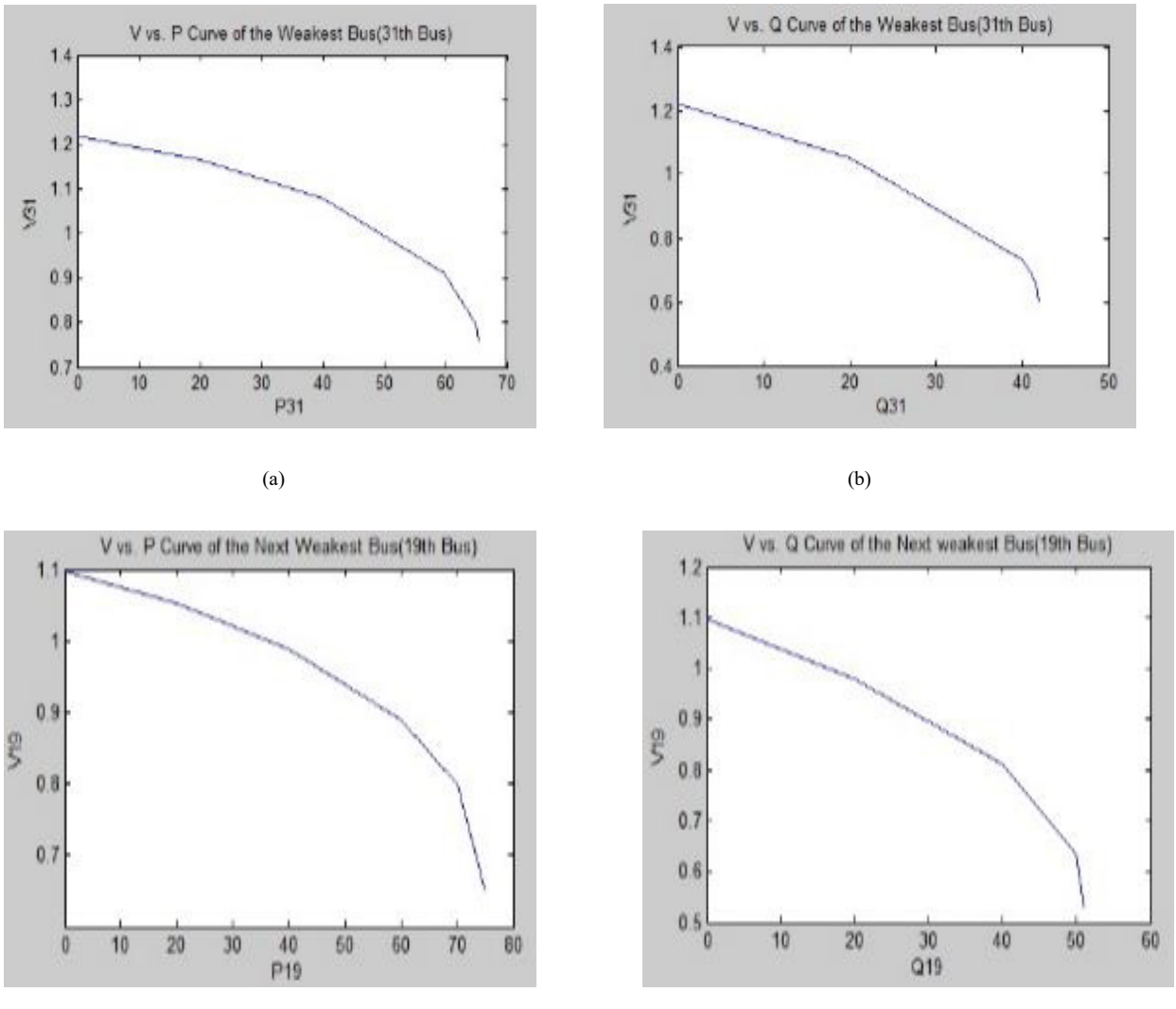


Figure 2. V-P and V-Q curve for different buses, **(a)** V vs P for 31st Bus, **(b)** V vs Q for 31st Bus, **(c)** V vs P for 19th Bus, **(d)** V vs Q for 19th Bus.

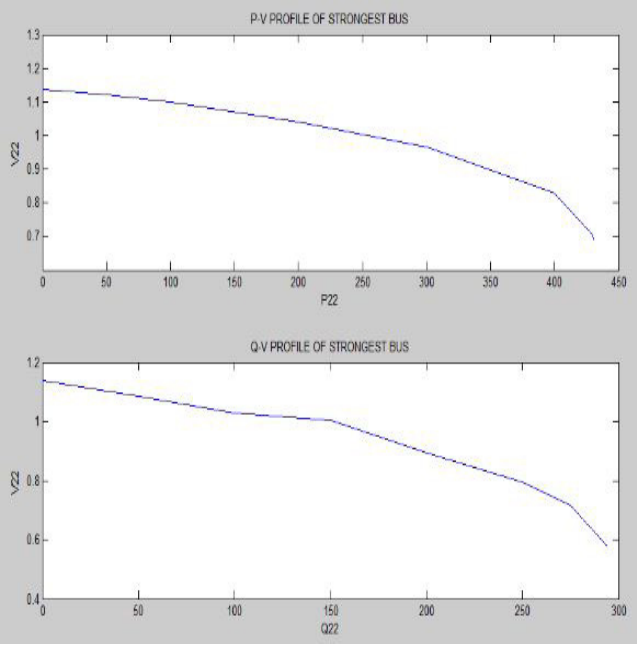


Figure 3. P-V and Q-V profile of strongest bus.

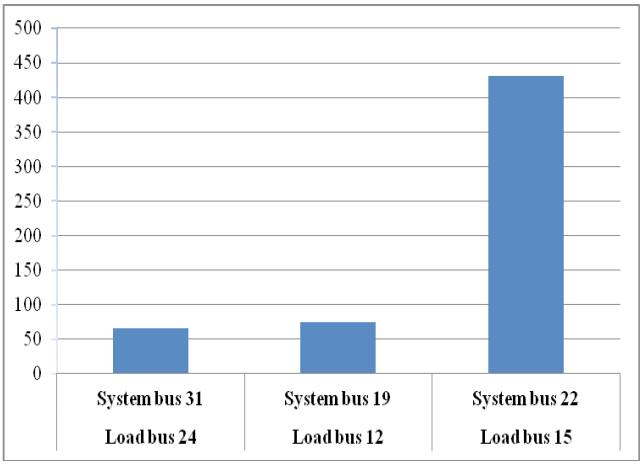


Figure 4. MWM for different buses.

In the bus data table, the buses are categorized based on their operational type, identified by numeric codes:

Type 1: Slack Bus

Type 2: PV Bus

Type 3: PQ Bus

The result as obtained from load flow analysis is given in the Table 3.

In voltage stability analysis, ∂Qi/∂Vi , derived from the Jacobian matrix, plays a crucial role. A smaller ∂Qi/∂Vi value indicates that the bus is less capable of handling variations in reactive power without significant voltage deviations, identifying it as a weaker bus. Conversely, a larger ∂Qi/∂Vi reflects a greater ability to maintain voltage stability under changing reactive power conditions, marking it as a stronger bus.

In this study, the minimum value of ∂Qi/∂Vi is associated with the 31st bus, designating it as the weakest bus. The 19th bus follows as the next weakest, while the 22nd bus, exhibiting the maximum value of ∂Qi/∂Vi, is identified as the strongest.

The P-V and Q-V profiles of the weakest, next weakest, and strongest buses are depicted in Figure 2.

The weakest and next weakest busses are find out after this research and plotted in the graph as shown in Figure 4.

3.0 Conclusion

Maximum Watt Margin (MWM) for different buses are plotted in the figure below where the degree of weakness is shown in Figure 5.

Hence, it can be observed from the curve that the Maximum Watt Margin (MWM) diminishes as the degree of weakness increases. Specifically, the weakest bus (31st bus) exhibits the lowest MWM, while the strongest bus (22nd bus) showcases the highest MWM, without compromising the system's voltage stability. Reactive power compensation can be employed to augment this maximum power transfer capability of a bus since the

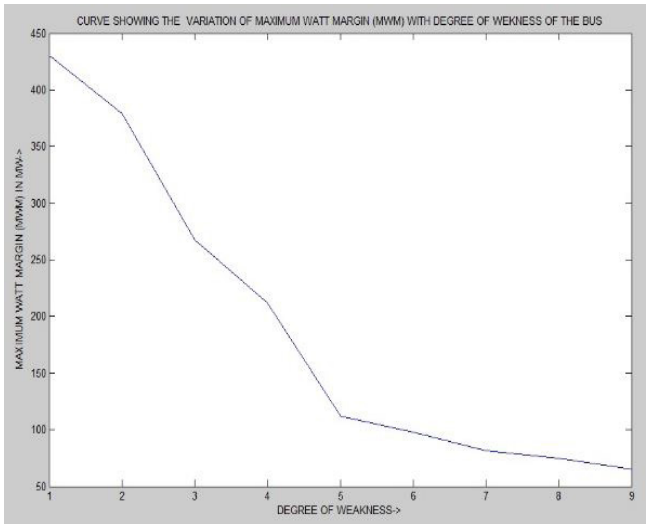


Figure 5. Curve showing the variation of Maximum Watt Margin (MWM) with degree of weakness of the bus.

bus's voltage magnitude is influenced by the level of reactive power.

Thus, Power system installation, operation, and planning are aided by load flow studies. Understanding how electrical power moves across a network and making sure that every component is functioning within its safe parameters are made easier with this study.

The study's main conclusion is that furnaces and foundries, which use a lot of power and draw current in the kiloampere or megaampere range while operating, should be served. Finding the strongest bus in the system that can meet the load's high-power requirement without experiencing voltage collapse is essential. Therefore, before deciding to build a foundry or other significant industry, this study is necessary.

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