Journal of Power and Energy Engineering, 2023, 11, 1-14
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Investigating the Effects of Slack Bus Selection in Load Flow Studies: A Comparative Analysis of Robust and Weak Grids

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How to cite this paper: Fiasorgbor, N.K. (2023) Investigating the Effects of Slack Bus Selection in Load Flow Studies: A Comparative Analysis of Robust and Weak Grids. *Journal of Power and Energy Engineering*, **11**, 1-14.
https://doi.org/10.4236/jpee.2023.119001

Received: March 27, 2023
Accepted: September 5, 2023
Published: September 8, 2023

Abstract

Load flow studies play a critical role in the analysis of power systems. They enable the computation of voltage, current, and power flows in a power system. They provide valuable insights into the steady-state performance of the power system under different operating conditions. Choosing a slack bus is a vital step in conducting load flow simulations. A slack bus is a PV bus that includes a generator and is used to balance real and reactive power during load flow studies. Many studies have been conducted on the selection of slack buses in load flow analysis. However, varied conclusions regarding the impact on system losses and power flows were obtained during these studies. Therefore, using the IEEE-14 bus test system, this study investigated the effects of slack bus selection in strong and weak grids by alternating slack buses among PV buses and observing the effects on bus voltage magnitude, bus voltage phase angle, total power flows, and active and reactive power losses. The study noted that the effect of slack bus selection on these system quantities is contingent upon the voltage stability of the grid. Whereas in a robust grid, system losses and power flows remained constant irrespective of the choice of slack bus, a weak grid experienced some variations in these system quantities under similar circumstances. The simulation results led to the conclusion that, to a large extent, the voltage stability of the grid plays a significant role in determining the degree to which slack bus selection affects system losses and other quantities in load flow studies.

Keywords

Load Flow, Slack Bus, System Losses, Voltage Stability

1. Introduction

Solving the load flow problem requires that the total power generation equals the sum of the total system load and the total system losses. However, the total system losses cannot be predicted in advance such that the total power generation needed to supply the known total system load plus the unknown total system losses cannot be precisely specified a priori. As a result, it is required to have at least one bus, known as the slack or swing bus, whose real and reactive power generation can be re-scheduled to supply the extra generation required to cover the total system losses [1]. Mathematically,

Total Power Generation = Total System Load + Total System Losses

The solution to the power-flow problem begins with identifying the system's known and unknown variables. The known and unknown variables are dependent on the type of bus. A bus without any generators connected to it is called a Load Bus (P-Q Bus). A bus, except the slack bus, with at least one generator connected to it is called a Generator Bus (P-V Bus). The slack bus (V-δ) is an arbitrarily selected bus that has a generator [2]. A slack bus, also known as a swing bus, is a reference bus in the power system that is used to balance the power flow equations. The slack bus has no specified voltage magnitude or power; its voltage phase angle is typically set to zero. The slack bus is critical in load flow analyses. It aids in determining the voltage magnitudes and phase angles of all other power system buses. Another key feature of the slack bus is that it aids in determining the power system's voltage stability limit. The voltage stability limit is the maximum voltage that can be maintained in the power system without compromising the stability of the power system. The voltage stability limit can be determined by adjusting the power injection at the slack bus [1] [3] [4].

Some studies have been undertaken to ascertain the impact of the choice of slack bus in load flow analyses. [5] performed a load flow analysis using Newton-Rapson iterative algorithms on the Nigerian 330-kV transmission grid. To assess the impact of slack bus selection, the study simulated three scenarios by alternating the slack bus of the transmission grid among three major buses. According to the study, changing the choice of slack bus did not affect the voltage magnitude of the buses, total real and reactive power at the load and generating nodes, but it does affect the phase angles and total real and reactive power losses on the transmission lines. The study concluded that caution must be exercised when selecting the appropriate slack bus. [2] used the Gauss-Seidel method to analyze power flows in a six-bus-bar system. The study investigated the impact of using various slack buses in load flow studies. At the start of each power flow analysis, the slack bus was identified using different generator buses without increasing the system load. The effects of changes in critical points were examined. The study concluded that the choice of slack bus did not affect the active and reactive power losses. This conclusion is in contrast with [5]. Another study on the selection of slack buses investigated two methods of allocating the cost of a transmission network among its users. The study used marginal and average participation and noted that there were no clear criteria for the selection of the slack bus in load flow studies. According to the study, network charges to network users vary with changes in the slack bus. As a result, the study recommended that a common choice for the slack node is a major load center. A slack bus near the major load centers would tend to increase the total network charges paid by generators while decreasing the portion of the transmission price borne by consumers. In contrast, a slack bus near the generation areas would increase the share of demand in total payments while decreasing generator charges [6]. Furthermore, just as [2] [3] and [6], [7] noted that the choice of a slack bus is made arbitrarily during the load-flow iterative process in such a way that the system power imbalance is minimized, and in the absence of better criteria, the largest generator is arbitrarily proposed as the slack bus, which is a good choice if the total imbalance is relatively large. While it is unimportant for the load-flow solution, which bus is used as the slack bus, the total system imbalance and hence power losses will be affected to some extent by the slack bus selection. When power imbalance is an issue, [7] recommended using a distributed slack bus. With the increased penetration of distributed generation into the power distribution system, the traditional load flow analysis that assumes a single slack bus has become impractical; reactive power generation management cannot be ignored any longer [8].

In sum, while [5] [6], and [7] concluded that load flow results could be affected by the choice of slack bus, [2] concluded that the choice of slack bus does not affect load flow results. [7] and [8] proposed using distributed slack buses, especially when the power imbalance is a concern. This study, therefore, intends to investigate and ascertain the probable causes of the varied conclusions in the reviewed literature. In contrast to the literature, in this study, the effects of the choice of the slack bus were examined using the same test system modeled as a strong grid and a weak grid to facilitate an easy and unbiased comparison of the results.

The ensuing sections of the paper are organised as follows: Section 2 formulates the load flow problem. The study's methodology is presented in Section 3. Section 4 briefly describes the IEEE 14 bus test system, and sections 5 and 6 provide the simulation results and discussions, respectively. The paper's conclusion is presented in Section 7.

2. Formulation of the Load Flow Problem

2.1. Load Flow Equations

Figure 1 is a two-bus network used to formulate the equations of the load flow problem [9].

The apparent power injected into the i^{th} bus of a power system is [9]

$$S_i = P_i + jQ_i = V_i I_i^*,\ \ i = 1,2,3,\cdots,n \tag{1}$$

Taking the complex conjugate of (1)

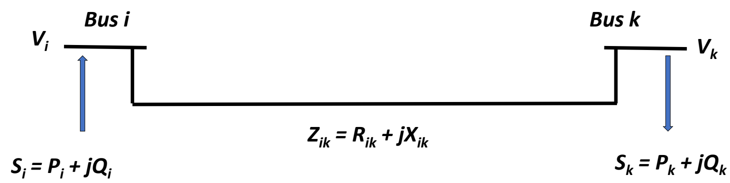

Figure 1. A Two-Bus network.

$$P_i - jQ_i = V_i^* I_i,\ i = 1, 2, 3, \cdots, n \tag{2}$$

In general,

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{ii}V_i + \cdots + Y_{in}V_n = \sum_{k=1}^{n}\left(Y_{ik}V_k\right) \tag{3}$$

where,

$$i = 1, 2, 3, \cdots, n$$

V_i is the voltage at the i^{th} bus.

I_i is the source current injected into the bus.

Y_{ik} is the admittance between buses i and k.

Substituting (3) into (2)

$$P_i - jQ_i = V_i^*\left(\sum_{k=1}^{n}\left(Y_{ik}V_k\right)\right),\ i = 1, 2, 3, \cdots, n \tag{4}$$

Equating real and imaginary parts, we get

Real power,

$$P_i = \text{Real}\left[V_i^*\left(\sum_{k=1}^{n}\left(Y_{ik}V_k\right)\right)\right] \tag{5}$$

Reactive power,

$$Q_i = -\text{Imaginary}\left[V_i^*\left(\sum_{k=1}^{n}\left(Y_{ik}V_k\right)\right)\right] \tag{6}$$

Let,

$$V_i = |V_i| e^{j\delta_i},\ V_k = |V_k| e^{j\delta_k},\ Y_{ik} = |Y_{ik}| e^{j\theta_{ik}} \tag{7}$$

Then

$$P_i = |V_i| \sum_{k=1}^{n} |V_k||Y_{ik}| \cos\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{8}$$

$$Q_i = |V_i| \sum_{k=1}^{n} |V_k||Y_{ik}| \sin\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{9}$$

where,

$$i = 1, 2, 3, \cdots, n$$

δ_i is the voltage phase angle at bus i.

δ_k is the voltage phase angle at bus k.

θ_{ik} is the power factor angle.

Equations (8) and (9) are known as the power flow equations and illustrate that the power transfer between two buses in a power system is dependent on:

1) The magnitude of the bus voltage at the sending and receiving ends.

2) The difference between the voltage phase angle at the sending and receiving

ends.

From Equations (8) and (9), for line flows to remain constant irrespective of the choice of slack bus, voltage magnitudes and the differences in the voltage phase angles between the sending and receiving ends must remain constant. Variations of the voltages and phase angles at the sending and receiving ends are expected to alter the power flows on the lines.

2.2. Load Models in Load Flow Analysis

Load modeling is one of the most significant parts of load flow analysis. Correct load modeling is critical for obtaining appropriate results. Static loads can be modeled as constant impedance load (Z), constant current load (I) and constant power load (P) and collectively called the ZIP load model. The ZIP load model usually refers to voltage dependency [10]. Active and reactive power flows varies with the square of the voltage magnitude in a constant impedance or constant admittance load model, varies directly with voltage magnitude in a constant current load model, and does not vary with changes in voltage magnitude in a constant power or constant MVA load model [11]. Representing static loads in exponential form gives Equation (10) below [11]:

$$P(V) = P_o\left(\frac{V}{V_o}\right)^{\alpha};\ Q(V) = Q_o\left(\frac{V}{V_o}\right)^{\beta} \tag{10}$$

where P and Q are the active and reactive components of the load, and V is the magnitude of the bus voltage. The subscript "o" specifies the initial conditions or states of the variables. The parameters of the model are defined by exponents α and β. When these exponents are set to 0, 1, or 2, the model respectively depicts the constant power, constant current, or constant impedance properties of the load components [11].

2.3. Power System Losses

The basic types of active power loss in the electric power system are as follows:

1) Resistance heat loss, directly proportional to the square of current flow [12],

$$\Delta P_1 = I^2 \cdot R \tag{11}$$

where,

I is current passing through the cable core (A).

R is the sum of resistance of both the cable/overhead line including (Ω).

2) Leakage loss, directly proportional to the square of voltage [12]

$$\Delta P_2 = U^2 \cdot G \tag{12}$$

where,

U is voltage between the cable core and ground (V);

G is leakage conductance of dielectric (1/Ω).

3) Dielectric magnetizing loss, directly proportion to the square of current and

the frequency [12]

$$\Delta P_3 = I^2 \omega L \tan\delta \tag{13}$$

where,

ω: AC angular frequency (1/s).

L: inductance of the cable (Wb/A).

$\tan\delta$: repeated magnetizing loss tangent of the cable dielectric.

4) Dielectric polarization loss, directly proportional to the square of voltage and the frequency [12]

$$\Delta P_4 = U^2 \omega C \tan\delta \tag{14}$$

where,

C is capacitance of the cable (F).

Equations (11)-(14) indicate that losses are dependent on the square of the current and voltage. Therefore, any variations in the current flowing in the lines and the bus voltages in terms of magnitude and phase angle at the sending and receiving ends will ultimately affect the losses in the grid.

3. Methodology

In this study, the IEEE-14 bus test system is simulated using PSS/E simulation tool to investigate the effect of slack bus selection on active and reactive power losses in robust and weak grids. The study was conducted using both Newton Raphson and Guass-Seidel methods to obtain network parameters while selecting PV buses in turns as the system slack bus [2] [5]. To start with the load flow simulations, the study first determined the voltage stability of the IEEE-14 bus test system by performing Q-V analysis. The Q-V nodal analysis is used to identify the weakest buses in the system as per **Figure 2** below [13] [14] [15] [16].

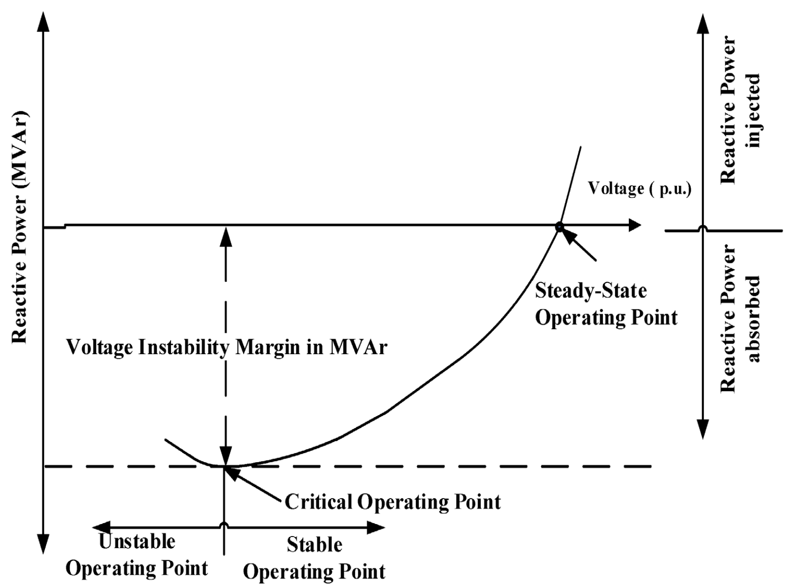

Figure 2. Q-V curve and reactive power margin.

The analysis showed that the IEEE 14 bus test system is a stable or strong grid with varied degrees of reactive power reserves at the load or PQ nodes. For this study, the IEEE 14 bus test system is therefore considered a strong or robust grid and simulated accordingly. When the system is on the verge of collapse, a marginal increase in load will induce a large increase in reactive power absorption. Therefore, a reactive power load is connected to bus 14, which is the most vulnerable bus based on its lowest reactive power reserve margin. This is expected to compromise the stability of the grid [4]. The weak and the robust grids are then simulated for comparative analysis.

4. Description of the IEEE-14 Bus System

The single-line diagram of the simulated IEEE-14 bus test system is shown in **Figure 3**. The test system has fourteen (14) buses, five (5) generators, and eleven (11) loads modeled as constant power loads [17]. The data for the test system is obtained from [18].

5. Simulation Results

5.1. Q-V Analysis

Q-V curves are used to determine the reactive power injection or withdrawal required at a bus in order to vary the bus voltage to the required value. The Q-V sensitivity at a load bus represents the slope of the Q-V curve at the given operating point. A positive Q-V sensitivity is an indication of stable operation. The smaller the sensitivity, the more stable the bus. As the system crawls in the vicinity of vulnerable voltage collapse, the sensitivity increases, and the voltage stability limit becomes infinite [4]. All the Q-V curves in **Figure 4** revealed adequate reactive power margin at all the PQ buses, which indicates that the IEEE 14 bus test system is stable and not easily susceptible to voltage collapse under normal operating conditions.

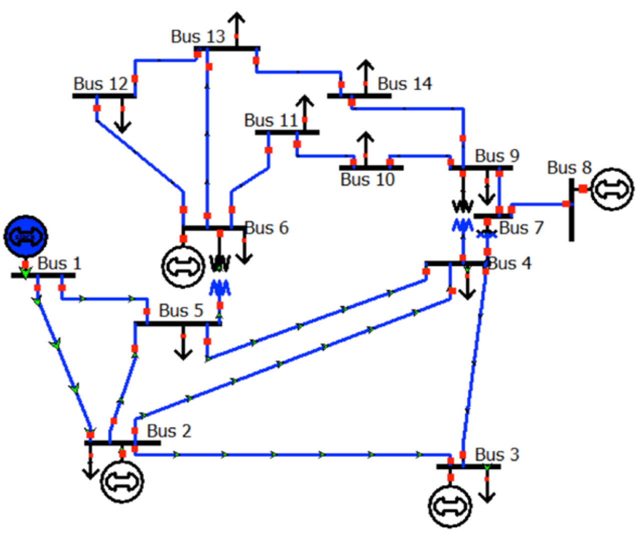

Figure 3. IEEE-14 bus system single line diagram [17].

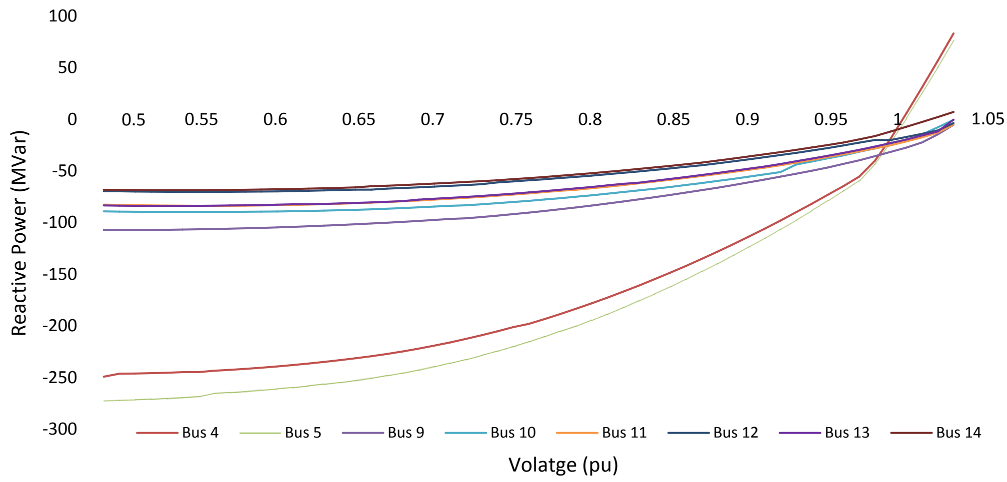

Figure 4. Q-V curves analysis.

5.2. Simulation of IEEE 14 Bus Test System—Strong Grid

Simulations were conducted using Newton-Raphson and Gauss-Seidel methods, but both load flow methods yielded the same results, probably due to the small system size used for this study.

5.2.1. Voltage Magnitudes of Buses in Strong Grid

Load flow analysis using Newton Raphson and Gauss-Seidel methods was conducted on the network while alternating the slack bus among all PV buses. Table 1 shows that the voltage magnitudes at all buses have remained constant in the strong grid, irrespective of the bus chosen as the slack bus.

5.2.2. Voltage Phase Angle of Buses in Strong Grid

Since the change in active power flow is directly proportional to the change in voltage phase angle, constant phase angle differences between connected buses are expected to yield a fairly constant flow between these buses irrespective of the choice of slack bus. Table 2 shows that the phase angle difference between sending and receiving end buses are essentially constant.

5.2.3. Network Losses and Power Mismatch

Table 3 and Figure 5 show that the power losses in the IEEE 14 bus test system have remained constant irrespective of the choice of slack bus.

5.3. Simulation of IEEE 14 Bus Test System—Weak Grid

From the Q-V plots in Figure 4, the weakest bus in the IEEE-14 bus test system is bus 14 based on its reactive power reserve, which agrees with [14]. A 50 MVar load, greater than the reactive power (29.63 MVar) withdrawal required to maintain the bus voltage at 0.95 pu, was arbitrarily selected and connected to bus 14 to introduce voltage instability into the grid. The voltage at bus 14 in the robust grid, which was 1.0344 pu in Table 1, dropped to 0.7841 pu with bus 3 as the slack bus, as seen in Table 4.

Table 1. Voltage magnitude of buses in strong grid.

Slack Bus	Bus 1	Bus 2	Bus 3	Bus 6	Bus 8
Bus Numbers	Voltage Magnitude	Voltage Magnitude	Voltage Magnitude	Voltage Magnitude	Voltage Magnitude
1	1.0647	1.0647	1.0647	1.0647	1.0647
2	1.0450	1.0450	1.0450	1.0450	1.0450
3	1.0100	1.0100	1.0100	1.0100	1.0100
4	1.0122	1.0122	1.0122	1.0122	1.0122
5	1.0115	1.0115	1.0115	1.0115	1.0115
6	1.0700	1.0700	1.0700	1.0700	1.0700
7	1.0593	1.0593	1.0593	1.0593	1.0593
8	1.0900	1.0900	1.0900	1.0900	1.0900
9	1.0541	1.0541	1.0541	1.0541	1.0541
10	1.0495	1.0495	1.0495	1.0495	1.0495
11	1.0562	1.0562	1.0562	1.0562	1.0562
12	1.0550	1.0550	1.0550	1.0550	1.0550
13	1.0502	1.0502	1.0502	1.0502	1.0502
14	1.0344	1.0344	1.0344	1.0344	1.0344

Table 2. Voltage phase angle difference between connected buses in strong grid.

Sending Bus	Receiving Bus	Slack Bus 1	Slack Bus 2	Slack Bus 3	Slack Bus 6	Slack Bus 8
1	2	4.49	4.39	4.39	4.39	4.39
1	5	10.66	10.57	10.57	10.57	10.57
2	3	8.76	8.75	8.75	8.76	8.75
2	4	7.15	7.15	7.15	7.15	7.15
3	4	−1.61	−1.6	−1.6	−1.61	−1.6
4	5	−0.98	−0.97	−0.97	−0.97	−0.97
4	7	3.16	3.16	3.16	3.16	3.16
4	9	4.79	4.79	4.79	4.8	4.79
5	6	5.34	5.33	5.32	5.33	5.33
6	11	0.45	0.45	0.45	0.45	0.45
6	12	0.84	0.83	0.84	0.84	0.83
6	13	0.9	0.89	0.9	0.9	0.89
7	8	0	0	0	0	0
7	9	1.63	1.63	1.63	1.64	1.63
9	10	0.21	0.21	0.21	0.2	0.21
9	14	1.21	1.2	1.2	1.2	1.2
10	11	−0.19	−0.19	−0.2	−0.19	−0.19
12	13	0.06	0.06	0.06	0.06	0.06
13	14	0.74	0.74	0.74	0.74	0.74

Table 3. Network losses and power mismatch in strong system.

		Slack Bus 1	Slack Bus 2	Slack Bus 3	Slack Bus 6	Slack Bus 8
Total Power Flows	MW	259.0	259.0	259.0	259.0	259.0
	MVAR	73.5	73.5	73.5	73.5	73.5
Network Losses	MW	14.3	14.3	14.3	14.3	14.3
	MVAR	59.40	59.40	59.40	59.40	59.40
Power Mismatch	MW	0.00	0.00	0.00	0.00	0.00
	MVAR	0.00	0.00	0.00	0.00	0.00

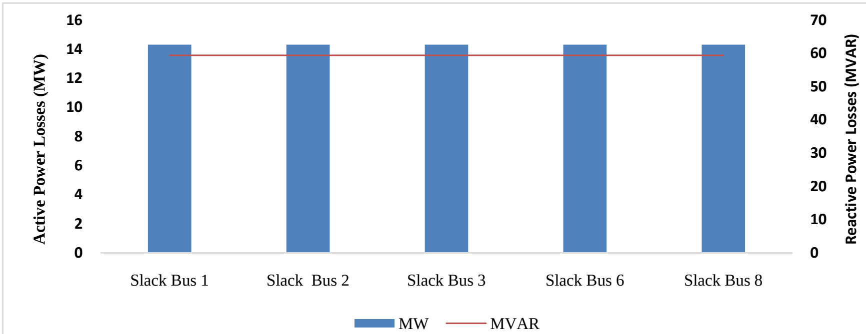

Figure 5. Network losses.

Table 4. Voltage magnitude of buses in weak grid.

Slack Bus	Bus 1	Bus 2	Bus 3	Bus 6	Bus 8
Bus Numbers	Voltage Magnitude	Voltage Magnitude	Voltage Magnitude	Voltage Magnitude	Voltage Magnitude
1	1.0600	1.0551	1.0323	1.0600	1.0426
2	1.0364	1.0450	1.0206	1.0450	1.0283
3	0.9905	0.9978	1.0100	1.0100	0.9936
4	0.9619	0.9676	0.9524	1.0012	0.9723
5	0.9598	0.9640	0.9465	1.0023	0.9677
6	0.9594	0.9654	0.9439	1.0700	0.9825
7	0.9628	0.9692	0.9505	1.0276	1.0082
8	1.0049	1.0110	0.9930	1.0672	1.0900
9	0.9274	0.9342	0.9136	1.0062	0.9661
10	0.9246	0.9314	0.9104	1.0098	0.9609
11	0.9379	0.9443	0.9229	1.0359	0.9678
12	0.9282	0.9346	0.9122	1.0397	0.9535
13	0.9100	0.9166	0.8938	1.0212	0.9372
14	0.8016	0.8096	0.7841	0.9085	0.8408

5.3.1. Voltage Magnitudes of Buses in Weak Grid

Load flow analysis using Newton Raphson and Gauss-Seidel methods was conducted on the network while alternating slack bus among all PV buses. Table 4 shows that the voltage magnitudes at all buses varied with the choice of slack bus.

5.3.2. Voltage Phase Angle of Buses in Weak Grid

Table 5 shows that the phase angle difference between sending end and receiving end buses varied with the choice of slack bus.

5.3.3. Network Losses and Power Mismatch

Table 6 and Figure 6 show the active and reactive power losses in the IEEE-14 bus test system varied with the choice of slack bus.

5.4. Simulation of the Weak Grid without Var Limits

As a weak grid, the IEEE 14 bus test system is further simulated while ignoring reactive power limits. The results, as indicated in Table 7, reveal that network losses remained constant irrespective of the choice of slack.

Table 5. Voltage phase angle difference between connected buses in weak grid.

Sending Bus	Receiving Bus	Slack Bus 1	Slack Bus 2	Slack Bus 3	Slack Bus 6	Slack Bus 8
1	2	4.47	4.71	4.87	4.51	4.71
1	5	10.32	10.4	10.95	10.73	10.93
2	3	8.95	8.79	9.38	8.64	8.92
2	4	6.89	6.74	7.15	7.07	7.29
3	4	−2.06	−2.05	−2.23	−1.57	−1.63
4	5	−1.04	−1.05	−1.07	−0.85	−1.07
4	7	3.79	3.73	3.95	3.25	3.87
4	9	5.83	5.74	6.08	4.93	5.78
5	6	6.32	6.23	6.74	5.95	6.23
6	11	0.55	0.56	0.51	0.18	0.58
6	12	0.9	0.89	0.92	0.7	0.85
6	13	0.46	0.46	0.46	0.28	0.46
7	8	0.110	0.110	0.110	0.100	0.270
7	9	2.04	2.01	2.13	1.68	1.91
9	10	0.26	0.25	0.3	0.31	0.23
9	14	−1.39	−1.37	−1.37	−0.89	−1.31
10	11	−0.26	−0.25	−0.2	0.04	−0.27
12	13	−0.44	−0.43	−0.46	−0.42	−0.39
13	14	−1.3	−1.27	−1.42	−1.34	−1.15

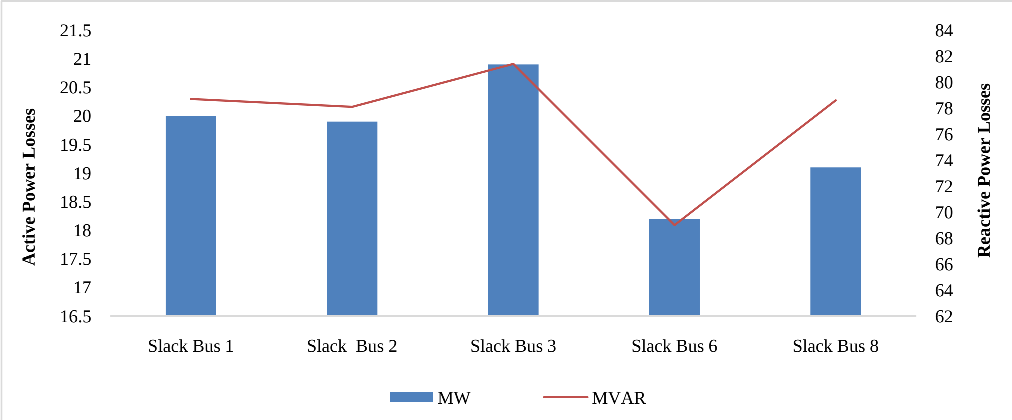

Figure 6. Active and reactive network losses.

Table 6. Network losses and power mismatch in weak system.

	Slack Bus	Bus 1	Bus 2	Bus 3	Bus 6	Bus 8
Total Power Flows	MW	259.0	259.0	259.0	259.0	259.0
	MVAR	73.5	73.5	73.5	73.5	73.5
Network Losses	MW	20.0	19.9	20.9	18.2	19.1
	MVAR	78.7	78.1	81.4	69.0	78.6
Power Mismatch	MW	0.00	0.00	0.00	0.00	0.00
	MVAR	0.00	0.00	0.00	0.00	0.00

Table 7. Network losses and power mismatch in weak grid without var limits.

	Slack Bus	Bus 1	Bus 2	Bus 3	Bus 6	Bus 8
Total Power Flows	MW	259.0	259.0	259.0	259.0	259.0
	MVAR	123.5	123.5	123.5	123.5	123.5
Network Losses	MW	17.8	17.8	17.8	17.8	17.8
	MVAR	68.0	68.0	68.0	68.0	68.0
Power Mismatch	MW	0.00	0.00	0.00	0.00	0.00
	MVAR	0.00	0.00	0.00	0.00	0.00

6. Discussion of Results

In the strong grid, the voltage magnitudes at the buses remained constant irrespective of the choice of slack bus. The differences between the voltage phase angle at the sending and receiving ends were also constant. These parameters, however, varied with the choice of the slack bus in the weak grid.

6.1. Active and Reactive Power Flows

From Equations (8) and (9), the change in active and reactive power flows depend on the difference between the voltage phase angles and the voltage magnitudes at the sending and receiving ends. This was, however, not evident in the load flow simulations, especially, in the weak grid where there were variations in the voltage magnitudes and voltage phase angle differences. The active and reactive power flows remained unchanged in both the weak and strong grids. Though this result is in contrasts with Equations (8) and (9), it is not unexpected. The loads are modeled as constant power loads and are thus expected to remain constant, while the load current is adjusted inversely in proportion to the voltage variation to ensure that the load power is always constant.

6.2. Active and Reactive Power Losses

The active and reactive power losses remained constant in the strong grid irrespective of the choice of slack bus. However, the active and reactive power losses varied with the choice of slack bus in the weak grid. From Equations (11)-(14), it is seen that losses are dependent on the square of the bus voltage and load current. Changes in the bus voltages in the weak grid are therefore expected to cause an inverse change in the load current since the loads are modeled as constant power loads. The variations in the voltage magnitudes of the buses and consequently the load current in the weak grid resulted in the variations in active and reactive power losses when the slack bus is changed.

7. Conclusion

The slack bus serves as a reserve for unaccounted active and reactive power which constitutes system losses. The study has revealed that the choice of slack bus does not affect real and reactive power losses in a strong or adequately compensated grid. However, in weak grids, the choice of slack bus affects the real and reactive power losses. The study has also revealed that active and reactive power flows are not impacted by the choice of slack bus both in the weak and strong grids due to the fact that the loads are modeled as constant power loads.

Disclaimer

The views and opinions expressed in this article are those of the author and do not reflect the official position of ERERA.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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