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The Effect of Adding Generator Bus to The Short Circuit Current Level in Electrical Power System

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A B S T R A C T

The need for electrical energy is changing and increasing, requiring system flexibility always to be changed and developed. On the other hand, changes in the configuration of the electric power system due to the addition of components or sub-systems also change system parameters such as impedance or level of fault current (short circuit current). This paper presents a study of changes in the fault current caused by adding a new generating bus to an electric power system. This paper aims to determine the change in short-circuit current due to the addition of generators on new buses connected to existing buses to identify the most suitable location for adding these generators based on short-circuit current levels. Three-phase short circuit faults are simulated and analyzed on the IEEE 14 bus standard system using ETAP software with a base MVA 615 MVA. The addition of generators was carried out at five locations with varying generating capacities. The research results show that the short circuit current will change significantly when adding a generator bus to bus 13, with an average percentage change of 5,656%. The smallest change occurs when adding a generator to bus 2, with an average percentage change of 2,417%. The research results conclude that connecting a generator to a new bus linked to an existing generator bus (PV bus) is more effective than connecting it to a new bus associated with a load bus (PQ bus).

INTRODUCTION

With increasing population growth and rapid technological developments, the demand for electrical energy will keep increasing. To address this growth, it is essential to reconfigure the network and expand electricity supply capacity by building transmission lines and adding new generating units throughout different areas of the power system.

The electric power system is described as a configuration of generating and loading buses interconnected by transmission or distribution lines. Among these buses is a swing bus, which functions as the reference bus. During analysis, the components of this power system are modeled as an impedance or admittance matrix that connects the voltage, power, and currents flowing between the buses. With the addition of generators or changes in transmission lines, the configuration and arrangement of impedance or admittance matrix in the system will also change. These changes will technically affect many aspects of operation, such as power flow and protection behavior, as well as the settings of the installed protection equipment. Setting protective equipment is carried out by calculating the fault or short circuit current where one of the variables taken into account is the system impedance [1], [2].

Generally, changes that occurred in the electric power system configuration modeled in the impedance matrix Z_{bus} can be categorized into four types [3] namely: adding a new bus and its impedance Z_b to the reference bus; adding a new bus and impedance Z_b to an existing bus; addition of impedance Z_b from the existing non-reference bus to the reference bus; and adding impedance Z_b between the two existing non-reference buses.

The short circuit current calculations and analysis are crucial in setting up protective equipment and assessing reliability, safety, and system power quality. Suppose the short circuit current that occurs does not match the protection device's settings, the protection system will not work properly. In that case, the fault cannot be controlled, and it will damage the equipment and the electric power system. For this reason, if there are plans for adding or simplifying subsystems, calculating and analyzing the short circuit current must be done. The short circuit current can be calculated and analyzed using various methods and computer software. Various types of faults can occur in the power system, leading to short circuit currents; they are the symmetrical fault, a balanced fault that impacts all phases simultaneously, and the asymmetrical fault, which involves only one or two stages. Symmetrical faults have the characteristics of large short circuit currents, which can be calculated. Meanwhile, asymmetric faults

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are more complex and can be calculated using the symmetric component method [4].

As electrical power systems become increasingly complex and significant advances in computing equipment and techniques, the study of short circuit currents becomes more extensive and advanced. Researchers have introduced several techniques and methods; studies have been conducted on various aims, techniques, and possible scenarios. In reference [5], the short circuit current is computed at a particular bus by simulating the addition of a special branch between the faulted bus and the ground. Research in [6] applies a hybrid compensation method, combining a phase coordinate approach with Monte Carlo Simulation (MCS). Similarly, in [7] and [8] the authors utilize the compensation method to calculate short circuit current. In [9], the simple generalized minimal residual (SGMRES) method is used for short circuit current calculation, while reference [10] employs the Generalized Minimal Residual (GMRES) approach. Reference [11] uses an arbitrary topology for short circuit current computation, and in [12] the suppression method is applied for the same purpose. In [13], the short circuit current is determined using the loop analysis method. Reference [14] integrates the compensation theorem with Thevenin's equivalent circuit to calculate the short circuit current, whereas [15] employs the superposition principle. Short circuit current calculations can be performed at various voltage levels (transmission and distribution) using both bus impedance matrix (Z_{bus}) and admittance matrix (Y_{bus}) models [16]–[18]. In [16], the short circuit current of the distribution network and its load is computed using the bus admittance matrix.

The bus impedance matrix (Z_{bus}) defines the relationship between current and voltage in a system. It includes diagonal elements known as driving point impedance or self-impedance [19] and [20]. The self-impedance diagonal element represents the sum of the primitive admittances of all components connected to the reference bus [17]. The off-diagonal elements, also called transfer impedance, are equal to the negative of the primitive admittance for all components connected between two buses. A reference point is established for fault current calculations.

The bus impedance matrix method is quite accurate for calculating short circuit currents. This method first forms the system's bus admittance matrix (Ybus). Then, it is converted into a bus impedance matrix (Z_{bus}) [17], the relationship between the two can be seen in equations (1) and (2).

$$Y_{bus}^{s} = \begin{bmatrix} Y_{11}^{s} & Y_{12}^{s} & Y_{13}^{s} & Y_{1n}^{s} \\ Y_{21}^{s} & Y_{22}^{s} & Y_{23}^{s} & Y_{2n}^{s} \\ Y_{n1}^{s} & Y_{n2}^{s} & Y_{n3}^{s} & Y_{nn}^{s} \end{bmatrix} \tag{1}$$

$$\left[Z_{bus}^{s} = {Y_{bus}^{s}}^{-1}\right] \tag{2}$$

This paper examines the impact of adding new generator buses and network lines to an existing bus (type 2) on the resulting short circuit current levels. This type of change represents changes in the electric power network due to connecting new power plants from renewable energy sources such as photovoltaics and other renewable energy sources (RES), which are currently trending. Adding new generators is usually carried out/connected to an existing electricity network bus. The short circuit current is determined using the bus impedance matrix method and simulated with ETAP software.

The sub-transient symmetrical three-phase short circuit current at bus k is calculated using the following equation (3) [3]:

$$I_f{}'' = \frac{V_f}{Z_{kk}} \tag{3}$$

The addition of a new bus ***p*** connected via line impedance (Z_b) to the existing bus **k**, with an injection current I_p will result in a current entering the original network at bus **k** [3]. The following is the impedance matrix equation after adding a new bus:

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \\ V_p \end{bmatrix} = \begin{bmatrix} & & & & Z_{1k} \\ & & & & Z_{2k} \\ & & Z_{orig} & & \vdots \\ & & & & Z_{Nk} \\ Z_{k1} & Z_{k2} & \cdots & Z_{kN} & Z_{kk} + Z_b \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \\ I_p \end{bmatrix} \tag{4}$$

From equations (3) and (4), it can be seen that adding a generator will change the impedance matrix of the Zkk + Zb system. So, equation 3 becomes:

$$I_f{}''_{new} = \frac{V_f}{Z_{kk} + Zb} \tag{5}$$

To show the changes in short circuit current level due to changes/additions of new buses, this paper uses the 14-Bus system from IEEE as an example case. Changes in short circuit current at a bus location are then analyzed according to the location of the additional generator (bus) and the amount of capacity addition carried out. From this analysis, both the optimum location and additional capacity that can be connected to an existing system will be obtained. The result can be used to adjust the protection's component settings.

METHOD

Figure 1 shows the single-line diagram of the IEEE 14-bus system.

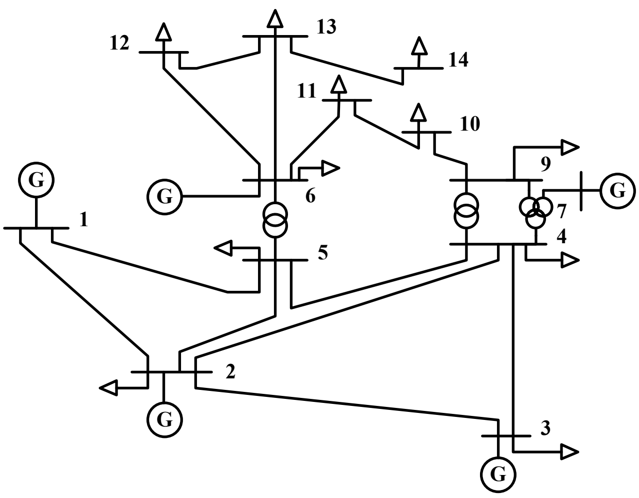

Figure 1. A 14-Bus system of IEEE single-line diagram [21]

This system consists of 14 buses, with bus 1 as the swing bus, buses 2, 3, 6, and 8 as generator buses, and the remaining buses

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as load (PQ) buses [22]. Transmission lines interconnect the buses. In this study, the IEEE 14-bus system is based on an MVA rating of 615 MVA, corresponding to the system's largest generating component. Table 1 lists the transmission line parameters connecting the buses.

Table 1. Network Parameter (Transmission and Distribution Line)

Line	R (pu)	X (pu)	B (pu)	Rasio Tap
1-2	0.0194	0.05917	0.053	1
1-5	0.054	0.22304	0.049	1
2-3	0.047	0.19797	0.044	1
2-4	0.0581	0.17632	0.037	1
2-5	0.057	0.17388	0.034	1
3-4	0.067	0.17103	0.346	1
4-5	0.0134	0.04211	0.013	1
4-7	0	0.20912	0	1
4-9	0	0.55618	0	1
5-6	0	0.25202	0	0.9
6-11	0.095	0.1989	0	1
6-12	0.1229	0.25581	0	1
6-13	0.0662	0.13027	0	1
7-8	0	0.17615	0	1
7-9	0	0.11001	0	1
9-10	0.0318	0.0845	0	1
9-14	0.1271	0.27038	0	1
10-11	0.0821	0.19207	0	1
12-13	0.2209	0.19988	0	1
13-14	0.1709	0.34802	0	1

R represents the electrical resistance of the transmission line conductor, and X denotes the electrical reactance, accounting for the transmission line's inductive and capacitive components. This system is represented in matrix form by a Z matrix of order 14 x 14. Meanwhile, table 2 presents data for 5 synchronous generators located on the generator buses.

Table 2. Generator data

Generator Bus no.	1	2	3	4	5
MVA	615	60	60	25	25
X_l (p.u)	0.24	0	0	0.134	0.134
r_a (p.u)	0	0	0.003	0.001	0.004
X_d (p.u)	0.898	1.05	1.05	1.25	1.25
X'_d (p.u)	0.3	0.19	0.185	0.232	0.232
X''_d (p.u)	0.23	0.13	0.13	0.12	0.12
T'_{do}	7.4	6.1	6.1	4.75	4.75
T''_{do}	0.03	0.04	0.04	0.06	0.06
X_q (p.u)	0.646	0.98	0.98	1.22	1.22
X''_q (p.u)	0.4	0.13	0.13	0.12	0.12
T'_{qo}	0.	0.3	0.3	1.5	1.5
T''_{qo}	0.033	0.1	0.099	0.21	0.21

Each generator is characterized by parameters such as x_l, the positive sequence symmetric reactance, r_a, the armature resistance, x_d and x_q, the direct and quadrature-axis reactances. Additionally, xd' and xq' represent the direct and quadrature-axis transient reactances, while x_d” and x_q” are the direct and quadrature-axis sub-transient reactances [23]. The parameters T'_{do} and T'_{qo} correspond to the direct and quadrature-axis transient time constants, and T''_{do} and T''_{qo} represent the sub-transient time constants for the direct and quadrature axes [24]. Figure 3 also provides the power data for each bus, including the active and reactive power on the generator (PG, QG) and the load buses (PL, QL).

Using the single-line diagram, detailed component data, line impedance, and power information for each bus in the system, the short-circuit currents resulting from faults occurring on each bus are calculated utilizing ETAP software. These calculations accurately represent the fault currents at each bus and are considered the baseline values before making any modifications to the system's configuration. These calculated values represent the pre-modification fault conditions, providing critical system analysis and planning insights. Figure 2 illustrates the methodology employed for this analysis, presented as a detailed flow chart to enhance understanding and ensure a systematic approach to the fault current calculations.

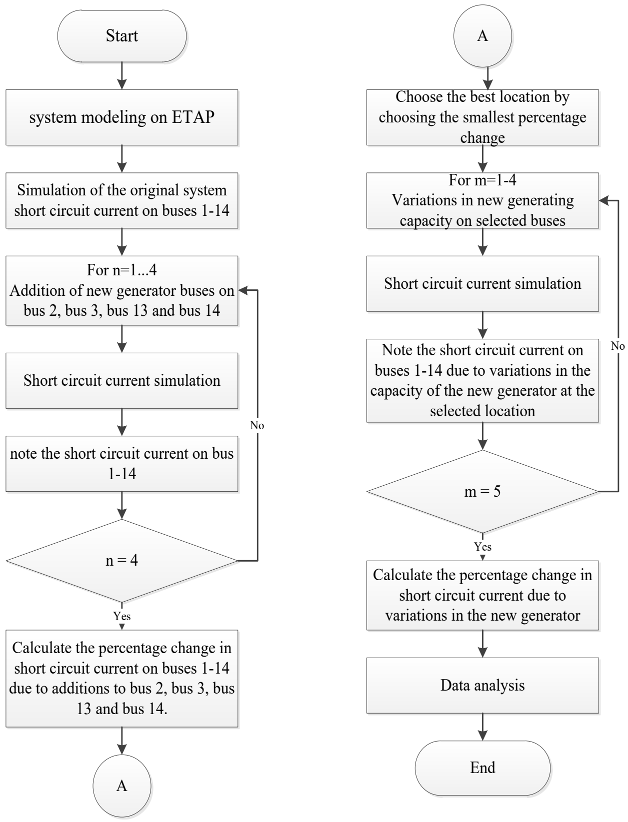

Figure 2. Flowchart used to analyze the effect of adding a generator bus to an existing network

Configuration changes are carried out by introducing a new generator bus alternately connected to different buses within the system, including Bus 2 and Bus 3 (the generating buses) and Bus 13 and Bus 14 (the load buses). For each instance of adding a new generator bus to these locations, the resulting impact on the short-circuit current at various other buses within the system is carefully analyzed and assessed. This analysis helps to identify the extent of change in short-circuit currents caused by the addition. The location that demonstrates the least impact on the short-circuit current variations across the system is the optimal site for placing additional generator buses. Examining these changes provides insight into the overall effect of adding generator buses. It highlights the differences between connecting new generator buses to existing ones versus load buses. Through this process, the study aims to optimize the system configuration for enhanced stability and minimal fault to short-circuit current levels.

The next step in the study focuses on varying the capacity of the additional generators installed at the optimal location determined during the analysis phase. This step plays a critical role in exploring and understanding the trends and patterns of changes in short-circuit currents that manifest across other buses within the network due to integrating a generator bus with an existing bus. The capacity variations allow for a more detailed examination of the relationship between the size of the generator and its influence on the system's fault currents.

By systematically analyzing these variations, the study provides valuable insights into how adding generation capacity affects the system's overall fault response. This includes identifying potential changes in fault current magnitudes and distribution and understanding their implications for system protection and stability. The findings of this analysis are crucial for optimizing the system's design, ensuring it can effectively accommodate the new generation capacity while maintaining balanced and reliable operation under fault conditions.

In this research, the variations in generator capacity are calculated relative to the base system configuration to maintain consistency and comparability in the analysis. The range of capacity increments introduced includes 61.5 MVA (10%), 123 MVA (20%), 184 MVA (30%), 246 MVA (40%), and 307.5 MVA (50%), representing systematic increases from the baseline capacity. These incremental variations allow for a detailed and structured evaluation of how different generator sizes influence system performance, particularly in short-circuit current changes.

Furthermore, Figure 3 visually represents the updated single-line system diagram after the modifications. The diagram clearly illustrates the addition of the new generator bus, which is directly connected to Bus 2. This connection plays a significant role in the system configuration. It serves as a key focus for assessing the impact of the generator addition on the network's operational dynamics and fault-handling capability. This comprehensive approach ensures a thorough understanding of the implications of generator capacity variations on the power system.

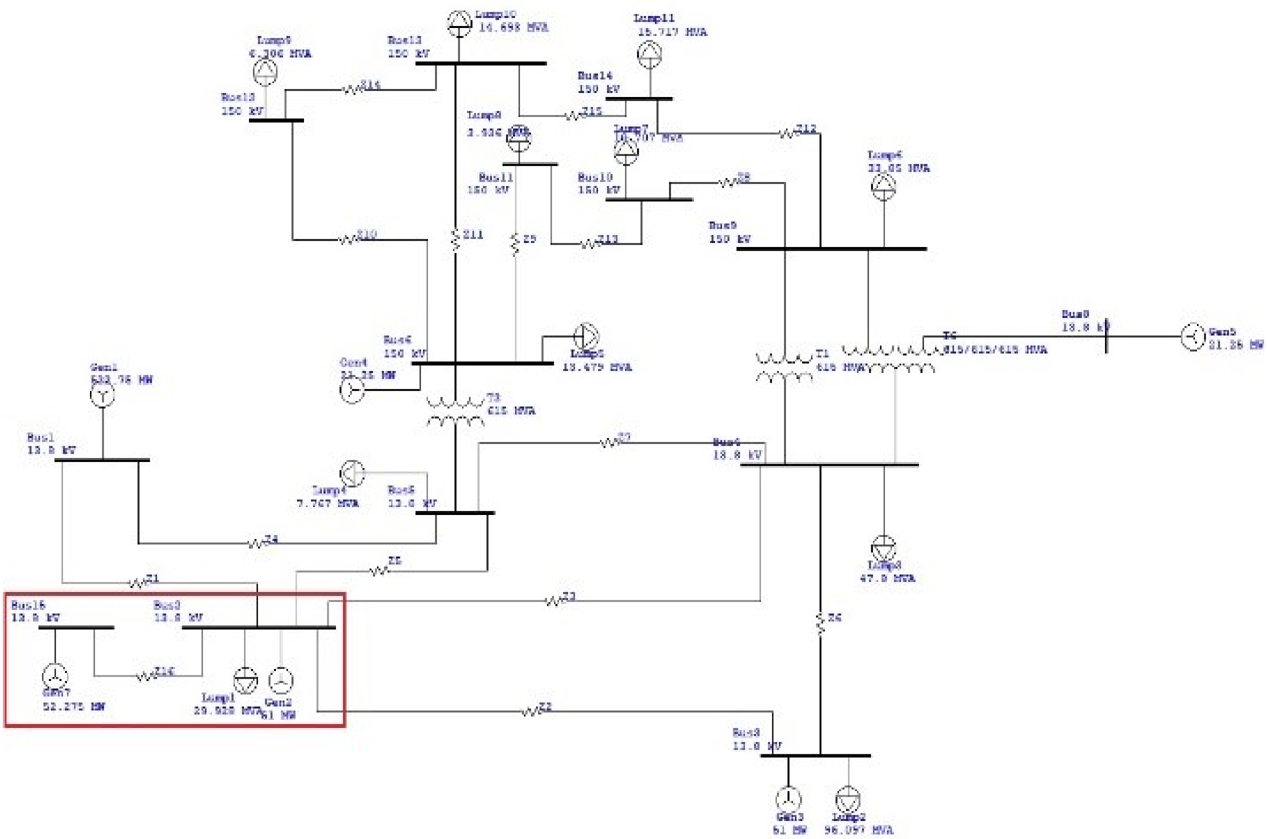

Figure 3. Single-line diagram of IEEE 14-Bus after addition bus Generator at Bus 2

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RESULTS AND DISCUSSION

Result

Table 3 presents the short circuit current for all buses in the network before adding a new generating bus (original system) and the short circuit current when adding new buses connected to buses 2, 3, 13, and 14, assuming the fault is located at each bus.

Table 3. Short-Circuit Current Resulting from the Connection of a 61.6 MVA Generator to a New Bus Linked to Buses 2, 3, 13, and 14

Fault Location	Short Circuit Current before bus addition	Location of 61.6 MVA Generator Bus Addition			
		Bus 2	Bus 3	Bus 13	Bus 14
Bus 14	10.45	10.65	10.648	11.227	10.65
Bus 13	10.457	10.658	10.656	11.243	10.658
Bus 12	10.426	10.626	10.624	11.206	10.626
Bus 11	10.464	10.665	10.663	11.243	10.665
Bus 10	10.48	10.682	10.68	11.259	10.682
Bus 9	10.494	10.696	10.694	11.273	10.696
Bus 8	96.491	98.117	98.132	101.059	98.117
Bus 6	10.472	10.673	10.672	11.256	10.673
Bus 5	142.966	147.294	146.939	148.902	147.294
Bus 4	145.412	149.77	149.939	151.741	149.77
Bus 3	125.265	128.23	132.566	128.288	128.23
Bus 2	159.36	166.693	164.139	164.268	166.693
Bus 1	164.095	169.515	167.873	168.331	169.515

The highest short circuit current is observed at bus 1, while the lowest occurs when a fault happens at bus 12. When the system undergoes modifications, such as adding new generating buses, the short-circuit current levels at each bus are subject to change.

The percentage change in short-circuit current levels for Buses 1 through 14 is evaluated to analyze the impact of such modifications. This analysis considers explicitly the addition of new generating buses at strategic locations, including Buses 2, 3, 13, and 14, with an incremental generating capacity increase of 61.5 MVA. The results of this analysis, which highlight how these modifications affect short-circuit current levels across the system, are summarized and presented in Table 4. This information provides valuable insights into the network's response to generation capacity and configuration changes.

Table 4 shows that if the generator capacity is added on the new bus connected to bus 2, the most significant percentage increase in short circuit current will occur on bus 2 (4.601%). The same condition happens if generator capacity is added on a new bus connected to buses 3, 13, and 14: the largest percentage change will occur on buses 3, 13, and 14, respectively (5.828%, 7.516%, and 7.521%). This fact demonstrates that the short circuit current will experience significant changes at a specific bus when a generator bus is added. From various locations of additional generator buses in Table 3, it can also be seen that the addition of generators on the new bus connected to bus 2 causes the most minor percentage change compared to the addition of generator buses at other locations in the system. With this result, bus 2 is the best location if there is a scenario of additional generators bus in the system.

Table 4. Percentage Change in Short Circuit Current Due to Connecting 61.6 MVA Generator to a New Bus Linked to Buses 2, 3, 13 and 14

Fault Location	Percentage Change in Short Circuit Current based on new generating capacity (%)			
	Bus 2	Bus 3	Bus 13	Bus 14
Bus 14	1.914	1.895	7.435	**7.521**
Bus 13	1.922	1.903	**7.516**	7.449
Bus 12	1.918	1.899	7.481	7.414
Bus 11	1.921	1.902	7.444	7.435
Bus 10	1.927	1.908	7.433	7.452
Bus 9	1.925	1.906	7.423	7.461
Bus 8	1.685	1.701	4.734	4.749
Bus 6	1.919	1.909	7.487	7.439
Bus 5	3.027	2.779	4.152	4.149
Bus 4	2.997	3.113	4.352	4.354
Bus 3	2.367	**5.828**	2.413	2.414
Bus 2	**4.601**	2.999	3.079	3.017
Bus 1	3.303	2.302	2.581	2.581
AVERAGE	**2.417**	**2.465**	**5.656**	**5.649**

Bus 2 and bus 3 are generator buses, while buses 13 and 14 are load buses. From the short circuit, current analysis carried out and shown in Table 3, it can be seen that the placement of a new generator bus on the generation bus causes a smaller average percentage change in short circuit current compared to the addition of a new generator bus is carried out on the load bus.

Another aspect that will be known is the trend of changes in short circuit current on the best buses due to the percentage increase in generating capacity. To find out this, on bus 2 as the best location, changes were made by adding a new generator bus with capacities of 61.5 MVA, 123 MVA, 184 MVA, 246 MVA, and 307.5 MVA.

Table 5 presents the short-circuit current levels at buses 1 to 14 following the addition of a new generator at Bus 2, identified as the optimal bus. Figure 4 illustrates the average percentage change in short-circuit current resulting from the increased generating capacity.

Table 5. Variations in short-circuit current on buses 1–14 due to the addition of generator capacity on new buses connected to bus 2

Fault Location	The amount of additional generating capacity (MVA)				
	61,5	**123**	**184**	**246**	**307,5**
Bus 14	10.650	10.793	10.900	10.985	11.053
Bus 13	10.658	10.801	10.909	10.994	11.061
Bus 12	10.626	10.768	10.875	10.96	11.027
Bus 11	10.665	10.809	10.916	11.001	11.069
Bus 10	10.682	10.862	10.934	11.019	11.087
Bus 9	10.696	10.841	10.949	11.035	11.103
Bus 8	98.117	99.278	100.143	100.827	101.369
Bus 6	10.673	10.818	10.925	11.011	11.078
Bus 5	147.294	150.455	152.848	154.763	156.297
Bus 4	149.77	152.952	155.359	157.285	158.827
Bus 3	128.23	130.371	131.978	133.256	134.274
Bus 2	166.693	172.193	176.441	179.896	182.697
Bus 1	169.515	173.492	176.513	178.937	180.883

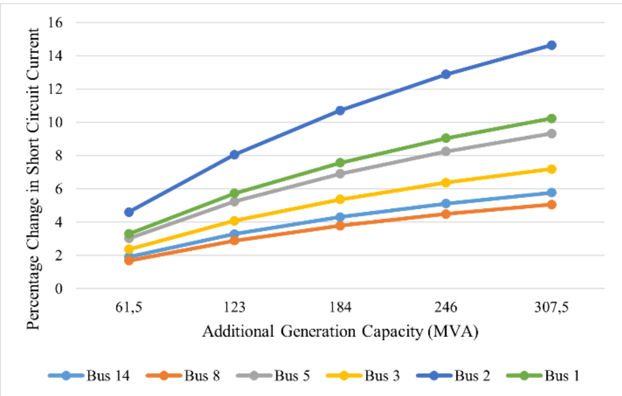

Figure 4. Percentage change in short circuit current on bus 1-14 when adding several variations of capacity generators on new buses connected to bus 2

Figure 4 shows the percentage change in short circuit current resulting from this addition. The trend of short circuit current changes as a function of generating capacity follows a straight line. In other words, as the added generating capacity increases, the percentage change in short circuit current also increases.

Discussion

In this study, a new generator is installed on an additional bus connected to an existing bus within the system. Including this new generator bus changes, the short-circuit current across the network. The study's findings reveal that, based on the analysis of short-circuit current variations, the most optimal location for placing the generator bus is an existing generator bus.

Previous studies have explored the impact of the location of new power plants on the power system. However, to date, no study has specifically examined the changes in short-circuit currents in the system when new power plants are added through new buses connected to existing buses within the system.

Research conducted by Daniel indicates that placing a power plant near a substation results in a smaller change in short-circuit current compared to positioning the plant further away from the substation [25]. Meanwhile, a study by Langlang on adding new generators to the distribution system shows that placing a distributed generator (DG) on a bus near the main generator causes a significant increase in short-circuit current during the subtransient period. This is due to the combined contribution of both the main generator and the DG to the fault current [26]. n another study, Langlang further explores DG placement and finds that the highest short-circuit current occurs at the bus closest to the main generator [27].

Another study that examined the influence of generator placement on changes in short-circuit current was conducted by Haymanot. His research found that placing distributed generators (DG) at weak points or farther from the main power source can increase the contribution of short-circuit current at those locations [28]. Meanwhile, a study by Saad revealed that DG installed closer to the fault point contributed a higher short-circuit current compared to DG placed farther from the fault point [29].

CONCLUSIONS

Incorporating electrical power network components, particularly generating units, leads to modifications in the network configuration, resulting in changes to both the power flow and short circuit current within the system. This paper presents an analysis and simulation to examine how short circuit current varies due to the addition of a generating bus to an existing bus within the system, using the IEEE 14-bus system as a test case. The analysis and simulation reveal that adding a generator bus to an existing bus increases short circuit levels at other buses, with varying percentages. For instance, when a generator with a capacity of 10% of the system rating is added to bus 2, the short circuit current increases from 1,685% to 4,601% compared to the previous state. When a generator with a capacity of 50% of the system rating is added, the increase ranges from 5,055% to 14,644% from the initial condition. These findings indicate that a larger increase in generating capacity results in a linear trend of changes in short circuit current across all other buses in the system. Furthermore, adding a generator to a new bus connected to an existing generator bus (PV bus) is more efficient than connecting it to a new bus linked to a load bus (PQ bus). This occurs because the change in short-circuit current is smaller when generators are added to new buses connected to PV buses than when they are added to new buses connected to PQ buses.

Future research could focus on comparing the changes in short-circuit currents in the electric power system when generators are added to new buses versus when they are added to existing buses.

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