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Modeling of IEEE 9-Bus System with Load Flow and Short Circuit Analyses

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Abstract:
Load Flow and Short Circuit Analyses have been performed on standard IEEE 9-Bus System. This paper is going to describe in detail how these analyses were performed and what results were achieved. In addition to the performance of these two analyses on the standard test system, they were also performed by removing a voltage- controlled generator from the test system. It is revealed that by removal of a generator, the magnitude of short- circuit fault current in a system would reduce as compared to the case where all generators were present in the system.

Keywords: *IEEE 9- Bus system, Load flow analysis, Short circuit (SC) analysis*

1. Introduction

Before installing a power system in the real world, many tests and analyses are digitally performed on computer simulations in order to determine the exact requirements and necessary precautions for the installation of the actual system. As we know that within power systems, electric power flows from the point of generation to the required destination via different paths of network. This flow comprises of reactive and active power known as load flow. It is very important to investigate this load flow so as to plan and determine the steady operation of system. Such investigations employs systematic analytical approaches so as to examine the different voltages on bus, phase angle, as well as reactive and active power that is flowing within various branches of load such as generators and transformers when steady state is attained.

The important knowledge gained from such analysis gives the absolute values as well as phase angles of load bus voltage reactive powers and voltage phase angles at generator buses, real and reactive power flows on transmission lines together with power at the reference bus. In addition to analytical techniques, numerical methods are also employed to solve load flow equations, as they become nonlinear and requires solution by method of iteration. However, such numerical solutions mostly provide only approximate solution. For more than thirty years different numerical investigations have been carried out to analyze power flow problems. Out of them widely used methods are Fast decoupled methods the Gauss-Seidel and Newton-Raphson and [1-4].

Moreover, due to sudden and mammoth developments in industry the society requires electric systems which keep on enhancing in size and complexity. In such systems the power flow equations range to several thousand with such magnitude of equations it is not feasible for any numerical technique to provide solution which converges. Such

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difficulty compels electrical engineers to resort to more suitable and reliable techniques. Hence the issue is that industry is looking for technique that is more feasible for the analysis of power systems

Analytical calculations are appropriate when estimation of characteristics of smaller magnitude of circuits is being carried out, however for the more precise and accurate analysis it is imperative to employ specialized programs.

Digital computers are being used in calculation s of power flow equations since 1950s. With the rapid advancement in computing power all sort of load flow studies can now be conveniently carried out.

Load Flow Analysis is one of such analyses. It is important for planning, economic scheduling, operation, and the distribution of power between different sources. It is also required for many other analyses such as transient stability and contingency studies. This analysis is also required to determine the effects of new loads and new generating stations on the power system, so that the system can be extended. This analysis involves finding voltages, currents, real and reactive power flows at different points in a power system under normal/steady-state conditions. [2, 3]

Short-Circuit analysis is mainly required for the protection of the power system and its equipment Sizing. It is performed on different buses under faulty conditions which can cause a short-circuit in the system. It involves finding the huge short- circuit current that flows in the system in the event of a fault. This analysis is also a major part of the system's protection coordination study, which involves the sizing and placement of protective equipment (fuses, circuit breakers, etc.) in the system, in order to protect the system. [4-6].

1.1. Bus Classification

Any node where more than one component like electric generators and transmission lines are connected is known as bus. In electrical engineering the bus is concerned with four quantities which include potential difference and its phase angle, active and reactive power. [11,12].

Out of them 02 quantities are already known whereas remaining two has to be determined via solution of equation [13].

1.2. Slack Bus

The slack bus is a sort of reference bus used to satisfy the condition of power balance. It is mostly concerned with generation unit which is adjusted to employ the power balance condition [12].

1.3. Generator (PV) Bus

Generator bus is essentially concerned with the voltage control. It is connected with generating unit where power generated from the bus is controlled with the help of prime mover. Whereas the control over voltage so produced is made by varying the generator excitation. Mostly the limits are set for reactive power and it depends on the specifications of machine used.

1.4. Load (PQ) Bus

The load bus is not due to generator but we can obtain this from old data, measurements or from forecast. In this case real power provided to the system is taken as positive, whereas the electric power utilized within system is taken as negative. In this bus P and Q are known variable while |V| and δ are unknown variables. [8, 12].

1.5. Power Flow Analysis Methods

From this analysis we mean investigation of various variables of electrical system such as voltage, current, active power etc at various points in a system, once the system has attained steady state.This is carried out by solving simultaneous equations. These solutions form the platform for solving equations for performance of power system [4]

1.6. Gauss-Seidel Method

This method is developed based on the Gauss method. It is an iterative method used for solving set of nonlinear algebraic equations [14]. The method makes use of an initial guess for value of voltage, to obtain a calculated value of a particular variable. The initial guess value is replaced by a calculated value. The process is then repeated until the iteration solution converges. The convergence is quite sensitive to the starting values assumed. But this method suffers from poor convergence characteristics [15].

1.7. Fast Decoupled Method

This method is considered as speedy and efficient for obtaining the solutions of problems pertaining to power flow. This method is basically an extension of Newton-Raphson method. This method was first presented in 1974 by Stott and Alsac in 1974 [16-18]. Since this method is based on Newton-Raphson method so it provides much simplification in carrying out calculations, also reliable results can be obtained, rapid convergence and this method soon became mostly employed method in power flow problems.

In this method polar coordinates and some approximations are used so fast algorithms for power solutions are obtained. However, the use of certain approximations also results in non-convergence in some cases. For instance, in case of large resistance-to-reactance ratios as well as for the case where low voltages appears at some buses. In such cases the solutions do not converge nicely due to approximations, so one has to resort some assumptions so as to simplify Jacobian Matrix.

To overcome these difficulties arising due to non convergence of solutions various investigations have been carried out. For instance one of them is co n- convergence of systems with high R/X ratios, and others with low voltage buses.

1.8. Newton-Raphson Method

Sir Isaac Newton and Raphson formulated this method so it is named after them. This method employs an iterative method. By using this method we can approximate non linear simultaneous equation into linear ones with the use Taylor series. However, Taylor series is expanded to the first order approximations only.

This numerical technique is widely used in the calculation of power flow due to its powerful convergence characteristics as compared with similar techniques.

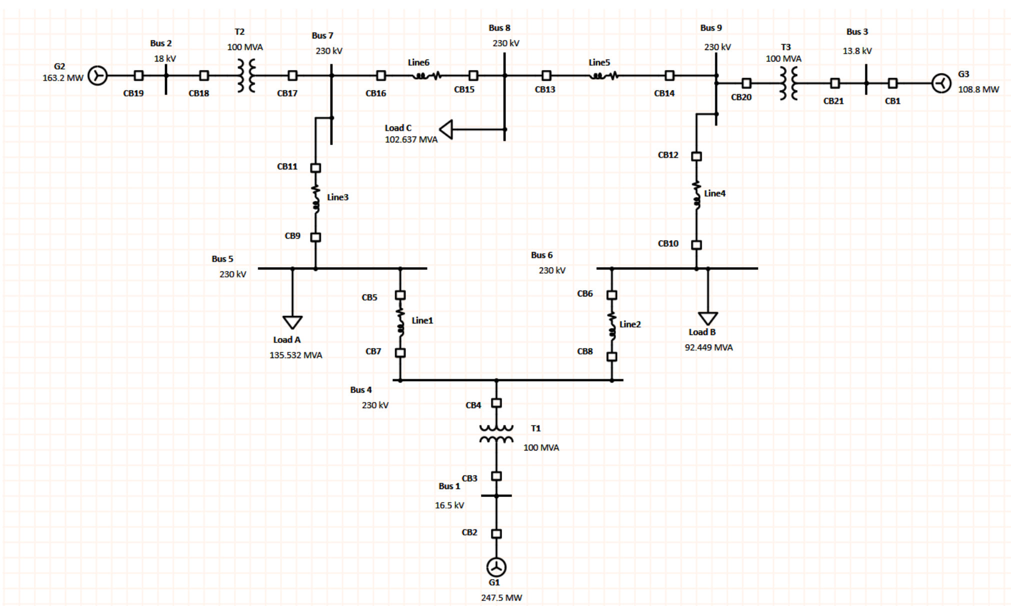

Fig. 1. IEEE 9-Bus System

2. Methodology

For this study, ETAP software has been used. The Load Flow and Short Circuit analyses are first performed on the standard IEEE 9-Bus system, and their results are recorded. The Load Flow has been evaluated by the software using Newton- Raphson iterative method. After this, one generator has been removed from this test system and the above mentioned two analyses are performed again. The results of these analyses on this new system are recorded and then compared with the results obtained from the standard system.

3. Test System Details

The test system for this study was the IEEE 9-Bus system. The SLD of this system is shown in figure-1. The system comprises of 3 generators, connected to 3 generator buses. These are buses 1, 2 and 3 respectively. After this, we have 3 step-up transformers, one after each generator bus, which step up the voltage to the transmission level. These transformers are connected to buses 4, 7 and 9 respectively. These buses are further connected to 3 load buses, namely buses 5, 6 and 8. The system has 1 swing generator operating at a voltage of 1.04p.u. and 2 voltage-controlled generators operating at a voltage of 1.025p.u. The system consists of 3 load buses interconnected through 6 transmission lines. The transmission lines are modeled with vertical configuration of conductors and a conductor spacing of 10ft, with a single ground wire. Gymnastic conductor is used. The loads are modeled with a requirement of 230kv and varying real and reactive powers. Also, circuit breakers are connected on each end of the transmission lines and generator buses for protection from overloading or faults.

The Load Flow and Short Circuit analyses are performed on this standard system first. After this, generator 3 is removed from the system, and then the above 2 analyses are repeated for this modified system and the results are compared.

4. Simulation and Discussion

In this section, we will describe the simulations performed in this study and discuss their results.

4.1. Load Flow Analysis on standard IEEE 9-Bus System

Bus	Voltage			Generation		Load		Load Flow				
ID	kV	% Mag	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF
*Bus 1	16.500	104.000	0.0	65.725	63.710	0.000	0.000	Bus 4	65.725	63.710	3079.7	71.8
*Bus 2	18.000	102.500	3.6	163.000	40.218	0.000	0.000	Bus 7	163.000	40.218	5253.7	97.1
*Bus 3	13.800	102.500	0.7	85.000	36.403	0.000	0.000	Bus 9	85.000	36.403	3774.2	91.9
Bus 4	230.000	100.534	-2.1	0.000	0.000	0.000	0.000	Bus 5	32.707	38.097	125.4	65.1
								Bus 6	33.014	21.151	97.9	84.2
								Bus 1	-65.721	-59.248	220.9	74.3
Bus 5	230.000	100.523	-2.1	0.000	0.000	127.160	50.855	Bus 4	-32.705	-38.153	125.5	65.1
								Bus 7	-94.455	-12.702	238.0	99.1
Bus 6	230.000	100.527	-2.1	0.000	0.000	88.631	29.544	Bus 4	-33.013	-21.209	98.0	84.1
								Bus 9	-55.618	-8.334	140.4	98.9
Bus 7	230.000	100.530	-2.1	0.000	0.000	0.000	0.000	Bus 5	94.459	12.662	238.0	99.1
								Bus 8	68.524	10.788	173.2	98.8
								Bus 2	-162.983	-23.450	411.2	99.0
Bus 8	230.000	100.524	-2.1	0.000	0.000	97.897	34.250	Bus 9	-29.375	-23.412	93.8	78.2
								Bus 7	-68.522	-10.838	173.2	98.8
Bus 9	230.000	100.531	-2.1	0.000	0.000	0.000	0.000	Bus 6	55.619	8.280	140.4	98.9
								Bus 8	29.376	23.354	93.7	78.3
								Bus 3	-84.995	-31.634	226.5	93.7

Fig. 2. Load Flow Report of IEEE 9-Bus System

As we have studied theoretically, the real power flows when there is a difference between the magnitudes of voltages between 2 buses, and reactive power flows when there is a difference between the voltage phase angles of 2 buses. This is proven here in the simulation as well, as we can see figure-2.

4.2. Short Circuit Analysis on standard IEEE 9-Bus System

Whenever a short-circuit fault occurs, it has 2 components: AC component and DC component. The AC component has further 3 stages; sub transient, transient and steady state. At the instance of fault occurrence, the sub transient current exists. It has the highest magnitude and the shortest time duration (0.5 cycles).

4.2.1. Sub-Transient

Sub transient current rapidly decreases to the transient stage. It is relatively longer (from 1.5 cycles to 4 cycles approx.). This transient current further reduces to the steady-state value, which occurs after about 30 cycles, and its magnitude is sustained throughout the rest of the fault. As shown in figure 3.

NOTE: The steady-state current mentioned in figure is still the fault current, as its magnitude is still many times greater than the nominal current.

1/2 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			'Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
Bus 1	16.500	1.903	-58.126	58.158	5.739	-76.221	76.436	55.589	3.208	55.682	-56.165	39.901	68.896
Bus 2	18.000	2.101	-53.339	53.381	4.504	-68.620	68.768	47.512	2.858	47.598	-49.166	42.253	64.828
Bus 3	13.800	2.009	-58.226	58.261	4.246	-74.556	74.677	51.843	2.730	51.915	-53.250	45.873	70.284

Fig. 3. Short Circuit Fault Sub-Transient Component

In the above-mentioned results, we can see the sub transient magnitudes of symmetrical and unsymmetrical fault currents (in kA) which flow through the 3 generator buses in the event of a fault. The current is highest during this stage as the generator's impedance is lowest here.

4.2.2. Transient

30 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			*Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
Bus 1	16.500	1.072	-44.505	44.518	4.431	-67.263	67.409	47.569	2.318	47.625	-45.094	32.785	55.752
Bus 2	18.000	1.073	-39.918	39.933	3.362	-59.997	60.091	40.522	2.015	40.572	-38.465	33.910	51.278
Bus 3	13.800	1.077	-45.140	45.153	3.268	-66.365	66.446	45.131	1.992	45.175	-43.012	37.841	57.289

Fig. 4. Short Circuit Fault Transient Component

Comparing the results of the sub transient and transient fault currents, we see that both of these are identical. This is due to the fact that ETAP calculates both these currents using the sub transient impedance values, but in reality, the impedances of both these currents are different, and therefore, there magnitudes are different as well. As shown in Figure 4

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4.2.3. Steady-State

30 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			*Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
Bus 1	16.500	1.072	-44.505	44.518	4.431	-67.263	67.409	47.569	2.318	47.625	-45.094	32.785	55.752
Bus 2	18.000	1.073	-39.918	39.933	3.362	-59.997	60.091	40.522	2.015	40.572	-38.465	33.910	51.278
Bus 3	13.800	1.077	-45.140	45.153	3.268	-66.365	66.446	45.131	1.992	45.175	-43.012	37.841	57.289

Fig. 5. Short Circuit Fault Steady State Component

Comparing the steady-state current values with the sub transient and transient current values, we can see that its magnitude is lower than the other two fault currents. This is because the impedance of the generator during the steady-state stage becomes equal to the synchronous reactance. The fault current will not decrease any further than this value. Load Flow Analysis on standard IEEE 9-Bus System after removing one PV Generator. As shown in figure 5.

The voltage-controlled generator maintains the voltage throughout the system. Removing it causes a voltage drop at all the buses (except the generator buses). The load supplied by this generator is now being fed by the remaining 2 generators. Therefore, the power flow at the remaining 2 generator buses increases.

4.3. Short Circuit Analysis on standard IEEE 9-Bus System after removing one PV Generator

The short-circuit analysis is repeated after removing one of the PV generators. We see that the magnitude of the overall fault current reduces, when compared to the original test system's fault current. This is due to the obvious fact that now there is one less generator to feed the fault. Shown in figure 6.

Bus		Voltage		Generation		Load		Load Flow				
ID	kV	% Mag	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF
*Bus 1	16.500	104.000	0.0	144.168	87.251	0.000	0.000	Bus 4	144.168	87.251	5669.7	85.6
*Bus 2	18.000	102.500	1.1	163.000	57.607	0.000	0.000	Bus 7	163.000	57.607	5409.9	94.3
Bus 4	230.000	99.480	-4.6	0.000	0.000	0.000	0.000	Bus 5	57.490	36.383	171.7	84.5
								Bus 6	86.663	35.745	236.6	92.4
								Bus 1	-144.153	-72.128	406.7	89.4
Bus 5	230.000	99.468	-4.6	0.000	0.000	124.507	49.794	Bus 4	-57.488	-36.432	171.8	84.5
								Bus 7	-67.019	-13.361	172.5	98.1
Bus 6	230.000	99.467	-4.6	0.000	0.000	86.773	28.924	Bus 4	-86.659	-35.783	236.6	92.4
								Bus 9	-0.114	6.859	17.3	-1.7
Bus 7	230.000	99.475	-4.6	0.000	0.000	0.000	0.000	Bus 5	67.021	13.312	172.4	98.1
								Bus 8	95.961	26.515	251.2	96.4
								Bus 2	-162.982	-39.828	423.4	97.1
Bus 8	230.000	99.464	-4.6	0.000	0.000	95.843	33.531	Bus 9	0.114	-6.980	17.6	-1.6
								Bus 7	-95.957	-26.551	251.3	96.4
Bus 9	230.000	99.465	-4.6	0.000	0.000	0.000	0.000	Bus 6	0.114	-6.920	17.5	-1.6
								Bus 8	-0.114	6.920	17.5	-1.6

Fig. 6. Short Circuit Analysis after Removing One PV Generator

4.3.1. Sub-Transient

when compared to the original test system's fault current. This is due to the obvious fact that now there is one less generator to feed the fault. As shown in figure 7.

1/2 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
Bus 1	16.500	1.775	-50.525	50.556	5.278	-68.754	68.957	48.888	3.013	48.981	-49.026	36.946	61.388
Bus 2	18.000	1.977	-46.802	46.844	4.260	-61.903	62.049	42.043	2.712	42.130	-43.360	39.040	58.345

Fig. 7. Short Circuit Fault Sub-Transient Component after Removing One PV Generator

4.3.2. Transient

Short circuit analysis of transient component on a 9-Bus system after removing one generator is shown in figure 8.

1.5-4 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
Bus 1	16.500	1.775	-50.525	50.556	5.278	-68.754	68.957	48.888	3.013	48.981	-49.026	36.946	61.388
Bus 2	18.000	1.977	-46.802	46.844	4.260	-61.903	62.049	42.043	2.712	42.130	-43.360	39.040	58.345

Fig. 8. Short Circuit Fault Transient Component after Removing One PV Generator

4.3.3. Steady-State

Short circuit analysis of the steady state component on a 9-Bus system after removal of a single generator is shown in figure 9.

30 Cycle - 3-Phase, LG, LL, & LLG Fault Currents

Prefault Voltage = 100 % of the Bus Nominal Voltage

Bus		3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			Line-to-Line-to-Ground		
ID	kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
Bus 1	16.500	0.972	-37.859	37.872	3.958	-59.730	59.861	41.205	2.122	41.260	-38.452	29.700	48.586
Bus 2	18.000	0.982	-34.213	34.227	3.092	-53.286	53.376	35.319	1.866	35.369	-33.060	30.597	45.046

Fig. 9. Short Circuit Fault Steady-State Component after Removing One PV Generator

4.4. Comparison of the system before and after removing the PV Bus

4.4.1. Load Flow Comparison

TABLE I. LOAD FLOW COMPARISON BEFORE AND AFTER REMOVING PV BUS

	Before removing PV Bus	After removing PV Bus
***Voltage magnitude at Bus 1**	104%	104%
***Voltage magnitude at Bus 2**	102.5%	102.5%
***Voltage magnitude at Bus 3**	102.5%	-
Voltage magnitude at Bus 4	100.534%	99.480%
Voltage magnitude at Bus 5	100.523%	99.468%
Voltage magnitude at Bus 6	100.527%	99.467%
Voltage magnitude at Bus 7	100.530%	99.475%
Voltage magnitude at Bus 8	100.524%	99.464%

Voltage magnitude at Bus 9	100.531%	99.465%

Here we can see that after removing the PV generator from bus 3, the voltages at all the buses (except the generator buses) drop, as has been discussed above. Shown in table-I

4.4.2. Short Circuit Comparison:

NOTE: The steady-state fault currents in the table II below are 3-phase fault currents. The results will remain same for other types of faults. Shown in table-II

TABLE II. SHORT CIRCUIT COMPARISON BEFORE AND AFTER REMOVING PV BUS

	Before removing PV Bus	**After removing PV Bus**
***Steady-State Current at Bus 1**	44.518kA	37.872kA
***Steady-State Current at Bus 2**	39.933kA	34.227kA
***Steady-State Current at Bus 3**	45.153kA	-

Here we can see that the fault current reduces after removing a PV generator from the system, as there is one less generator to feed the fault here, as has been discussed above as well.

5. Conclusion

In this paper a numerical study has been carried out for load flow and short circuit analysis on standard IEEE 9-bus system. From the above study we conclude that, by removal of a voltage-controlled generator from our system, the magnitude and phase angles of voltages will reduce for all the buses other than the remaining generator buses. Since this was a particularly small test system, the voltage drop was minimum and did not affect the system greatly. But, had it been a large practical system, then such a removal of a voltage-controlled generator would have damaging effects on the transmission system and can also damage the connected loads due to under-voltage. Moreover, it is also found that by removal of a generator, the magnitude of short- circuit fault current in a system would reduce as compared to the case where all generators were present in the system.

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