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# Line to Ground and Line to Line Fault Analysis in IEEE Standard 9 Bus System

Sagnik Datta[1], Aveek Chattopadhyaya[1], Surajit Chattopadhyay[2], Arabinda Das[3]

[1] Electrical Engineering Department, Supreme Knowledge Foundation Group of Institutions, Mankundu, India
[2] Electrical Engineering Department, GKCIET, Malda, India
[3] Electrical Engineering Department, Jadavpur University, Jadavpur, India

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**ABSTRACT**

Line to Ground (LG) and Line to Line (LL) faults are the two most frequently encountered faults in any power system network. For the purpose of designing advanced protection systems, detection of the location as well as the identification of the type of fault, from a remote location is of paramount importance. In this paper a Discrete Wavelet Transform based statistical analysis has been carried out to detect the fault type and location of LG and LL faults. IEEE standard 9 bus system has been considered for this purpose. Faults are made to occur in the load buses and outgoing currents from the generator buses are analyzed by Discrete Wavelet Transform (DWT) as these current waveforms are non-stationary in nature. Statistical parameters are calculated from the approximate and detail coefficients which have been derived from the DWT. Based upon these parameters, a rule set has also been made. Simulation work is performed with the help of MATLAB. Methods proposed here can be helpful for designing better protection schemes.

## 1. INTRODUCTION

Electrical power system network consisting of several sources and loads helps in transfer of power from generating stations to consumers. Complexity in all the sectors of power system is increasing. Thus, for reliable operation of power system networks, proper identification of type and location of fault has become very much important. Two most frequently occurring faults in any power system network are line to ground (LG) and line to Line (LL) faults. A lot a research work is being carried out in the field of fault identification of power system networks. Elkalashy et al. [1] proposed a novel selectivity technique to detect the fault feeder in MV networks using the directionality of DWT detail coefficient of a residual current of each feeder. Wavelet transformation is used to analyze power system transients for identification of fault locations in double circuit transmission lines by Andanapalli et al. [2]. Dubeya et al. [3] proposed DWT and Independent component analysis (ICA) for detection of faulty negative sequence current in series compensated transmission line using Matlab or Simulink. Xie et al. [4] proposed a Wavelet transform based methods of measuring time and frequency information of high frequency transients produced by the faults on transmission lines for the purpose of locating the fault point. A relaying principle using Wavelet based artificial neural networks capable of classifying transients–including faults occurring on a protected line has been shown by Abdullah [5]. Devi et al. [6] has proposed a method of analysis of faults with different load conditions for localization, detection and classification of faults in transmission lines. Patel et al. proposed a novel technique or fault detection in high voltage transmission line using the wavelet transform during power swing condition [7, 8]. A method for identification of Line to Ground Fault in a standalone Wind Energy Conversion System using multi-resolution based DWT analysis has been proposed by Ray et al. [9]. Mishra et al. [10] proposed an improved method of transmission line fault classification using Wavelet Transform as well as impedance measurement and travelling wave theory. Chattopadhayay et al. [11] detected crawling of an induction motor by performing Wavelet decomposition of the stator current in Clarke Plane. Power Quality related different parameters have been assessed in Parke Plane by Chattopadhayay et al. [12]. Current Park Vector pattern approach is used for detection of electrical faults in an induction motor by S. Chattopadhyay et al. [13-15].

## 2. IEEE STANDARD 9 BUS SYSTEM

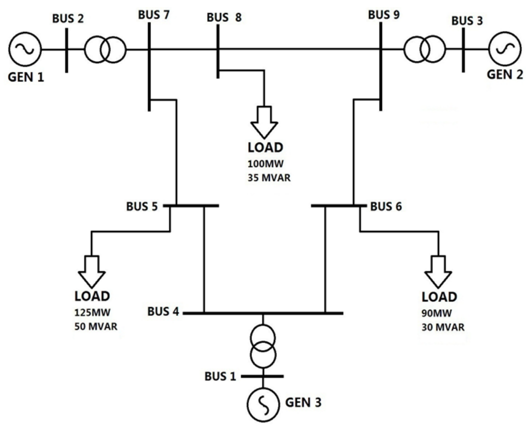



**Figure 1.** IEEE standard 9 Bus system

Single line diagram of IEEE standard 9 bus system is shown below in Figure 1. The power system network consists of three generators, generator 1, 2 and 3 connected to bus 1, 2 and 3 respectively. It also has three load buses–Bus 5, 6 and 8.

Voltage and current rating of generator 1, 2 and 3 are 247.5

MW and 16.5 kV; 192 MVA and 18 kV; 126 MVA and 13.8 kV respectively. The rating of the load connected to bus 5, 6 and 7 are 125 MW and 50 MVAR; 90 MW and 30 MVAR; 100 MW and 35 MVAR respectively. Work presented here, attempts to identify type of fault as well as location of LG and LL fault DWT based statistical parameter analysis of the waveforms of outgoing currents from different generator buses in faulty conditions. The faults are made to occur at the load buses. However, the work may be extended to other type of faults taking place at other locations of the network also.

## 3. FAULT SIMULATION

DWT based statistical parameter analysis of the outgoing currents from the generator buses in healthy as well as faulty conditions have been performed to detect type of the fault and its location. LG and LL faults are made to occur in the load buses. Switching time of faults is set to 0.3-0.5 sec. The sampling frequency is taken to be 1000 Hz and total time of simulation is 0.8 sec. Very small total simulation time has been chosen to minimize the data size generated by the simulation software and computation time of the analysis process.

## 4. RESULTS AND OBSERVATION

DWT based decomposition of the generator bus outgoing currents are performed and approximate and detail coefficients and the process is carried out for both healthy and faulty conditions. Nine levels of decomposition of the current waveforms have been performed. After obtaining approximate and details coefficients in each level RMS, skewness and kurtosis values are computed. Hence, total six parameters are taken into account–skewness of approximate coefficient (Sa), skewness of detail coefficient (Sd), kurtosis of approximate coefficient (Ka), kurtosis of detail coefficient (Kd), RMS of approximate coefficient (RMSa) and RMS of detail coefficient (RMSd). In the entire DWT analysis, Daubechies4 (DB4) wavelet is considered as the mother wavelet. Each generator bus outgoing current is analyzed separately. Percentage deviation of all the above mentioned parameters are calculated from their corresponding healthy condition values are calculated using equation 1 shown below. So, in a healthy case the percentage deviations of the above mentioned parameters will be zero.

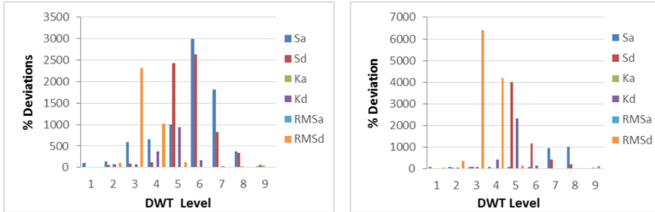
$$\%\ \text{Deviation} = \left|\frac{(\text{Healthy value}) - (\text{Faulty value})}{\text{Healthy value}}\right| \times 100 \qquad (1)$$

Results and the corresponding observations are presented below for all three generator buses one by one.

### 4.1 Observation from generator Bus 1

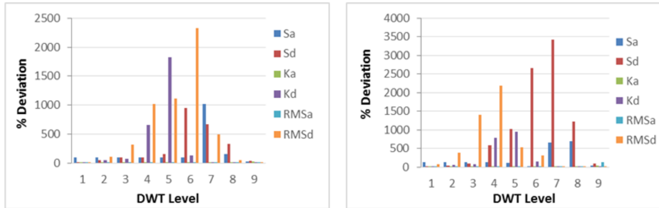
Percentage deviations of Sa, Sd, Ka, Kd, RMSa and RMSd are calculated and shown in Table A.1–A.6 (Appendix). Data given in the earlier mentioned tables have been presented in the form of graphs in Figures 2-4.

From Figure 2(a) it has been noticed that when LG fault occurs at Bus 5, percentage deviation of Sa at 6$^{th}$ level of decomposition is the greatest amongst all the parameters in all the levels. Figure 2(b) shows that for LL fault at Bus 5, greatest amount of percentage deviation occurs in RMSd at level 3.




2(a) 2(b)

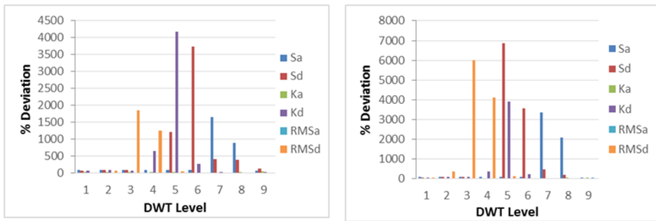
**Figure 2.** Percentage deviation of different parameters of GEN Bus 1 for (a) LG fault at Bus 5 and (b) LL fault at Bus 5




3(a) 3(b)

**Figure 3.** Percentage Deviation of different parameters of GEN Bus 1 for (a) LG fault at Bus 6 and (b) LL fault at Bus 6

From Figure 3(a) shows that percentage deviation of RMSd at level 6 is the greatest when LG fault takes place at Bus 6. Figure 3(b) shows that for LL fault at Bus 6, percentage deviation of Sd at 7$^{th}$ level of decompositions becomes the greatest amongst all the parameters in all the levels.




4(a) 4(b)

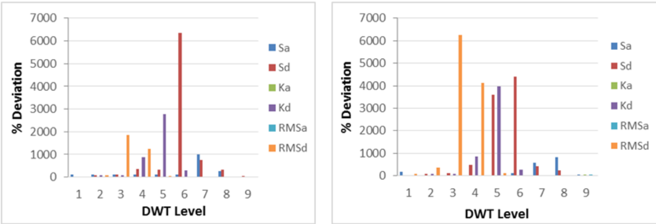
**Figure 4.** Percentage deviation of different parameters of GEN Bus 1 for (a) LG fault at Bus 8 and (b) LL fault at Bus 8

From Figure 4 (a) shows that when LG fault occurs at Bus 8, percentage deviation of Kd at level 5 is the greatest amongst all the parameters. Figure 4(b) suggests that for LL fault at Bus 8, greatest amount of percentage deviation occurs in Sd at level 5.

### 4.2 Observation from generator Bus 2

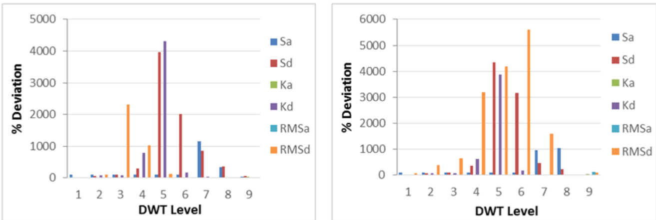
Percentage deviations of RMS, skewness and kurtosis of approximate and detail coefficients are calculated and shown in Table A.7–A.12 (Appendix). Data given in these tables have been presented in the form of graphs in Figures 5-7.

From Figure 5(a) it has been seen that greatest amount of percentage deviation takes place in Sd at level 6 when LG fault occurs at Bus 5. Whereas, Figure 5(b) shows that RMSd has the greatest amount of percentage deviation at level 3 when LL fault takes place at Bus 5.




5(a) 5(b)

**Figure 5.** Percentage deviation of different parameters of GEN Bus 2 for (a) LG fault at Bus 5 and (b) LL fault at Bus 5

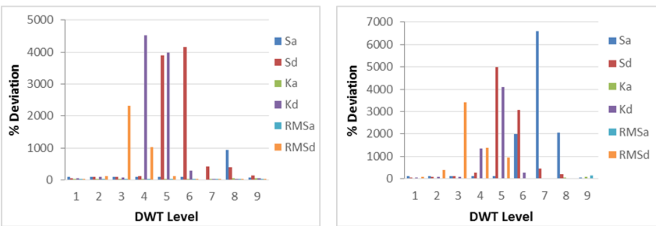



6(a) 6(b)

**Figure 6.** Percentage deviation of different parameters of GEN Bus 2 for (a) LG fault at Bus 6 and (b) LL fault at Bus 6

Figure 6(a) suggests that when LG fault takes place at bus 6, parameter Kd has the greatest amount of percentage deviation at level 5. Whereas, it has been observed from Figure 6(b) that for occurrence of LL fault at Bus 6, RMSd has the greatest amount of deviation at level 6.

Same procedure has been followed in case of LG and LL fault in Bus 8. In case of LG fault at Bus 8; Figure 7(a) given below, shows that the greatest amount of deviation is present in Kd at level 4. Figure 7(b) shown below suggests that for LL fault at Bus 8, Sa has the greatest amount of deviation is present in level 7.




7(a) 7(b)

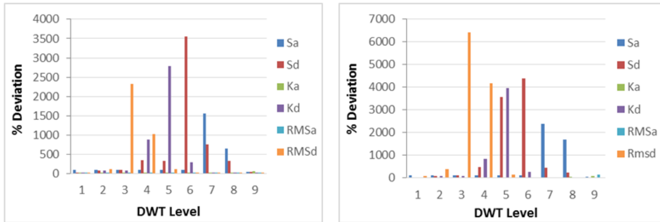
**Figure 7.** Percentage deviation of different parameters of GEN Bus 2 for (a) LG fault at Bus 8 and (b) LL fault at Bus 8

### 4.3 Observation from generator Bus 3

Percentage deviations of RMS, skewness and kurtosis of approximate and detail coefficients are calculated and shown in Table A.13–A.18 (Appendix). Data given in these tables have been presented in the form of graphs in Figures 8-10.

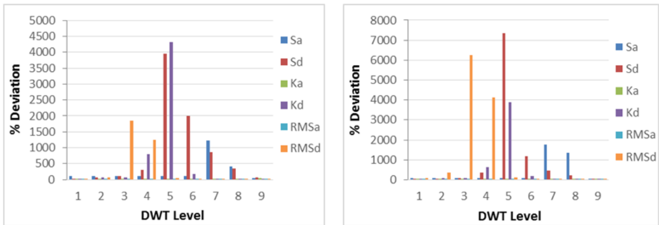
From 8(a), it can be observed that greatest amount of deviation is present in parameter Sd at level 6, when LG fault occurs at Bus 5. Whereas, Figure 8(b) shows that for LL fault at Bus 8, the amount of percentage deviation is greatest in RMSd at level 3.

Same procedure is followed for LG and LL fault at bus 6 and the graphs are shown in Figure 9(a) and 9(b), which are presented below. From Figure 9(a) it has been seen that for occurrence of LG fault at Bus 6 greatest amount of percentage deviation is present in Kd at level 5. Whereas, Figure 9(b) shows that for LL fault at Bus 6, Sd has the greatest amount of deviation at level 5.




8(a) 8(b)

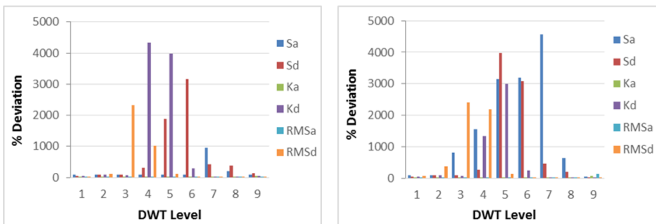
**Figure 8.** Percentage Deviation of different parameters of GEN Bus 3 for (a) LG fault at Bus 5 and (b) LL fault at Bus 5




9(a) 9(b)

**Figure 9.**

Graphical representations of the results for LG and LL faults at Bus 8 have been presented below in Figure 10(a) and 10(b).




10(a) 10(b)

**Figure 10.** Percentage deviation of different parameters of GEN Bus 3 for (a) LG fault at Bus 8 and (b) LL fault at Bus 8

From Figure 10(a) it has been observed that when LG fault occurs at Bus 8, percentage deviation of Kd at level 4 is the greatest. Whereas, the percentage deviation of Sa at level 6 is the greatest when LL fault takes place at Bus 8.

From the above discussion it can be observed that for a particular generator bus outgoing current, with the variation of type of fault and location of occurrence, parameter having the greatest amount of percentage deviation and the level at which it takes place changes. For a particular fault type and location one specific parameter possesses the greatest amount of deviation at a specific level of decomposition. Hence, by identifying the parameter and the level at which it has the greatest amount of deviation, location as well as the type of fault can be found out. It can also be seen that out of six parameters, four parameters turned out to be useful for fault analysis. These parameters are Sa, Sd, Kd, RMSd. Moreover, values of these parameters at five different levels–3, 4, 5, 6, 7 are used.

## 5. RULE SET

Based upon the observations made in the previous section a simple rule set has been prepared which can be used for discriminating the fault type and identifying the fault location by monitoring the outgoing current of any generator bus. It is presented in the Table 1 shown below.

**Table 1.** Rule set

| Fault Type | Fault Location | Generator Bus used for observation | | | | | |
|---|---|---|---|---|---|---|---|
| | | GEN Bus 1 | | GEN Bus 2 | | GEN Bus 3 | |
| | | Parameter with greatest % deviation | Level of occurrence | Parameter with greatest % deviation | Level of occurrence | Parameter with greatest % deviation | Level of occurrence |
| LG | Bus 5 | Sa | 6 | Sd | 6 | Sd | 6 |
| | Bus 6 | RMSd | 6 | Kd | 5 | Kd | 5 |
| | Bus 8 | Kd | 5 | Kd | 4 | Kd | 4 |
| LL | Bus 5 | RMSd | 3 | RMSd | 3 | RMSd | 3 |
| | Bus 6 | Sd | 7 | RMSd | 6 | Sd | 5 |
| | Bus 8 | Sd | 5 | Sa | 7 | Sa | 6 |

## 6. CASE STUDIES AND VALIDATION

As real verification is practically impossible, the rule set presented in the previous section has been validated by simulating faults in IEEE standard 9 bus system. Three unknown cases are considered where the total time of simulation, fault duration time as well as the prefault condition of the loads have been varied. Results of the case studies have been given below in Table 2.

From Table 2 it has been observed that results in every case are very much optimistic.

**Table 2.** Details of the case studies

| Sl. No. | Known Facts | | Observation from Bus | Parameter with greatest % deviation | Level of occurrence | Inference |
|---|---|---|---|---|---|---|
| | Simulation Details | Pre-fault Condition | | | | |
| 1 | Total simulation time 1 sec and fault duration 0.3–0.5 sec | Full load at Bus 5, 6 & 8 | GEN Bus 1 | Kd | 5 | LG at Bus 8 |
| | | | GEN Bus 2 | Kd | 4 | |
| | | | GEN Bus 3 | Kd | 4 | |
| 2 | Total simulation time 1.2 sec and fault duration 0.4–0.7 sec | Full load at Bus 5, 6 & No load at Bus 8 | GEN Bus 1 | Sd | 7 | LL at Bus 6 |
| | | | GEN Bus 2 | RMSd | 6 | |
| | | | GEN Bus 3 | Sd | 5 | |
| 3 | Total simulation time 1.5 sec and fault duration 0.6–0.9 sec | Full load at Bus 5, 8 & Half load at Bus 6 | GEN Bus 1 | RMSd | 3 | LL at Bus 5 |
| | | | GEN Bus 2 | RMSd | 3 | |
| | | | GEN Bus 3 | RMSd | 3 | |

## 7. SPECIFIC OUTCOME

The work presented here, shows a method of finding out fault type and location based upon a DWT based statistical parameter analysis of outgoing currents from the generator buses. Six different parameters are obtained for each generator bus outgoing currents in different conditions. Observation of the parameter having the greatest amount of percentage deviation from its corresponding healthy condition values and the level of occurrence reveals the type of fault and the location at which it takes place. A rule set has been prepared depending upon the observations and it has also been validated using three unknown cases where different simulation time, fault duration and load condition are used than that used for the analysis and preparation of the rule set. Results of the case studies have been found out to be very much satisfactory.

## 8. CONCLUSION

In the above work, LG and LL faults have been dealt with using DWT based statistical analysis of the outgoing currents from the generator buses and faults are considered at the load buses. Total six parameters are considered-skewness of approximate coefficient, skewness of detail coefficient, kurtosis of approximate coefficient, kurtosis of detail coefficient, RMS of approximate coefficient and RMS of detail coefficient. IEEE standard 9 bus system has been utilized for this purpose. Using the method proposed here, type and location of a fault can be found out by monitoring the outgoing currents from the generator buses. Present work only considers two types of faults and fault locations to be the load buses. However, this work can be extended for other type of faults occurring at locations other than load buses.

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## APPENDIX

**Table A.1** Percentage deviation of different parameters of GEN Bus 1 outgoing currents for LG fault at Bus 5

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 15.211 | 13.993 | 19.774 | 5.2 | 15.726 |
| 2 | 133.999 | 66.766 | 13.993 | 76.494 | 5.2 | 109.051 |
| 3 | 589.999 | 92.979 | 13.993 | 81.534 | 5.2 | 2323.788 |
| 4 | 655.999 | 119.936 | 13.993 | 379.765 | 5.2 | 1021.738 |
| 5 | 999.815 | 2429.487 | 13.993 | 933.977 | 5.2 | 115.739 |
| 6 | 2999.999 | 2640.625 | 13.866 | 170.576 | 5.198 | 9.653 |
| 7 | 1820 | 828.333 | 14.241 | 32.614 | 5.24 | 4.663 |
| 8 | 379.262 | 346.666 | 23.907 | 12.247 | 6.733 | 5.04 |
| 9 | 32.409 | 55.335 | 37.6197 | 20.721 | 14.078 | 5.945 |

**Table A.2** Percentage deviation of different parameters of GEN Bus 1 outgoing currents for LL fault at Bus 5

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 15.211 | 13.993 | 19.774 | 5.2 | 15.726 |
| 2 | 100 | 66.766 | 13.993 | 76.494 | 5.2 | 109.051 |
| 3 | 100 | 92.979 | 13.993 | 81.534 | 5.2 | 2323.788 |
| 4 | 100 | 119.936 | 13.993 | 379.765 | 5.2 | 1021.738 |
| 5 | 100 | 2429.487 | 13.993 | 933.977 | 5.2 | 115.739 |
| 6 | 100 | 2640.625 | 13.866 | 170.576 | 5.198 | 9.653 |
| 7 | 970 | 828.333 | 14.241 | 32.614 | 5.24 | 4.663 |
| 8 | 1035.023 | 346.666 | 23.907 | 12.247 | 6.733 | 5.04 |
| 9 | 32.124 | 55.335 | 37.619 | 20.721 | 14.078 | 5.945 |

**Table A.3** Percentage deviation of different parameters of GEN Bus 1 outgoing currents for LG fault at Bus 6

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 6.485 | 6.1 | 8.5 | 5.2 | 15.726 |
| 2 | 99.999 | 46.783 | 6.1 | 56.007 | 5.2 | 109.051 |
| 3 | 99.999 | 98.876 | 6.1 | 69.347 | 5.2 | 323.788 |
| 4 | 99.999 | 96.056 | 6.1 | 655.622 | 5.209 | 1021.738 |
| 5 | 99.999 | 155.128 | 6.093 | 1822.703 | 5.2 | 1115.739 |
| 6 | 99.999 | 946.875 | 5.990 | 137.063 | 5.198 | 2323.788 |
| 7 | 1023.333 | 670 | 6.277 | 21.134 | 5.24 | 499.663 |
| 8 | 159.447 | 333.333 | 13.9 | 5.392 | 6.733 | 56.04 |
| 9 | 22.005 | 41.006 | 25.187 | 11.78 | 14.07 | 5.945 |

**Table A.4** Percentage deviation of different parameters of GEN Bus 1 outgoing currents for LL fault at Bus 6

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 126.422 | 6.616 | 2.693 | 8.592 | 3.239 | 74.211 |
| 2 | 126.434 | 47.653 | 2.693 | 56.963 | 3.239 | 381.496 |
| 3 | 126.295 | 100.057 | 2.693 | 73.117 | 3.239 | 1408.286 |
| 4 | 126.116 | 582.984 | 2.693 | 788.769 | 3.240 | 2191.527 |
| 5 | 122.777 | 1029.487 | 2.693 | 956.976 | 3.241 | 539.941 |
| 6 | 33.676 | 2657.812 | 2.598 | 157.387 | 3.243 | 322.737 |
| 7 | 656.666 | 3427.5 | 1.988 | 1.738 | 3.125 | 5.418 |
| 8 | 696.774 | 1230.476 | 17.667 | 0.546 | 8.089 | 4.581 |
| 9 | 35.707 | 93.048 | 52.672 | 5.445 | 130.512 | 6.911 |

**Table A.5** Percentage deviation of different parameters of GEN Bus 1 outgoing currents for LG fault at Bus 8

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 73.891 | 28.326 | 82.418 | 0.834 | 8.696 |
| 2 | 100 | 97.458 | 28.326 | 96.078 | 0.834 | 72.833 |
| 3 | 100 | 97.45 | 28.326 | 82.215 | 0.834 | 1849.149 |
| 4 | 100 | 2.02 | 28.32 | 666.465 | 0.834 | 1258.423 |
| 5 | 100 | 1211.538 | 28.32 | 4183.274 | 0.834 | 55.165 |
| 6 | 100 | 3746.875 | 28.153 | 279.911 | 0.835 | 0.265 |
| 7 | 1653.333 | 426.666 | 27.557 | 30.129 | 0.815 | 1.211 |
| 8 | 897.695 | 397.142 | 47.998 | 23.852 | 0.497 | 0.851 |
| 9 | 70.233 | 141.92 | 59.5433 | 46.231 | 3.758 | 0.789 |

**Table A.6** Percentage deviation of different parameters of GEN Bus 1 outgoing currents for LL fault at Bus 8

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100.001 | 63.067 | 15.64 | 72.928 | 6.908 | 70.302 |
| 2 | 100.001 | 96.476 | 15.64 | 96.027 | 6.908 | 368.089 |
| 3 | 100.001 | 97.781 | 15.64 | 81.741 | 6.908 | 6007.505 |
| 4 | 100.001 | 36.246 | 15.633 | 362.521 | 6.909 | 4125.426 |
| 5 | 100.001 | 6867.094 | 15.626 | 3910.138 | 6.909 | 123.891 |
| 6 | 100.001 | 3581.25 | 15.5194 | 229.469 | 6.91 | 6.233 |
| 7 | 3373.333 | 459.166 | 12.548 | 2.144 | 6.873 | 7.818 |
| 8 | 2081.566 | 190.476 | 52.742 | 0.078 | 3.065 | 7.331 |
| 9 | 49.998 | 23.475 | 76.8148 | 3.3026 | 63.272 | 9.51 |

**Table A.7** Percentage deviation of different parameters of GEN Bus 2 outgoing currents for LG fault at Bus 5

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 15.693 | 7.92 | 20.23 | 0.834 | 8.696 |
| 2 | 99.999 | 72.465 | 7.92 | 80.349 | 0.834 | 72.833 |
| 3 | 99.999 | 99.852 | 7.92 | 71.922 | 0.834 | 1849.149 |
| 4 | 99.999 | 343.809 | 7.92 | 880.028 | 0.834 | 1258.423 |
| 5 | 99.999 | 327.444 | 7.92 | 2787.337 | 0.834 | 55.165 |
| 6 | 99.999 | 6348.437 | 7.756 | 293.552 | 0.835 | 0.265 |
| 7 | 1012.903 | 764.406 | 8.118 | 26.072 | 0.815 | 1.211 |
| 8 | 255.825 | 333.018 | 16.302 | 6.932 | 0.497 | 0.851 |
| 9 | 24.009 | 46.165 | 28.486 | 14.008 | 3.758 | 0.789 |

**Table A.8** Percentage deviation of different parameters of GEN Bus 2 outgoing currents for LL fault at Bus 5

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 176.14 | 16.054 | 3.646 | 20.501 | 6.908 | 70.301 |
| 2 | 23.843 | 73.674 | 3.646 | 81.75 | 6.908 | 368.089 |
| 3 | 24.191 | 99.969 | 3.646 | 79.684 | 6.908 | 6247.505 |
| 4 | 23.548 | 469.85 | 3.646 | 838.199 | 6.909 | 4125.426 |
| 5 | 17.236 | 3584.858 | 3.646 | 3973.585 | 6.909 | 123.891 |
| 6 | 99.999 | 4396.875 | 3.511 | 277.772 | 6.91 | 6.233 |
| 7 | 570.967 | 433.898 | 2.098 | 1.541 | 6.873 | 7.818 |
| 8 | 810.194 | 229.245 | 23.07 | 0.346 | 3.065 | 7.331 |
| 9 | 41.975 | 4.294 | 56.409 | 5.066 | 63.272 | 9.51 |

**Table A.9** Percentage deviation of different parameters of GEN Bus 2 outgoing currents for LG fault at Bus 6

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 13.691 | 16.14 | 17.893 | 5.2 | 15.726 |
| 2 | 99.998 | 62.987 | 16.14 | 73.073 | 5.2 | 109.051 |
| 3 | 99.999 | 100.156 | 16.14 | 75.927 | 5.2 | 2323.788 |
| 4 | 99.999 | 297.571 | 16.14 | 789.527 | 5.2 | 1021.738 |
| 5 | 99.999 | 3963.722 | 16.133 | 4319.746 | 5.2 | 115.739 |
| 6 | 99.999 | 2007.812 | 14.833 | 177.63 | 5.198 | 9.653 |
| 7 | 1158.064 | 851.694 | 15.156 | 34.101 | 5.24 | 4.663 |
| 8 | 343.689 | 356.603 | 25.814 | 13.13 | 6.733 | 5.04 |
| 9 | 34.934 | 57.3619 | 38.959 | 22.188 | 14.07 | 5.945 |

**Table A.10** Percentage deviation of different parameters of GEN Bus 2 outgoing currents for LL fault at Bus 6

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.997 | 13.71 | 3.886 | 17.945 | 3.239 | 74.211 |
| 2 | 100 | 63.02 | 3.886 | 72.967 | 3.239 | 381.496 |
| 3 | 100 | 100.252 | 3.886 | 82.423 | 3.239 | 640.286 |
| 4 | 100 | 347.534 | 3.886 | 618.437 | 3.24 | 3191.527 |
| 5 | 100 | 4356.782 | 3.886 | 3879.476 | 3.241 | 4191.527 |
| 6 | 100 | 3170.312 | 3.778 | 179.494 | 3.243 | 5608.286 |
| 7 | 970.967 | 454.237 | 2.748 | 1.162 | 3.125 | 1595.418 |
| 8 | 1038.834 | 223.584 | 27.812 | 0.53 | 8.089 | 4.5817 |
| 9 | 28.497 | 9.815 | 53.081 | 4.055 | 130.512 | 96.911 |

**Table A.11** Percentage deviation of different parameters of GEN Bus 2 outgoing currents for LG fault at Bus 8

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 40.078 | 24.780 | 49.328 | 5.2 | 15.726 |
| 2 | 100 | 89.154 | 24.78 | 92.201 | 5.2 | 109.051 |
| 3 | 100 | 98.293 | 24.78 | 71.016 | 5.2 | 2323.788 |
| 4 | 100 | 124.488 | 24.78 | 4514.134 | 5.2 | 1021.738 |
| 5 | 100 | 3890.536 | 24.746 | 3989.139 | 5.2 | 115.739 |
| 6 | 100 | 4165.625 | 24.601 | 288.689 | 5.1981 | 9.653 |
| 7 | 100 | 422.033 | 24.059 | 26.505 | 5.24 | 4.663 |
| 8 | 924.757 | 388.679 | 44.081 | 20.735 | 6.733 | 5.04 |
| 9 | 68.129 | 134.049 | 58.732 | 42.242 | 14.07 | 5.945 |

**Table A.12** Percentage deviation of different parameters of GEN Bus 2 outgoing currents for LL fault at Bus 8

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 35.081 | 14.6 | 43.699 | 3.239 | 74.211 |
| 2 | 100 | 87.018 | 14.6 | 90.932 | 3.239 | 381.496 |
| 3 | 100 | 100.185 | 14.6 | 71.781 | 3.239 | 3408.286 |
| 4 | 100 | 253.926 | 14.6 | 1335.055 | 3.24 | 1391.527 |
| 5 | 100 | 4980.126 | 14.586 | 4084.586 | 3.241 | 939.941 |
| 6 | 1980.001 | 3089.0625 | 14.479 | 252.857 | 3.243 | 0.737 |
| 7 | 6583.87 | 457.627 | 11.621 | 1.749 | 3.125 | 5.418 |
| 8 | 2050.485 | 195.283 | 50 | 0.357 | 8.089 | 4.581 |
| 9 | 50.942 | 18.404 | 77.441 | 3.0815 | 130.512 | 6.911 |

**Table A.13** Percentage deviation of different parameters of GEN Bus 3 outgoing currents for LG fault at Bus 5

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 15.693 | 23.04 | 20.2305 | 5.2 | 15.726 |
| 2 | 100 | 72.464 | 23.04 | 80.349 | 5.2 | 109.051 |
| 3 | 100 | 99.852 | 23.04 | 71.922 | 5.2 | 2323.788 |
| 4 | 100 | 343.809 | 23.04 | 880.028 | 5.2 | 1021.738 |
| 5 | 100 | 327.444 | 23.04 | 2787.337 | 5.2 | 115.739 |
| 6 | 100 | 3548.437 | 22.975 | 293.552 | 5.198 | 9.653 |
| 7 | 1558.62 | 764.406 | 23.346 | 26.072 | 5.24 | 4.663 |
| 8 | 657.758 | 333.018 | 33.932 | 6.932 | 6.733 | 5.04 |
| 9 | 47.09 | 46.165 | 54.88 | 14.008 | 14.07 | 5.945 |

**Table A.14** Percentage deviation of different parameters of GEN Bus 3 outgoing currents for LL fault at Bus 5

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 16.054 | 12.053 | 20.501 | 3.239 | 74.211 |
| 2 | 100 | 73.6748 | 12.053 | 81.75 | 3.239 | 381.496 |
| 3 | 100 | 99.969 | 12.053 | 79.684 | 3.239 | 6408.286 |
| 4 | 100 | 469.85 | 12.053 | 838.199 | 3.24 | 4191.527 |
| 5 | 100 | 3584.858 | 12.046 | 3973.585 | 3.241 | 139.941 |
| 6 | 100 | 4396.875 | 11.941 | 277.772 | 3.243 | 0.737 |
| 7 | 2396.551 | 433.898 | 9.418 | 1.541 | 3.125 | 5.418 |
| 8 | 1694.827 | 229.245 | 49.472 | 0.346 | 8.089 | 4.581 |
| 9 | 45.573 | 4.294 | 72.48 | 5.066 | 130.512 | 6.911 |

**Table A.15** Percentage deviation of different parameters of GEN Bus 3 outgoing currents for LG fault at Bus 6

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 13.691 | 19.173 | 17.893 | 0.834 | 8.696 |
| 2 | 99.999 | 62.987 | 19.173 | 73.073 | 0.834 | 72.833 |
| 3 | 99.999 | 100.156 | 19.173 | 75.927 | 0.834 | 1849.149 |
| 4 | 99.999 | 297.571 | 19.173 | 789.527 | 0.834 | 1258.423 |
| 5 | 99.999 | 3963.722 | 19.180 | 4319.746 | 0.834 | 55.165 |
| 6 | 99.999 | 2007.812 | 29.772 | 177.63 | 0.835 | 0.265 |
| 7 | 1217.241 | 851.694 | 9.651 | 34.101 | 0.815 | 1.211 |
| 8 | 412.5 | 356.603 | 29.803 | 13.13 | 0.497 | 0.851 |
| 9 | 42 | 57.361 | 46.982 | 22.332 | 3.758 | 0.789 |

**Table A.16** Percentage deviation of different parameters of GEN Bus 3 outgoing currents for LL fault at Bus 6

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 100 | 13.710 | 7.2 | 17.945 | 6.908 | 70.301 |
| 2 | 100 | 63.020 | 7.2 | 72.967 | 6.908 | 368.089 |
| 3 | 100 | 100.252 | 7.2 | 82.423 | 6.908 | 6247.505 |
| 4 | 100 | 347.534 | 7.2 | 618.437 | 6.909 | 4125.426 |
| 5 | 100 | 7356.782 | 7.193 | 3879.476 | 6.909 | 123.891 |
| 6 | 100 | 1170.312 | 7.11 | 179.494 | 6.9103 | 6.233 |
| 7 | 1755.172 | 454.237 | 5.313 | 1.162 | 6.873 | 7.818 |
| 8 | 1338.793 | 223.584 | 40.259 | 0.53 | 3.065 | 7.331 |
| 9 | 34.241 | 9.815 | 60.588 | 4.055 | 63.272 | 9.51 |

**Table A.17** Percentage deviation of different parameters of GEN Bus 3 outgoing currents for LG fault at Bus 8

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 40.0781 | 6.18 | 49.328 | 5.2 | 15.726 |
| 2 | 99.9999 | 89.154 | 6.18 | 92.201 | 5.2 | 109.051 |
| 3 | 99.999 | 98.293 | 6.18 | 71.016 | 5.2 | 2323.788 |
| 4 | 99.999 | 307.103 | 6.18 | 4342.718 | 5.2 | 1021.738 |
| 5 | 99.999 | 1890.536 | 6.18 | 3989.139 | 5.2 | 115.739 |
| 6 | 99.999 | 3165.625 | 6.037 | 288.689 | 5.198 | 9.653 |
| 7 | 958.62 | 422.033 | 5.73 | 26.505 | 5.24 | 4.663 |
| 8 | 209.051 | 388.679 | 17.883 | 20.735 | 6.733 | 5.04 |
| 9 | 99.018 | 134.049 | 41.227 | 42.242 | 14.07 | 5.945 |

**Table A.18** Percentage deviation of different parameters of GEN Bus 3 outgoing currents for LL fault at Bus 8

| DWT level | Sa | Sd | Ka | Kd | RMSa | RMSd |
|---|---|---|---|---|---|---|
| 1 | 99.999 | 35.081 | 3.126 | 43.699 | 3.239 | 74.211 |
| 2 | 99.999 | 87.018 | 3.126 | 90.932 | 3.239 | 381.496 |
| 3 | 811.416 | 100.185 | 3.126 | 71.787 | 3.239 | 2408.286 |
| 4 | 1549.476 | 253.926 | 3.126 | 1335.055 | 3.240 | 2191.527 |
| 5 | 3155.999 | 3980.126 | 3.126 | 2984.586 | 3.241 | 139.941 |
| 6 | 3199.999 | 3089.062 | 3.058 | 252.8574 | 3.243 | 0.737 |
| 7 | 4568.965 | 457.627 | 1.822 | 1.749 | 3.125 | 5.418 |
| 8 | 633.189 | 195.283 | 19.281 | 0.357 | 8.089 | 4.581 |
| 9 | 46.31 | 18.404 | 56.94 | 3.081 | 130.512 | 6.911 |