CHAPTER IV

FAULT CURRENT ANALYSIS

4.1 Fault Current Calculation

The presence of DG in distribution systems can increase the fault current level. This effect causes by some factors like penetration level, transient impedance of the DG, power system configuration, and the location of the DG.

The fault current at a system bus is calculated based on Thevenin model [21]. The new impedance matrix needs to be evaluated when the DG is connected to any bus in the network. The impedance matrix before the DG is added is shown in equation 4-1 while its modification after adding DG is derived in equation 4-2:

$$\left[V_{orig}\right]=\left[Z_{bus,orig}\right]\left[I_{orig}\right] \quad \textbf{(4-1)}$$

$$\left[\begin{array}{c} V_{orig} \\ \\ \hline V_{DG,p} \\ V_{DG,q} \end{array}\right] = \left[\begin{array}{cccc|cc} & & & & Z_{1k} & Z_{1m} \\ & Z_{bus,orig} & & & Z_{2k} & Z_{2m} \\ & & & & \vdots & \vdots \\ & & & & Z_{nk} & Z_{nm} \\ \hline Z_{k1} & Z_{k2} & \cdots & Z_{kn} & Z_{kk}+Z_{DG,k} & Z_{km} \\ Z_{m1} & Z_{m2} & \cdots & Z_{mn} & Z_{mk} & Z_{mm}+Z_{DG,m} \end{array}\right] \left[\begin{array}{c} I_{orig} \\ \\ \hline I_{DG,k} \\ I_{DG,m} \end{array}\right] \quad \textbf{(4-2)}$$

where V_{orig}, $Z_{bus,orig}$, I_{orig} are the voltage , impedance, and current matrices before DG is added. *n* is the number of the bus in the original system, *k* and *m* are the bus that DGs are connected. *p* and *q* are added bus system after DG is added. $Z_{DG,k}$, $Z_{DG,m}$ are the impedance of the DG. $V_{DG,p}$, $V_{DG,q}$, $I_{DG,k}$, and $I_{DG,m}$ are bus voltage and injected current of the DG respectively.

Following the Kron's reduction formula to equation 4-2, the new bus impedance matrix after DG is installed could be derived as:

$$\left[Z_{bus,new}\right]=\left[Z_{bus,orig}\right]-\left[Z_{col,DGs}\right]\left[Z_{common}\right]^{-1}\left[Z_{row,DGs}\right] \quad \textbf{(4-3)}$$

where

$$Z_{col,DGs} = \begin{bmatrix} Z_{1k} & \cdots & Z_{1m} \\ Z_{2k} & \cdots & Z_{2k} \\ \vdots & \vdots & \vdots \\ Z_{nk} & \cdots & Z_{nm} \end{bmatrix}$$

$$Z_{common} = \begin{bmatrix} Z_{kk} + Z_{DG,k} & & Z_{mk} \\ & \ddots & \\ Z_{km} & & Z_{mm} + Z_{DG,m} \end{bmatrix}$$

$$Z_{row,DGs} = \begin{bmatrix} Z_{k1} & Z_{k2} & \cdots & Z_{kn} \\ \vdots & \vdots & \vdots & \vdots \\ Z_{m1} & Z_{m2} & \cdots & Z_{mn} \end{bmatrix}$$

After forming the new impedance matrix, $Z_{bus,new}$. The three phase to ground fault current at bus *i* can be derived as:

$$I_{fi} = \frac{V_{fi}}{Z_{ii,new} + Z_f} \qquad \textbf{(4-4)}$$

where I_{fi} is fault current at bus *i*, V_{fi} is prefault voltage at bus *i*, Z_f is fault impedance, $Z_{ii,orig}$ and $Z_{kk,orig}$ are impedance matrices of system before and after installing new PV, respectively.

4.2 Simulation Results and Discussions

For the DGs which energy the DC source to the system via an inverter like PV, its control is determined how it is seen by the network [21]. In case the DG is grid-connected photovoltaic systems, its impedance is not constant because of the complex control of inverter. There is no standard exactly for it control and it is problematic for modeling. Therefore, the implementation in MATLAB-SIMULINK is proposed for the fault current analysis. The ability of simulation technique could evaluate the response of the complicated system while the DGs are connected. Several numerical differential equation solvers are applied in the simulation like method of Adams, modified Rosenbrock, Runge-Kutta, and trapezoidal. During the simulation, voltages and currents could be measured and recorded for further analysis.

In these case studies, the comparison of fault current levels between GCPV and SG are proposed to show its impact when these types of DG are installed in the system. Three phase fault is considered because of its highest fault current, three 1MW DGs are installed at buses 201, 211, and 218 in the 23-bus 22kV, 65MVAsc distribution system with the total load of 700kW as shown in Figure 4-1. Faults ($Z_f = 0.001$ ohms) are assumed at buses 202, 212, and 217 respectively to investigate the fault current near the substation, middle of the system, and at the end of the system.

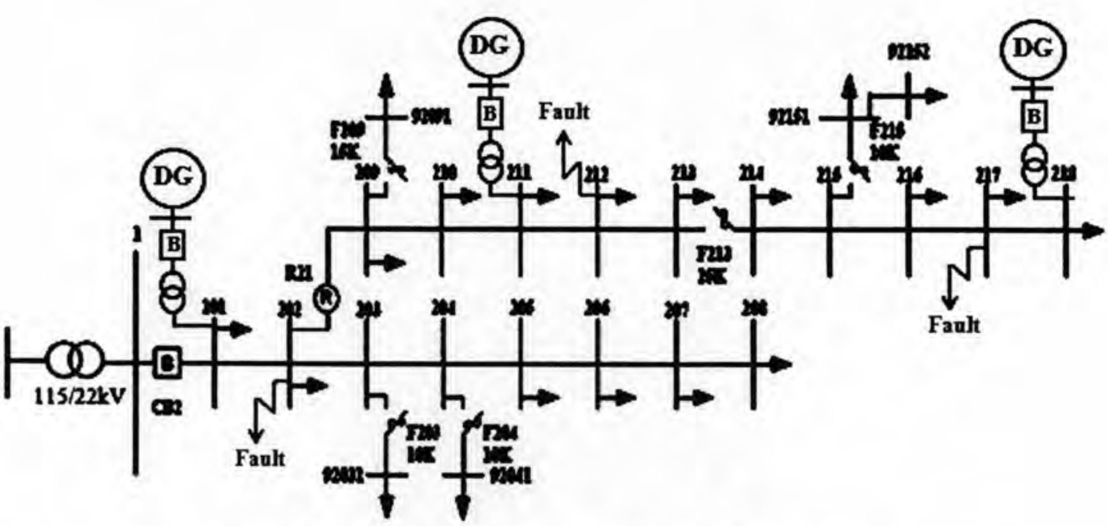

Figure 4-1 23 bus distribution system with DG installation

The simulation is from t=0 to 0.6s while the fault is assumed at t=0.35 to 0.55s for the fault analysis. During the simulation, the rms current of grid (Igrid), rms current of DG (I_{DG}), and rms fault current (Ifault) at faulted bus are recorded to show its impact. First, the system without the DG installation is tested, where figure 4-2 illustrates the Igrid and Ifault when the fault occurs at bus 202. Figures 4-3 and 4-4 are the curves comparison of Igrid and Ifault if the fault assumes at bus 202, 212, and 217 respectively. Then, the system with DG installation is simulated where figure 4-5 is the curve of Igrid, Ipv and Ifault while 3 GCPVs and fault assumed at bus 202. Figure 4-6 is also the curve of Igrid, Isg, and Ifault while SGs installation when fault assumed at bus 202. Table 4-1 and figure 4-7 are the fault current comparison with and without GCPVs installation where Table 4-2 and figure 4-8 are the fault current comparison with and without SGs installation. Figure 4-9 is the fault current comparison between GCPVs and SGs installation.

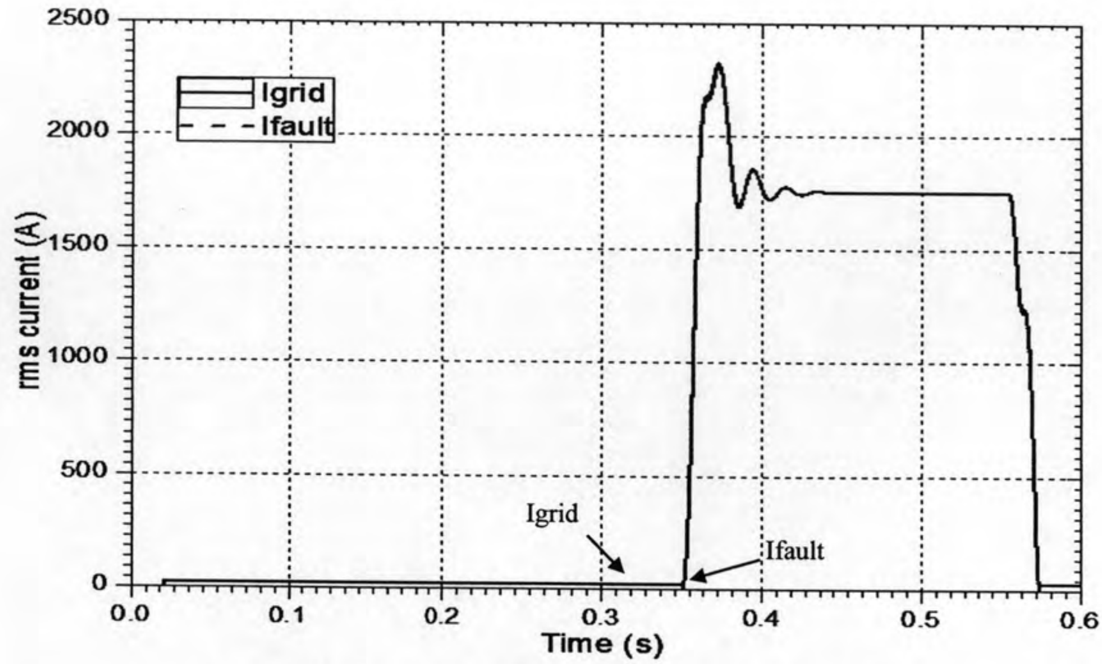

Figure 4-2 Igrid and Ifault when fault assumes at bus 202

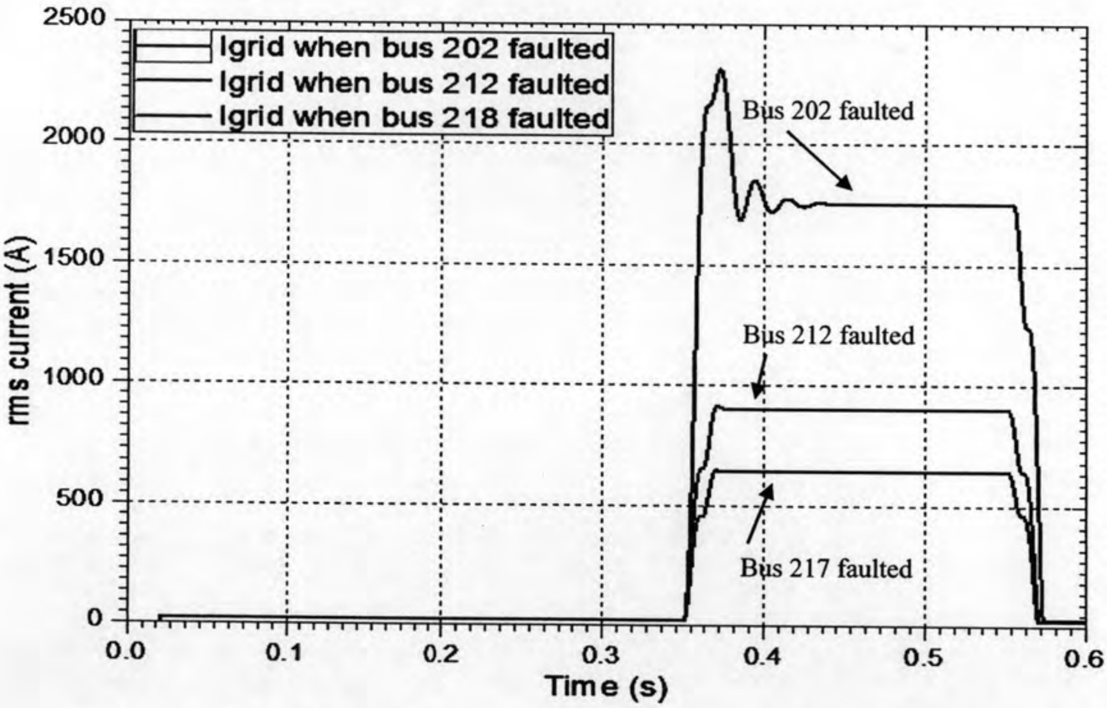

Figure 4-3 Igrid when fault assumes at bus 202, 212, and 217 respectively

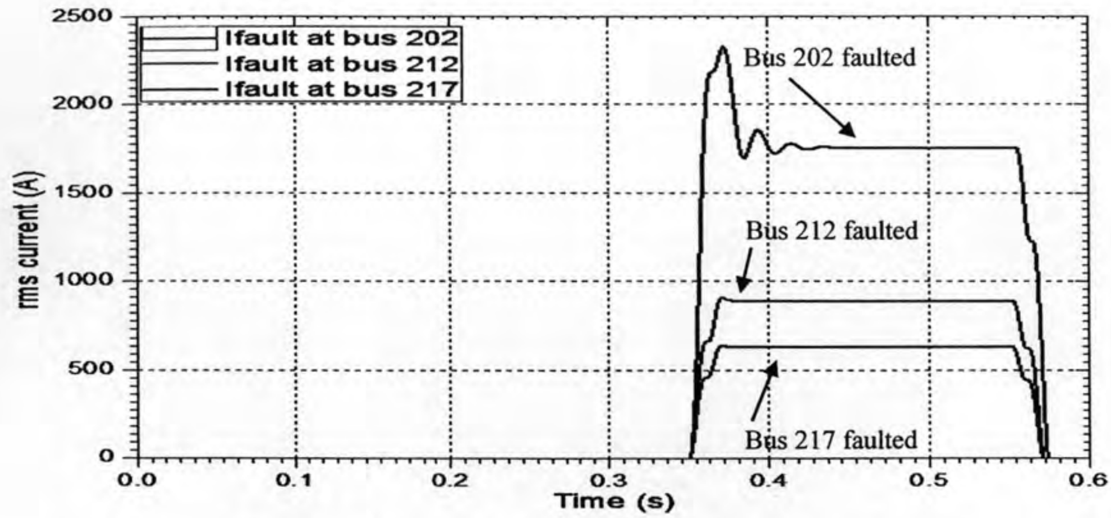

Figure 4-4 Ifault at bus 202, 212, and 217 respectively

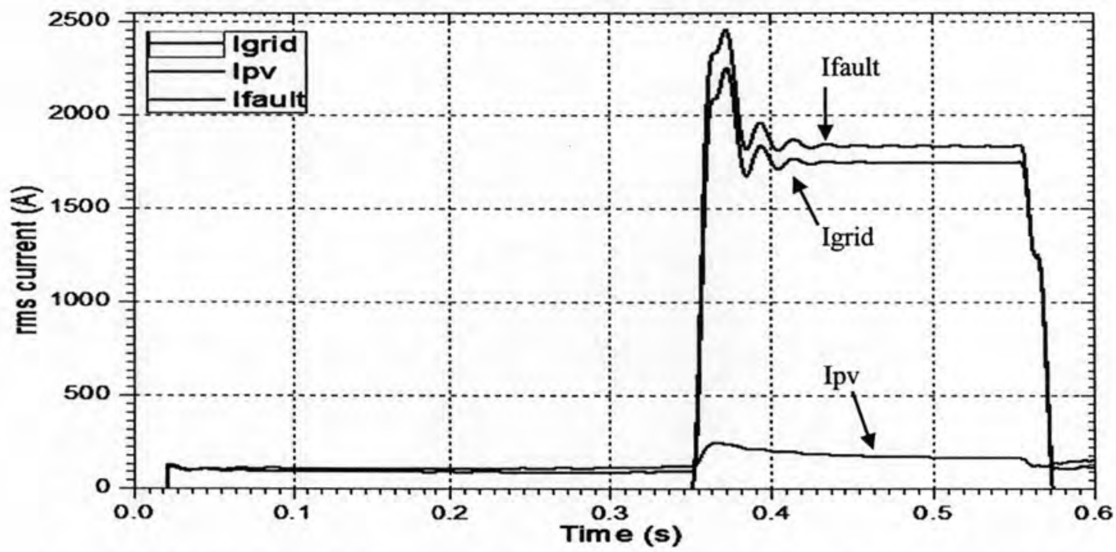

Figure 4-5 Igrid, Ipv, and Ifault when 3 GCPVs are installed and fault assumes at bus 202

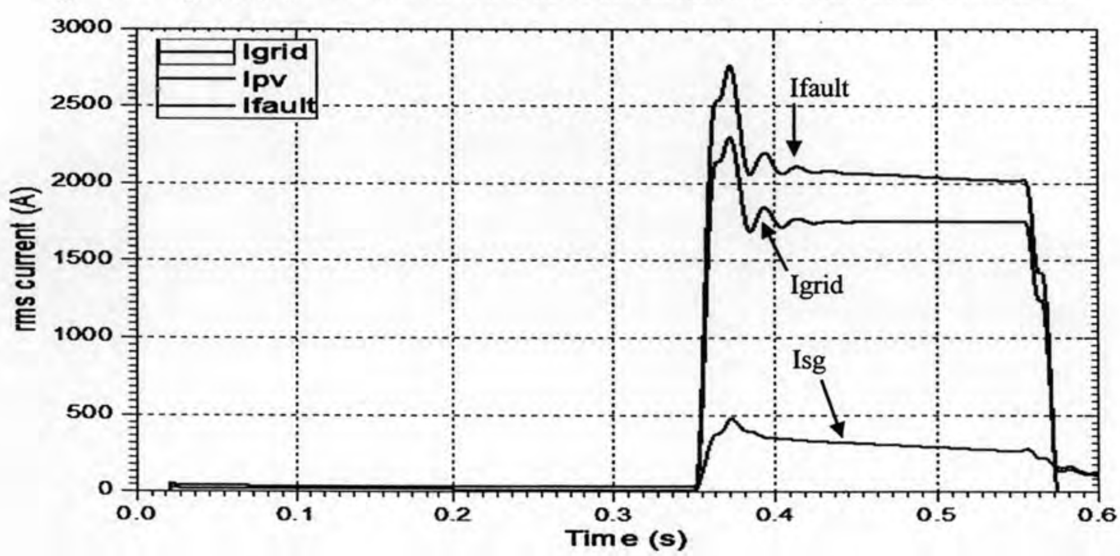

Figure 4-6 Igrid, Isg, and Ifault when 3 SGs are installed and fault assumes at bus 202

TABLE 4-1 FAULT CURRENT CONTRIBUTION RESULTS WHEN 3 GCPV SYSTEMS ARE INSTALLED

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
3 GCPVs	Igrid (A)	1751.0	870.5	606.1
	Ipv (A)	170.5	187.0	174.0
	Ifault (A)	1836.0	966.5	677.7

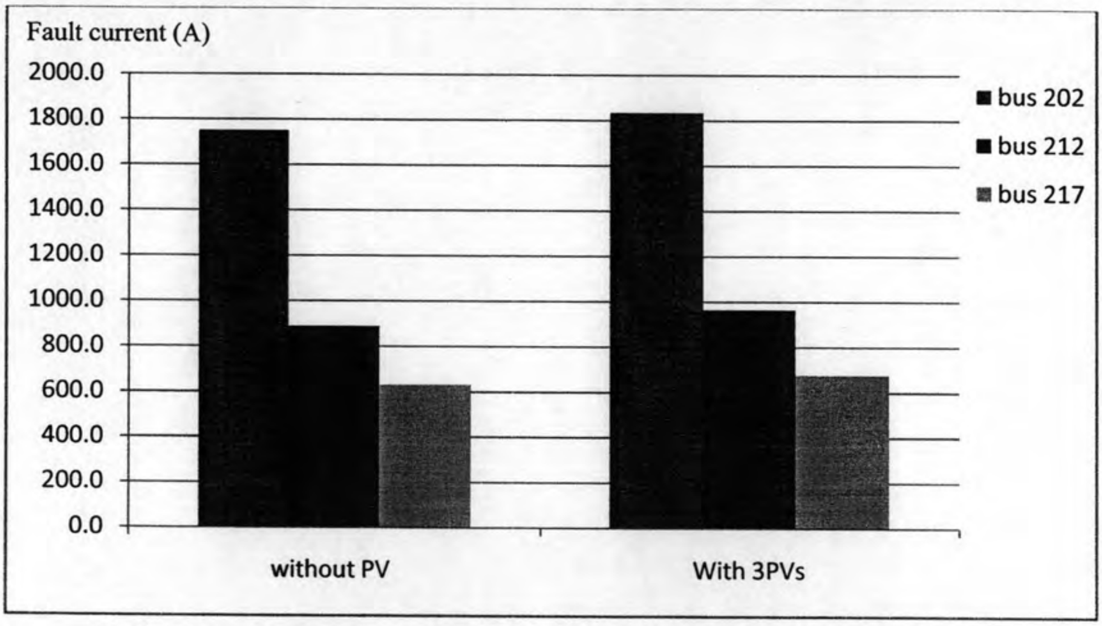

Figure 4-7 Fault current comparison with and without 3GCPVs installation

TABLE 4-2 FAULT CURRENT CONTRIBUTION RESULTS WHEN 3 SGS ARE INSTALLED

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
3 SGs	Igrid (A)	1752.0	891.5	635.5
	Isg (A)	271.0	197.0	180.0
	Ifault (A)	2024.0	1010.0	705.0

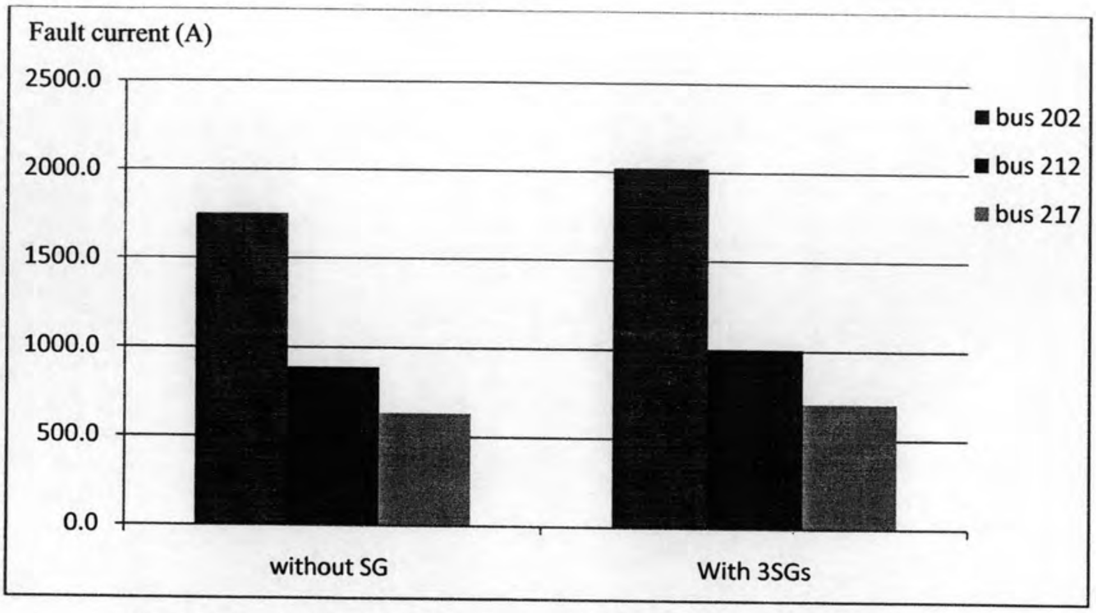

Figure 4-8 Fault current comparison with and without 3SGs installation

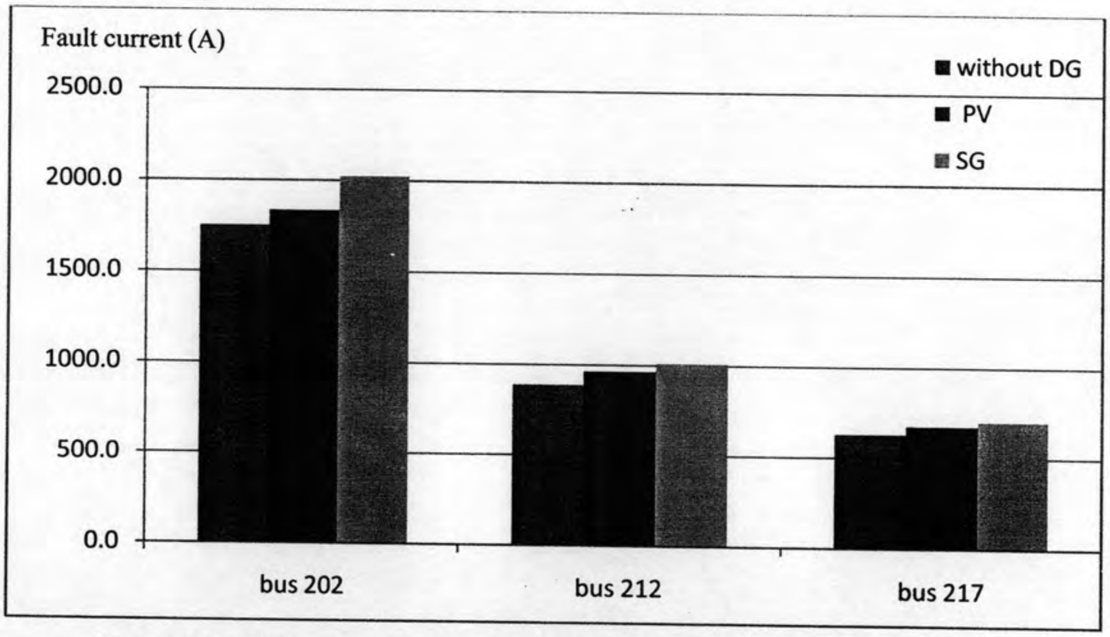

Figure 4-9 Fault current comparison between 3 GCPVs and 3 SGs installation

For another case study, there is only one 3MW DG is connected at bus 201, 211, or 218. Table 4-3 and figure 4-10 are the fault current contribution from the main grid and also from the GCPV, table 4-4 and figure 4-11 the fault current contribution from the main grid and also from the SG, and where figure 4-12 is the fault current comparison between GCPV and SG installation when DG is installed at bus 201.

TABLE 4-3 FAULT CURRENT CONTRIBUTION RESULTS WHEN ONE GCPV SYSTEM IS INSTALLED AT BUS 201

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
1 GCPV at bus 201	Igrid (A)	1749.0	836.0	579.4
	Ipv (A)	342.6	79.8	74.6
	Ifault (A)	1820.0	902.8	637.4

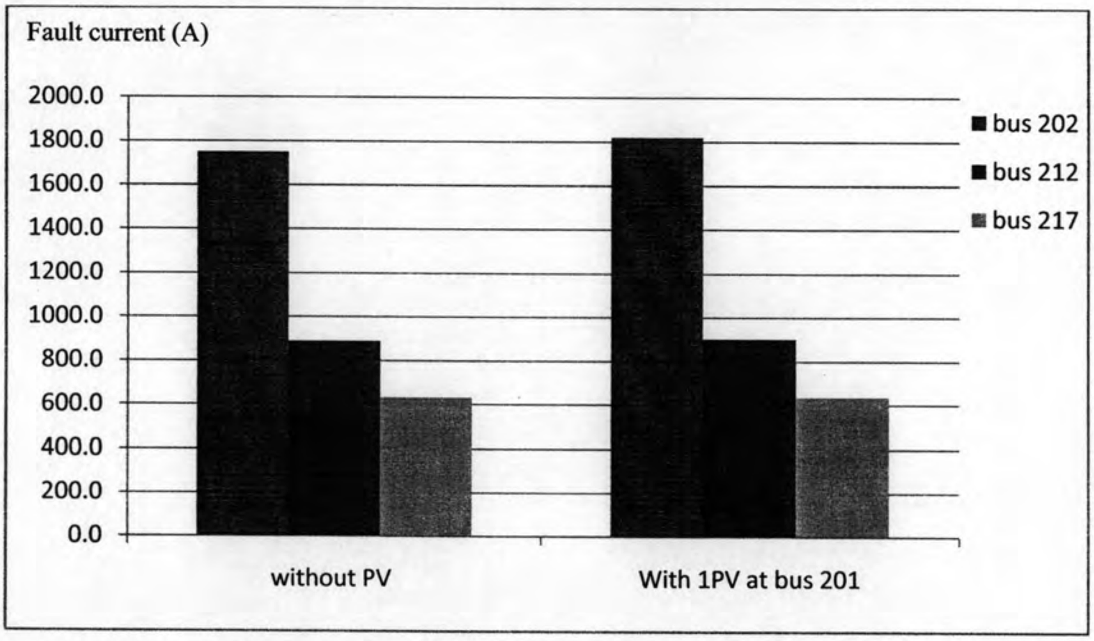

Figure 4-10 Fault current comparison with and without GCPV installation at bus 201

TABLE 4-4 FAULT CURRENT CONTRIBUTION RESULTS WHEN ONE SG IS INSTALLED AT BUS 201

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
1 SG at bus 201	Igrid (A)	1752.0	857.3	607.1
	Isg (A)	374.0	121.4	98.1
	Ifault (A)	1887.0	910.3	640.0

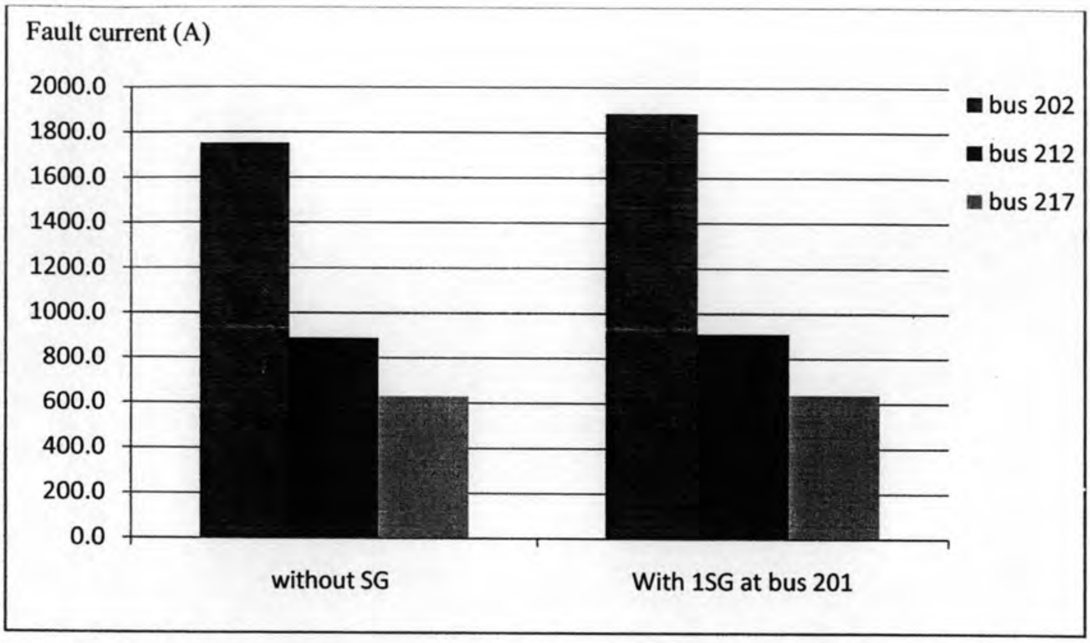

Figure 4-11 Fault current comparison with and without SG installation at bus 201

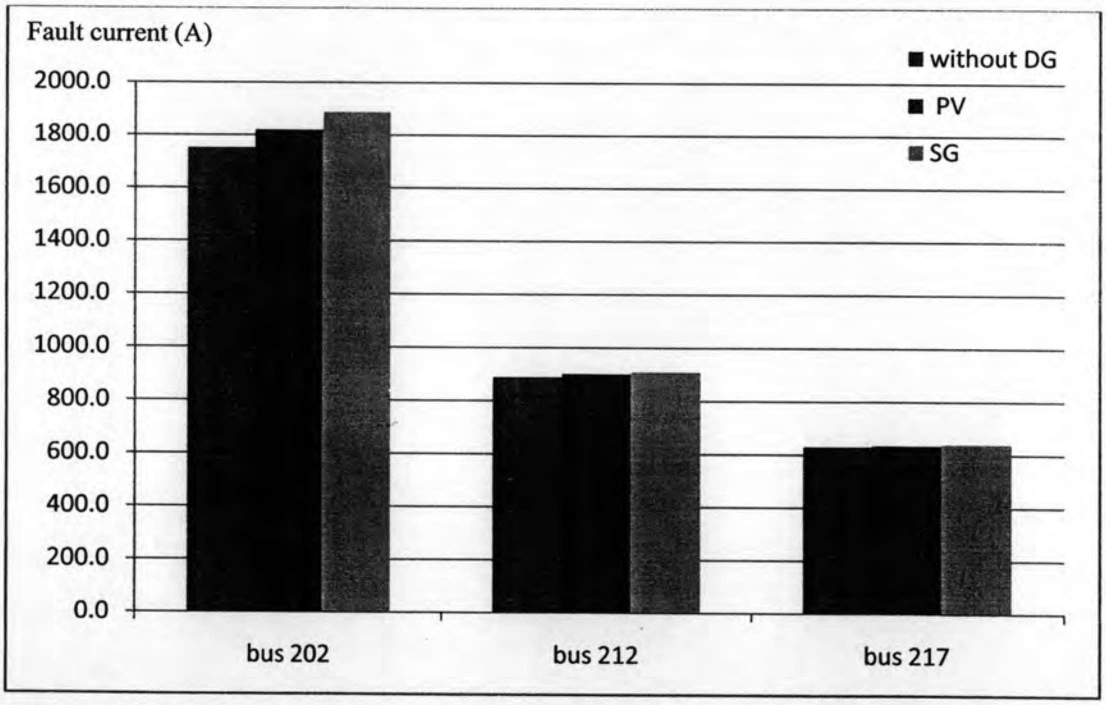

Figure 4-12 Fault current comparison between one GCPV or one SG installation at bus 201

Table 4-5 and figure 4-13 are the fault current contribution from the main grid and also from the GCPV, table 4-6 and figure 4-14 are the fault current contribution from the main grid and also from the SG, and where figure 4-15 is the fault current comparison between GCPV and SG installation when DG is installed at bus 211.

TABLE 4-5 FAULT CURRENT CONTRIBUTION RESULTS WHEN ONE GCPV SYSTEM IS INSTALLED AT BUS 211

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
1 GCPV at bus 211	Igrid (A)	1752.0	891.8	615.0
	Ipv (A)	84.5	119.7	80.9
	Ifault (A)	1817.0	971.4	681.6

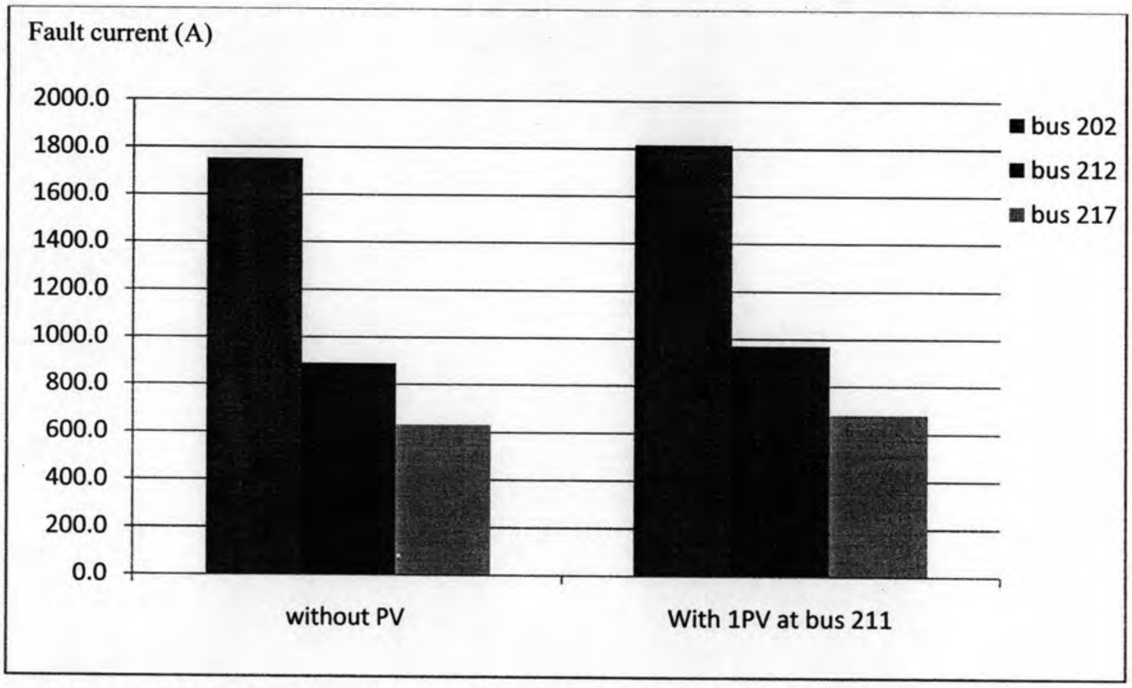

Figure 4-13 Fault current comparison with and without GCPV installation at bus 211

TABLE 4-6 FAULT CURRENT CONTRIBUTION RESULTS WHEN ONE SG IS INSTALLED AT BUS 211

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
1 SG at bus 201	Igrid (A)	1752.0	897.5	633.3
	Isg (A)	134.3	123.1	86.2
	Ifault (A)	1882.0	975.2	689.4

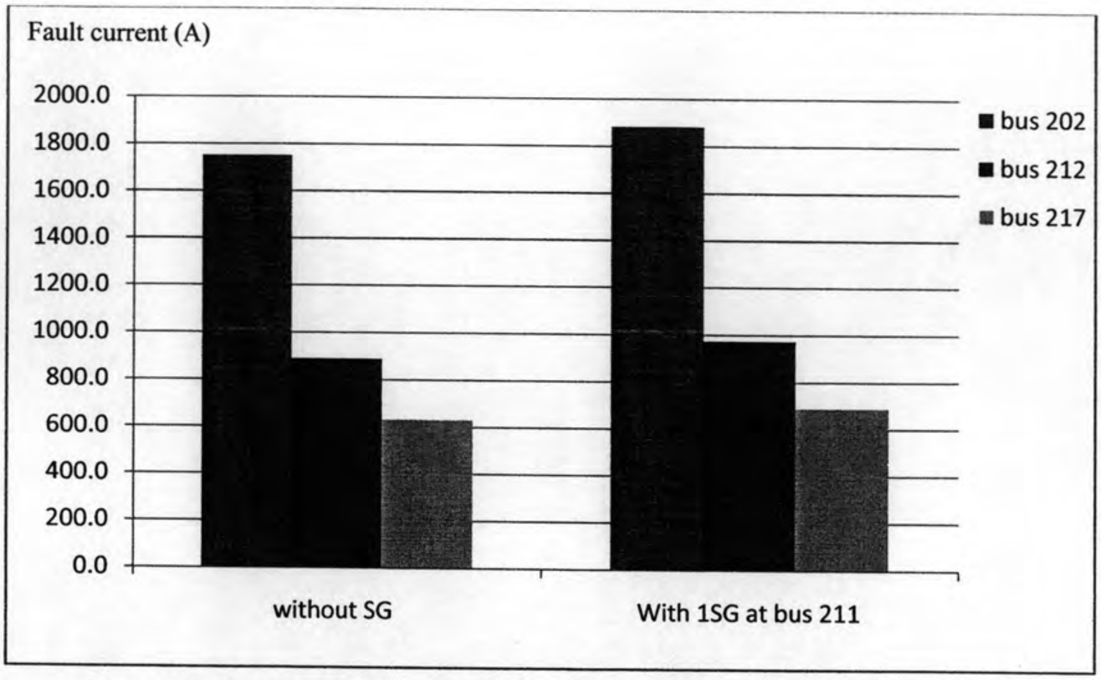

Figure 4-14 Fault current comparison with and without SG installation at bus 211

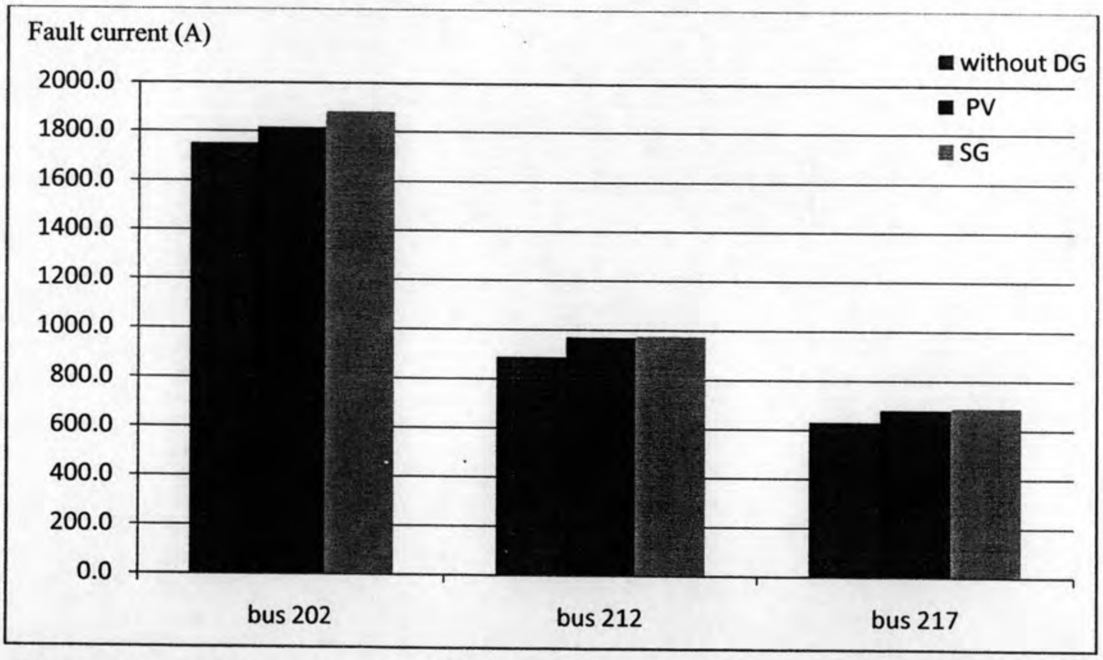

Figure 4-15 Fault current comparison between one GCPV or one SG installation at bus 211

Table 4-7 and figure 4-16 are the fault current contribution from the main grid and also from the GCPV, table 4-8 and figure 4-17 are the fault current contribution from the main grid and also from the SG, and where figure 4-18 is the fault current comparison between GCPV and SG installation when DG is installed at bus 218.

TABLE 4-7 FAULT CURRENT CONTRIBUTION RESULTS WHEN ONE GCPV SYSTEM IS INSTALLED AT BUS 218

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
1 GCPV at bus 218	Igrid (A)	1752.0	899.0	643.1
	Ipv (A)	83.3	86.5	103.1
	Ifault (A)	1814.0	973.0	707.7

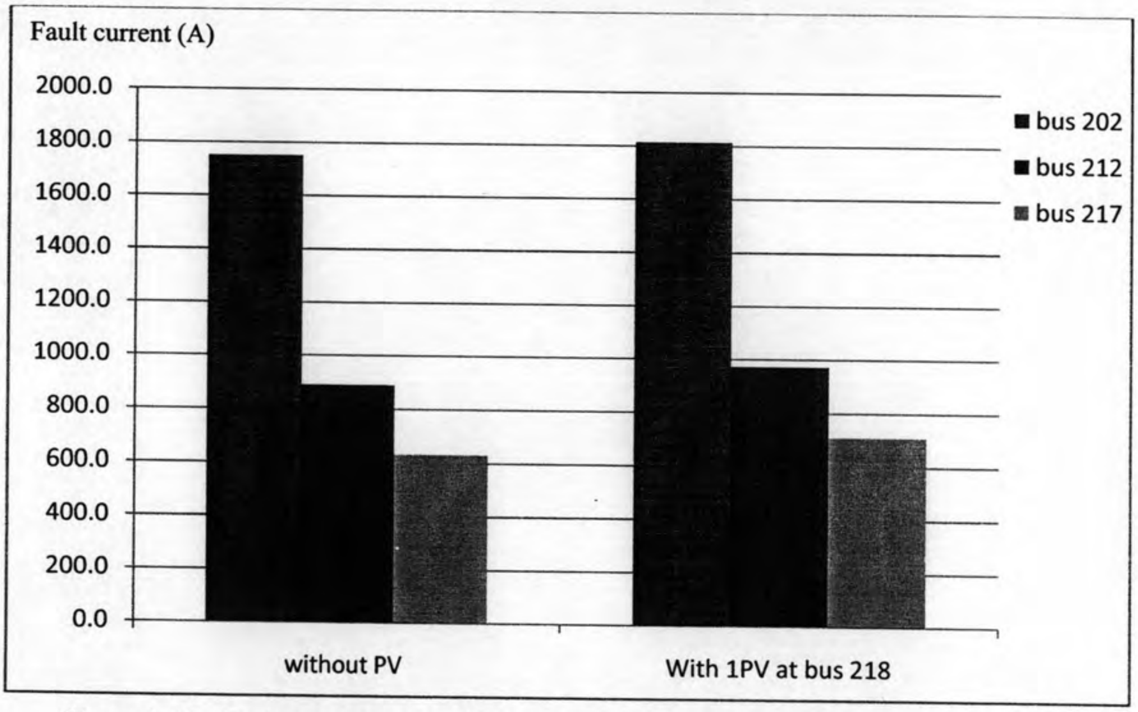

Figure 4-16 Fault current comparison with and without GCPV installation at bus 218

TABLE 4-8 FAULT CURRENT CONTRIBUTION RESULTS WHEN ONE SG IS INSTALLED AT BUS 218

Three phase fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1752.0	899.0	643.1
	Ifault (A)	1752.0	890.3	631.8
1 SG at bus 218	Igrid (A)	1752.0	899.0	643.1
	Isg (A)	125.6	128.1	129.2
	Ifault (A)	1877.0	974.0	719.8

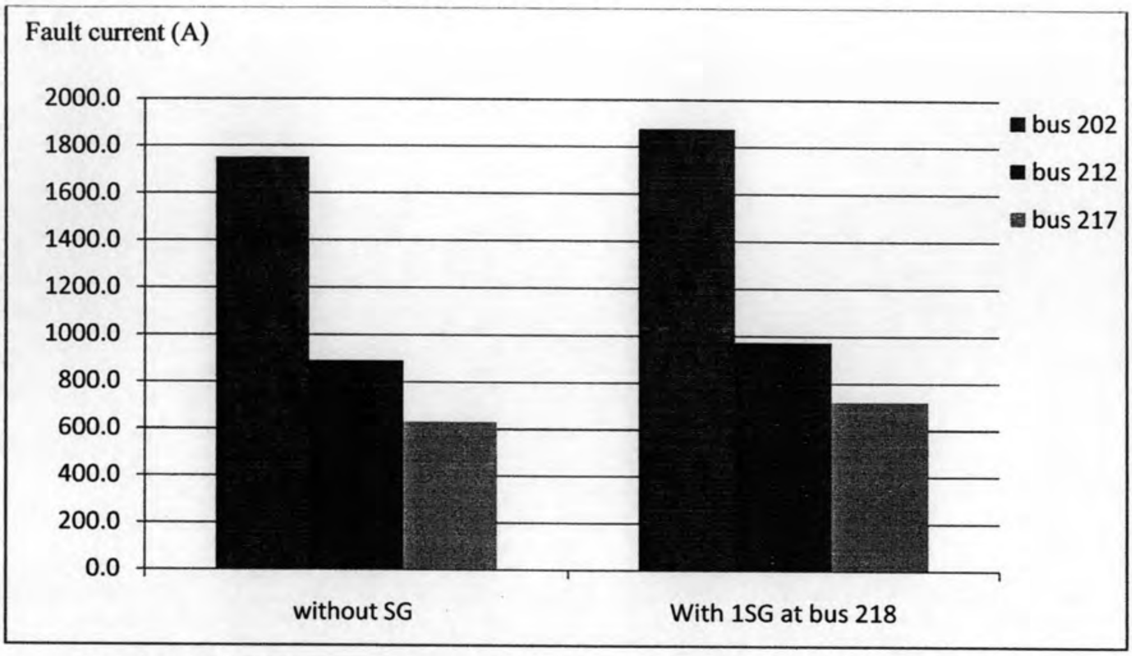

Figure 4-17 Fault current comparison with and without SG installation at bus 218

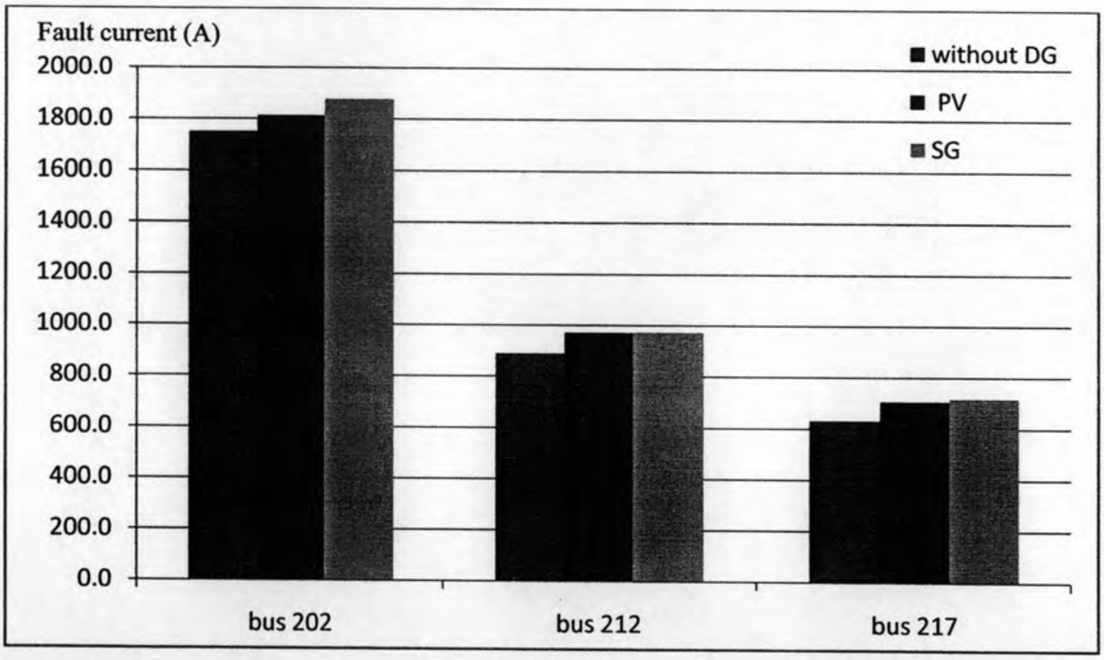

Figure 4-18 Fault current comparison between one GCPV or one SG installation at bus 218

The following tables and figures are single line ground fault (SLGF) comparison result between GCPV and SG. The testing cases are the same at three phase fault case studies, where 3 DGs are installed at buses 201, 211, and 218. Then, there is only one DG is installed at bus 201, 211, or 218. The results are shown as follows:

TABLE 4-9 SLGF CURRENT CONTRIBUTION RESULTS WHEN 3 GCPV SYSTEMS ARE INSTALLED

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.6	584.0
3 GCPVs	Igrid (A)	1741.0	808.3	555.9
	Ipv (A)	136.0	110.0	117.6
	Ifault (A)	1803.0	883.0	625.3

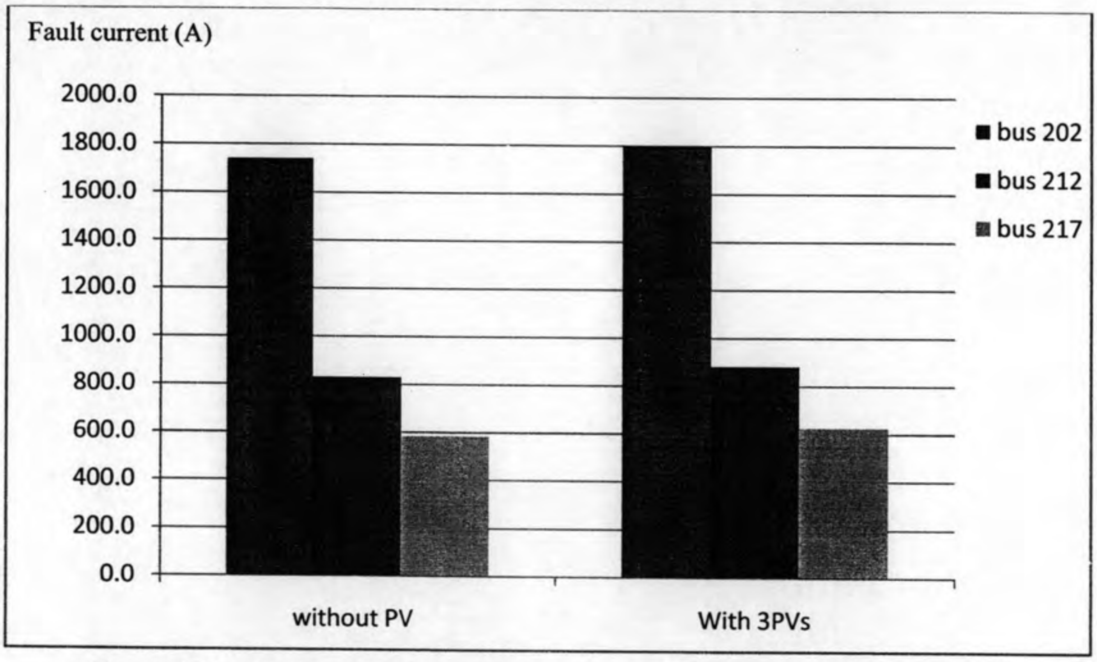

Figure 4-19 SLGF current comparison with and without 3 GCPV installations

TABLE 4-10 SLGF CURRENT CONTRIBUTION RESULTS WHEN 3 SGS ARE INSTALLED

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.4	584.0
3 SGs	Igrid (A)	1740.0	813.6	569.4
	Isg (A)	218.0	155.0	124.7
	Ifault (A)	1950.0	934.0	653.6

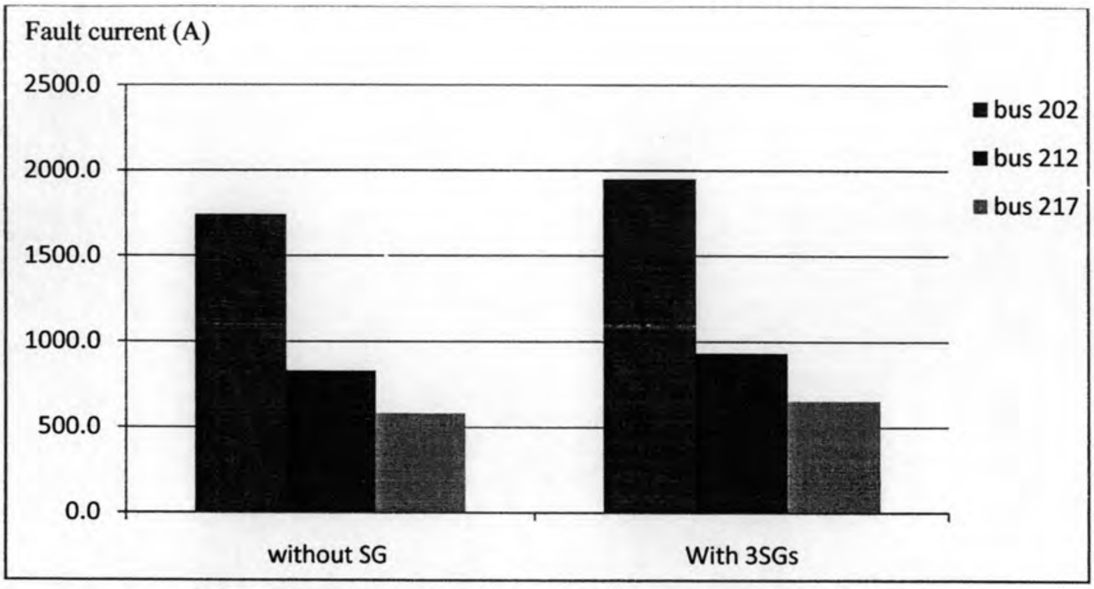

Figure 4-20 SLGF current comparison with and without 3 SG installations

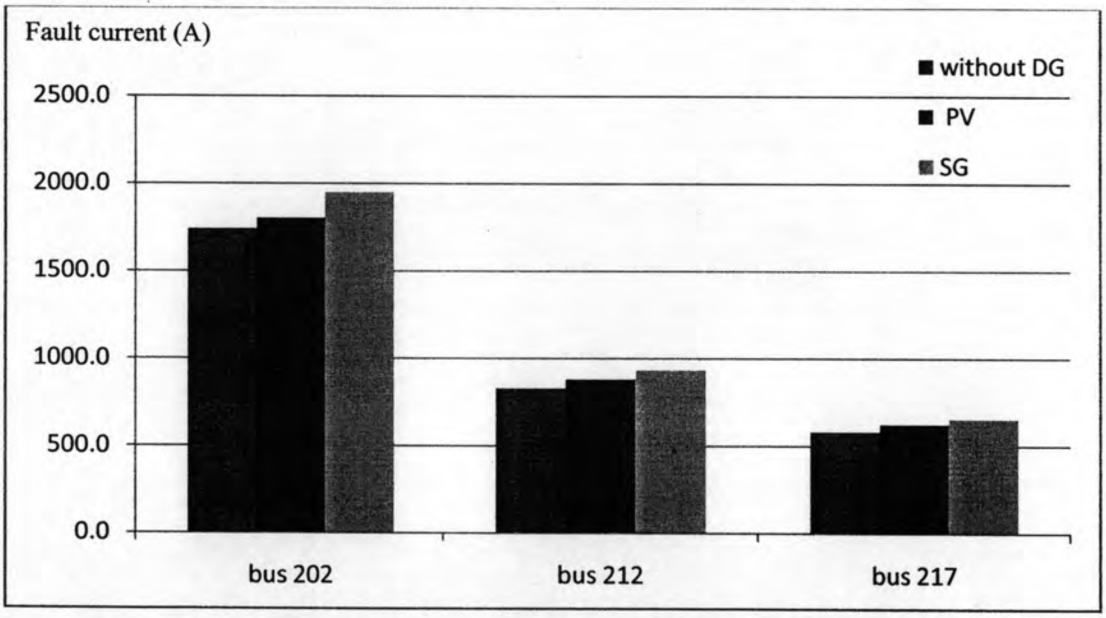

Figure 4-21 SLGF current comparison between 3 GCPVs and 3 SGs installation

TABLE 4-11 SLGF CURRENT CONTRIBUTION RESULTS WHEN ONE GCPV SYSTEM IS INSTALLED AT BUS 201

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.6	584.0
1 GCPV at bus 201	Igrid (A)	1739.0	777.4	531.0
	Ipv (A)	84.4	69.7	64.8
	Ifault (A)	1789.0	837.9	587.1

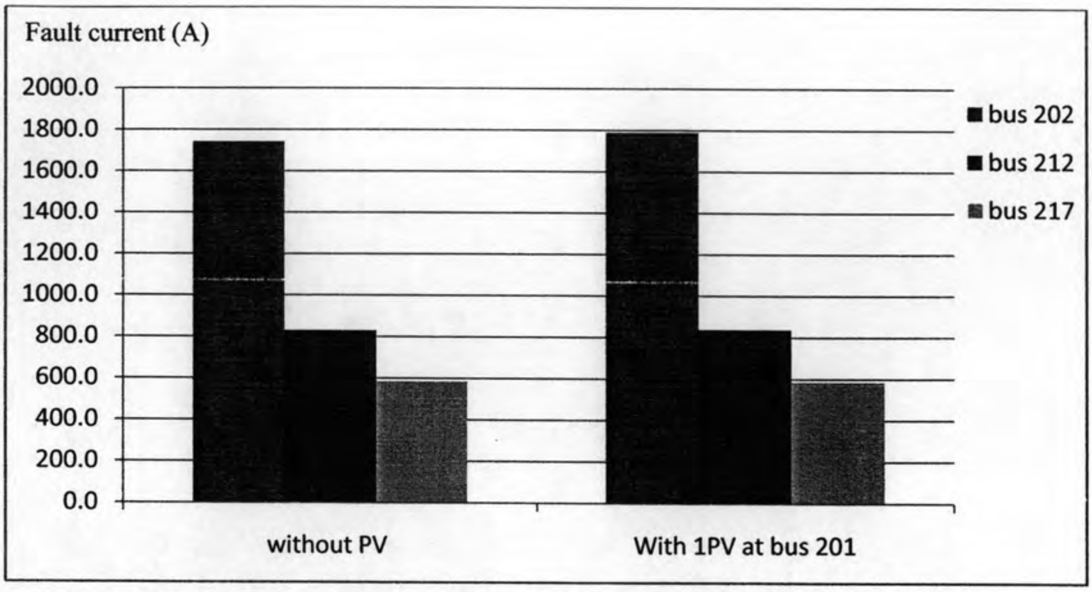

Figure 4-22 SLGF current comparison with and without GCPV installation at bus 201

TABLE 4-12 SLGF CURRENT CONTRIBUTION RESULTS WHEN ONE SG IS INSTALLED AT BUS 201

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.4	584.0
1 SG at bus 201	Igrid (A)	1742.0	784.1	548.8
	Isg (A)	182.0	94.9	69.3
	Ifault (A)	1878.0	848.7	590.5

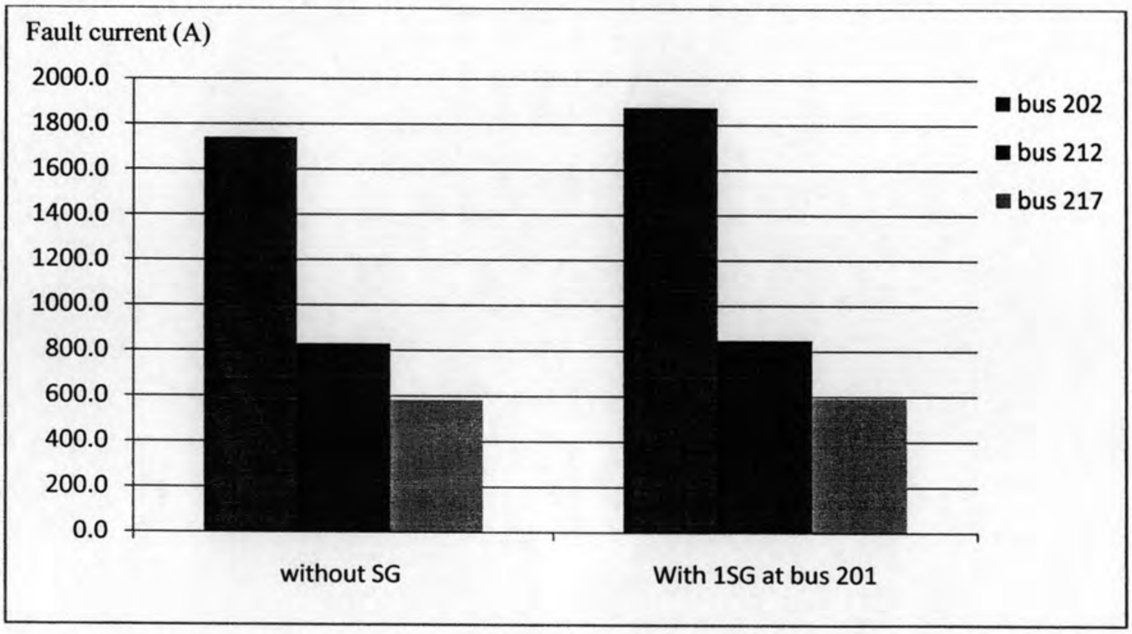

Figure 4-23 SLGF current comparison with and without SG installation at bus 201

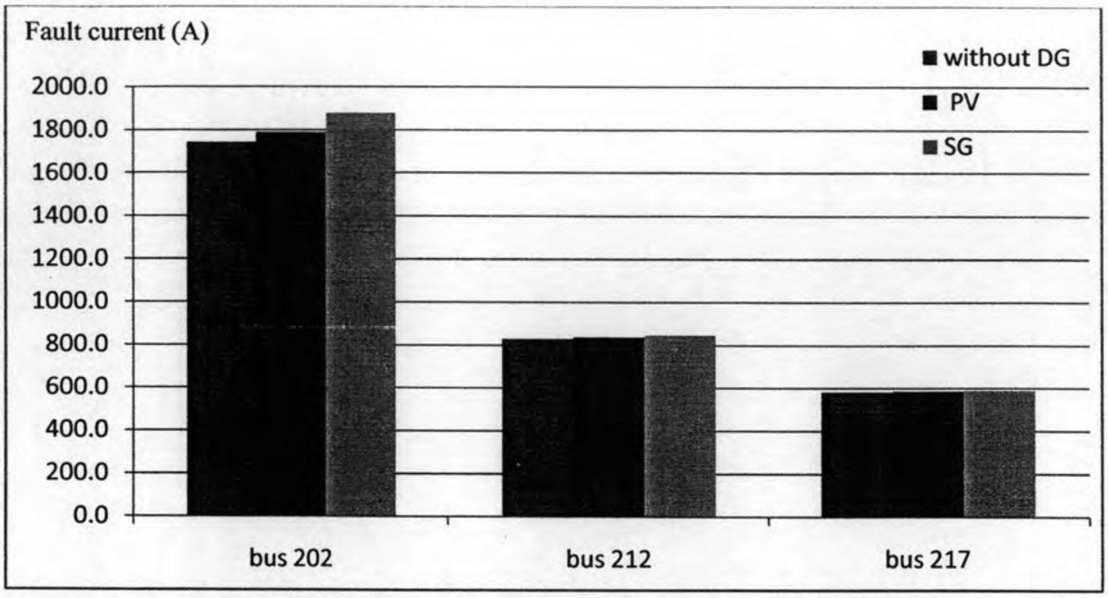

Figure 4-24 SLGF current comparison between one GCPV or one SG installation at bus 201

TABLE 4-13 SLGF CURRENT CONTRIBUTION RESULTS WHEN ONE GCPV SYSTEM IS INSTALLED AT BUS 211

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.6	584.0
1 GCPV at bus 211	Igrid (A)	1742.0	829.3	566.3
	Ipv (A)	68.6	83.0	69.5
	Ifault (A)	1789.0	888.5	622.3

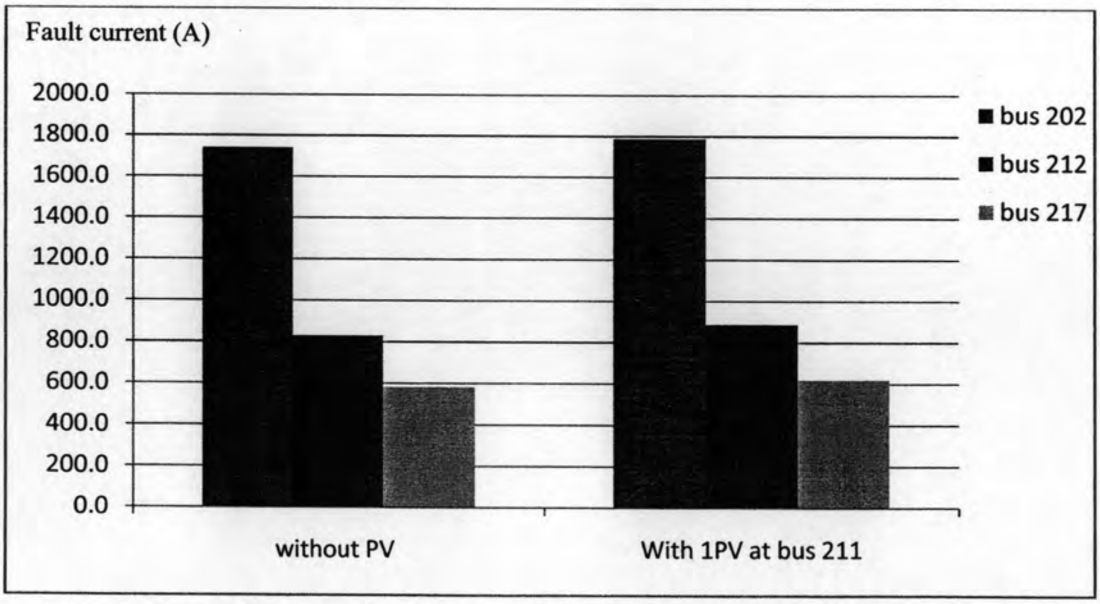

Figure 4-25 SLGF current comparison with and without GCPV installation at bus 211

TABLE 4-14 SLGF CURRENT CONTRIBUTION RESULTS WHEN ONE SG IS INSTALLED AT BUS 211

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.4	584.0
1 SG at bus 211	Igrid (A)	1742.0	831.6	574.1
	Isg (A)	126.4	117.0	84.1
	Ifault (A)	1873.0	914.8	630.7

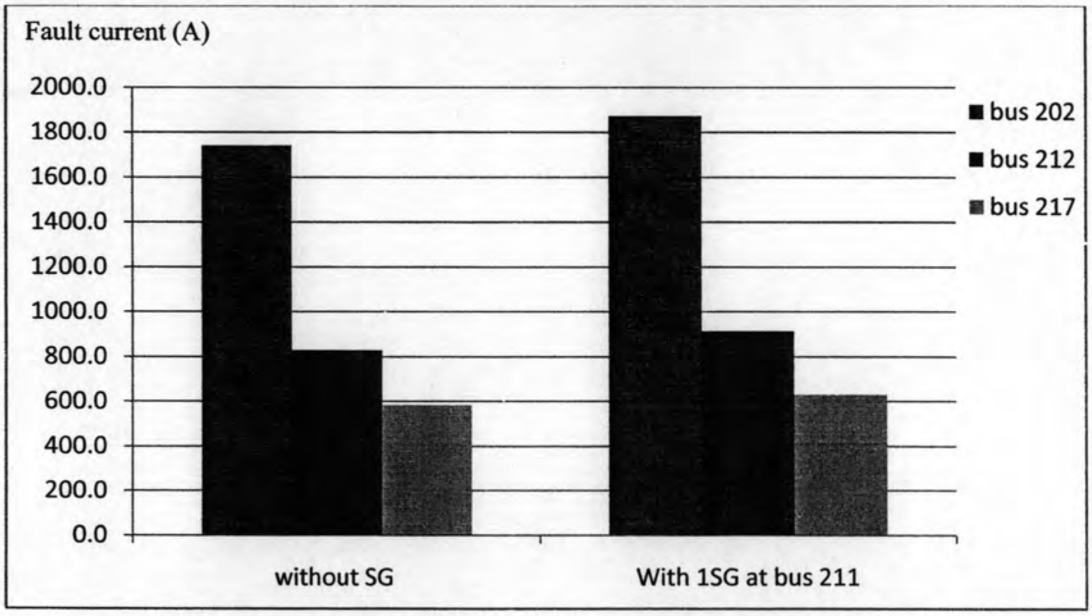

Figure 4-26 SLGF current comparison with and without SG installation at bus 211

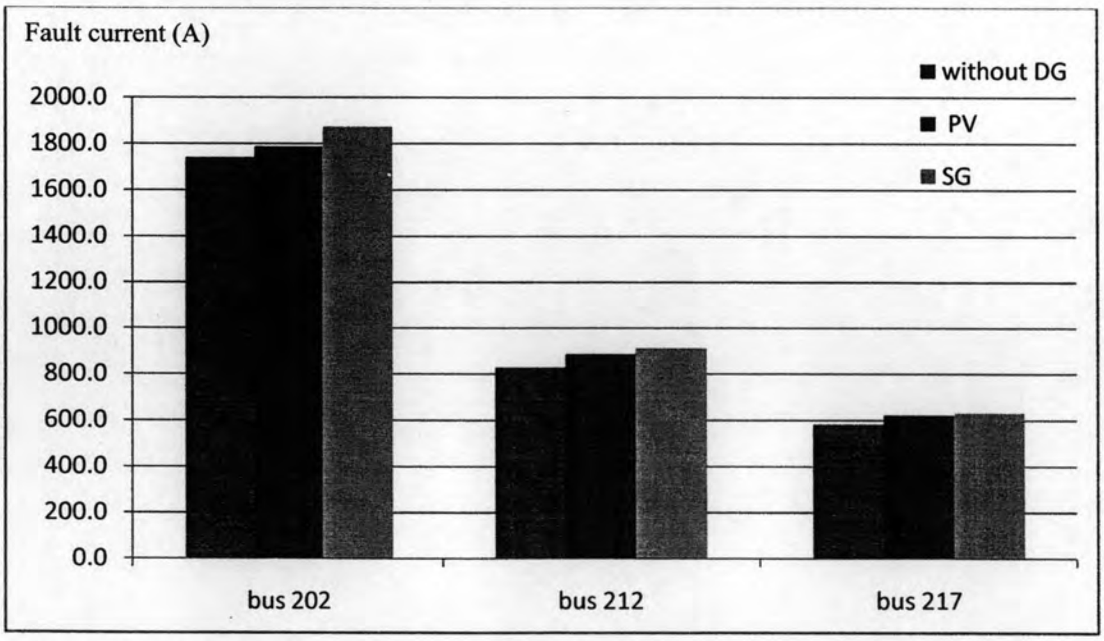

Figure 4-27 SLGF current comparison between one GCPV or one SG installation at bus 211

TABLE 4-15 SLGF CURRENT CONTRIBUTION RESULTS WHEN ONE GCPV SYSTEM IS INSTALLED AT BUS 218

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without GCPV	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.6	584.0
1 GCPV at bus 218	Igrid (A)	1742.0	835.8	591.3
	Ipv (A)	68.4	68.8	70.0
	Ifault (A)	1787.0	893.5	645.6

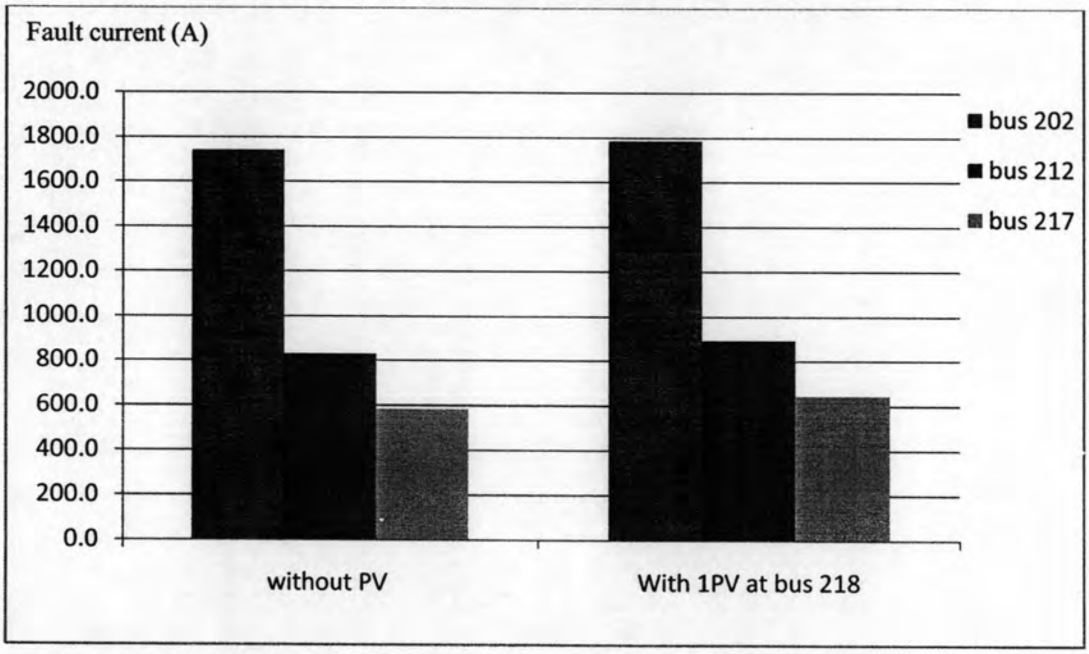

Figure 4-28 SLGF current comparison with and without GCPV installation at bus 218

TABLE 4-16 SLGF CURRENT CONTRIBUTION RESULTS WHEN ONE SG IS INSTALLED AT BUS 218

Single Line Ground Fault	Fault at bus	Bus 202	Bus 212	Bus 217
without SG	Igrid (A)	1742.0	840.0	596.0
	Ifault (A)	1742.0	830.4	584.0
1 SG at bus 218	Igrid (A)	1742.0	835.8	592.0
	Isg (A)	120.0	118.2	118.6
	Ifault (A)	1853.0	927.2	667.0

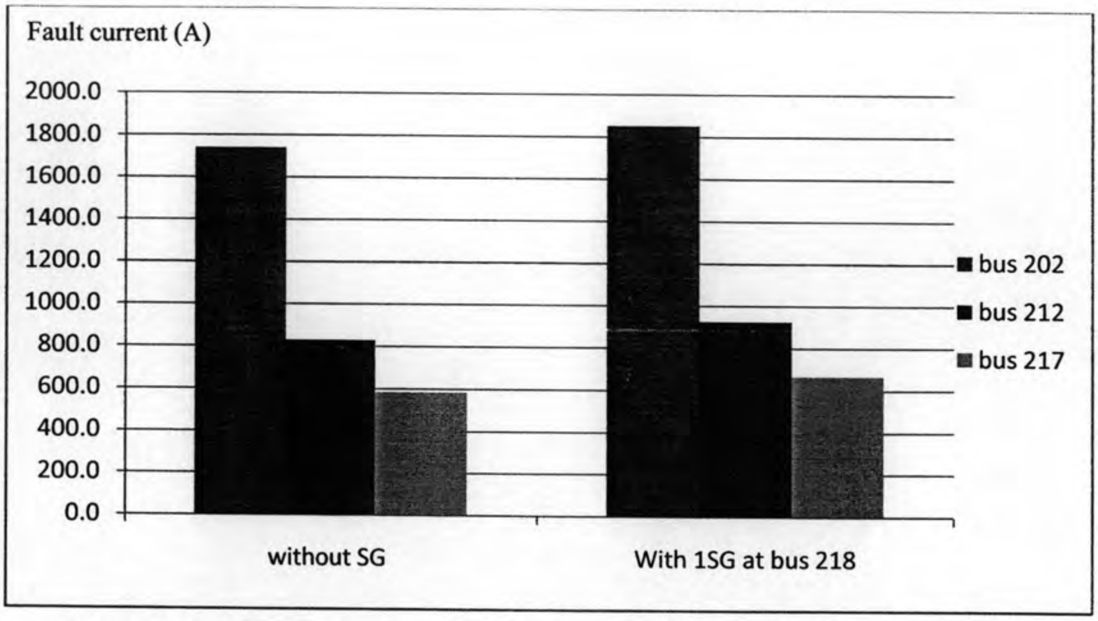

Figure 4-29 SLGF current comparison with and without SG installation at bus 218

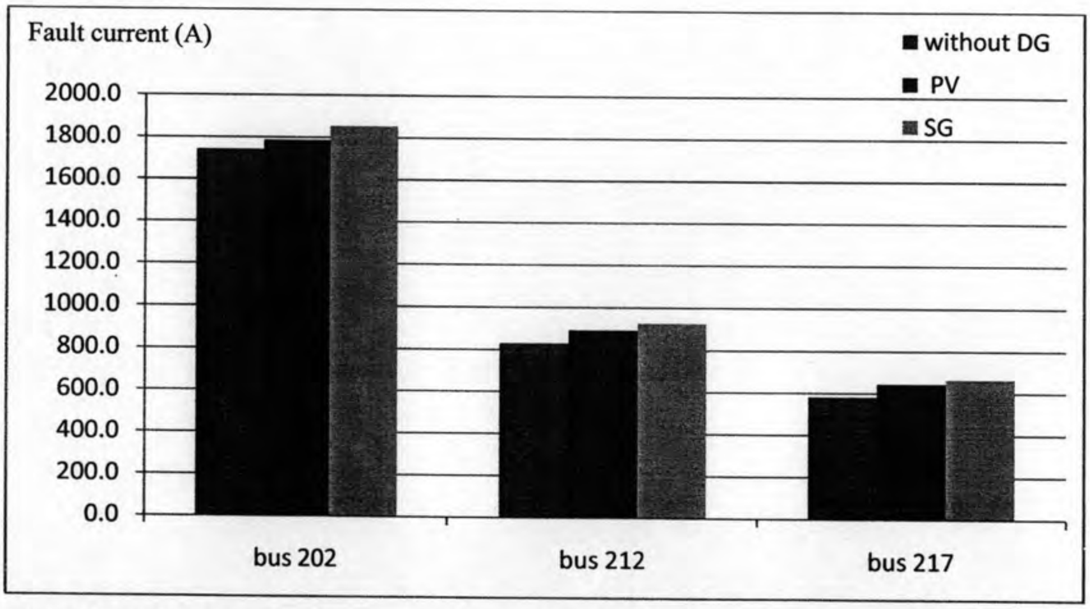

Figure 4-30 SLGF current comparison between one GCPV or one SG installation at bus 218

According to the tables and figures above, the following interpretations can be summarized:

1. From figures 4-2 to 4-4, when there is no DG in the system, the grid current and fault current contribution at the beginning of the line (near substation) are higher than those at the end of the line. Figures 4-5 and 4-6, the current contribution from the main grid during the fault is much higher than the current contribution from GCPV and SG.

2. From tables 4-1 and 4-2, the current contribution from the GCPV and SG are not vary too much even the fault is assumed from the beginning to the end of the bus. In contrary, from tables 4-3 to 4-16, the current contribution from main grid, GCPV, and SG increase if the fault occurs near the substation or DG connected bus. Tables 4-3 and 4-4 show that the fault current at bus 202 is much greater than the other two faulted buses because the DG is connected at bus 201 near the substation. Then, the fault current at buses 212 and 217 is slightly difference. Tables 4-11 and 4-12 also show that the fault current contribution decreases from the beginning of the substation to the end of the system if the DG is connected near the substation.
3. The three phase fault current is greater than single line ground fault current.
4. From figures 4-7 to 4-30, the presence of SG will increase the fault current greater than the presence of GCPV in the system. This is because of the fault current contribution from SG depends on transient and subtransient reactances, exciter characteristics of the machine, and also the prefault voltage. Its current contribution starts at 500-1000% for the first few cycles and decays to 200-400%. In contrary, the fault current contribution from GCPV is based on the inverter that depends on the maximum current level and duration for which the inverter's manufacturer current limiter have set to respond. Its current contribution starts at 100-400% or may even be less than 100%. It duration depends on controller setting and may last for less than a cycle.

4.3 Summary

In summary, following observations can be drawn:

- The presence of DG in the distribution system increases the fault current.
- The fault current contributions from DG systems increase when the DG penetration level installed in the system increases.
- The fault current contribution decreases if fault locations are further away from the substation.
- The fault current contribution greatly increases if the DG is installed near the substation.
- Fault current contribution from SG is greater than GCPV.