Analysis of System Impact of the Distributed Generation Using EMTP with Particular Reference to Voltage Sag

Sang-Min Yeo† and **Chul-Hwan Kim***

Abstract - With the advent of distributed generation, power systems are fundamentally impacted in regards to stability and power quality. Distributed generation has a positive impact on system restoration following a fault, higher reliability, and mitigation of effect due to voltage sag. However, distributed generation also has a negative impact on decrease of reliability such as changes of protective device setting and mal-operation.

Because bulk power systems consist of various sources and loads, it becomes complicated to analyze a power system with distributed generation. The types of distributed generation are usually classified by both rotating machinery and the inverter-based system.

In this paper, distributed generation is designed by rotating machinery, and the distributed system having a model of the distributed generation is simulated using EMTP. In addition, this paper presents the simulation results according to the types of distributed generation.

Keywords: Distribution system, Electric power systems, Fault, Generator, Voltage Sag

1. Introduction

Voltage sag is defined as a momentary decrease to between 0.1 and 0.9 pu in the RMS voltage magnitude for durations from 0.5 cycle to 1 minute, usually caused by a remote fault somewhere in the power system. Voltage sags are the most significant Power Quality (PQ) problems facing many industrial customers. Equipment used in modern industrial plants (process controllers, programmable logic controllers, adjustable speed drives, robotics) is actually becoming more sensitive to voltage sags as the complexity of the equipment increases. Even relays and contactors in motor starters can be sensitive to voltage sags, resulting in the shutdown of a process when they drop out. Because of the increased use of sensitive electronic equipment, these disturbances have a greater impact on customers than ever before. As a result, monitoring and assessment of the system performance at both the transmission and distribution voltage levels are becoming increasingly important [1-3]. Recently, there has been a considerable issue connecting new generation to the distribution network and this is known as embedded, distributed or dispersed generation [4-5].

Such distributed generation has certain advantages and disadvantages. When voltage sags occur in a power system, there is a reaction from distributed generation in which voltage sag may be mitigated or distributed generation may be experienced out-of-step. Distributed generation in distribution systems has various effects such as network voltage changes and increase in fault levels.

Many researchers have studied distribution networks including distributed generation [6-8]. Particularly, J. V. Milanovic and R. Gnativ investigated characteristics of voltage sags in radial networks with dynamic loads and embedded generators, and A. Girgis and S. Brahma studied the effect of the distributed generation of protective device coordination.

In this paper, the distribution system with distributed generator is simulated for various system conditions in order to analyze system impact of the distributed generation with particular reference to voltage sags. So, the distributed generation is designed by rotating machinery, and the distributed system using a model of the distributed generation is simulated using EMTP. Furthermore, this paper shows the simulation results according to the types of distributed generation.

2. Distributed Generation

Distributed generation was investigated by working groups, CIGRE (The International Conference on Large High Voltage Electric Systems) and CIRED (The International Conference on Electricity Distribution Networks). Distributed generation consists of synchronous or induction generators, or power electronic devices. The CIRED survey and the CIGRE report represented reasons for encouraging distributed generation. Various reasons are as follows [5].

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(1) Reduction in gaseous emissions
(2) Energy efficiency or rational use of energy
(3) Deregulation or competition policy
(4) Diversification of energy sources
(5) Ease of finding sites for smaller generators

Because environmental impact is a major factor in the consideration of electrical power schemes, distributed generation is classified into combined heat and power generation and renewable energy resources such as wind power, micro-hydro, solar photovoltaic, landfill gas, etc. The different classification of distributed generation is for types of generation, such as synchronous, induction generator or inverter-based systems.

The distributed generator is typically used to supply electric power to consumers. A distributed generator is connected to an electrical distribution network. Sometimes electric power generated by distributed generators flows reversely in the distributed network. As such it is important to check that they will not degrade the quality of supply to the consumer. Fig. 1 shows power flow at the distribution network with distributed generation.

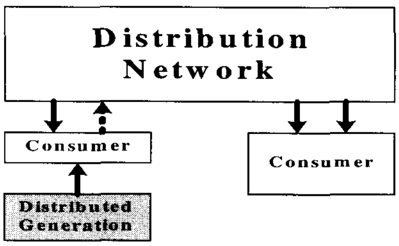

Fig. 1 Power flow at the distribution network

In this paper, we design a model of a synchronous generator using EMTP for simulation.

3. Voltage Sag [3],[9]

Voltage sags are typically caused by fault conditions. Fault resulting in voltage sags can occur within the plant or throughout the utility system. The voltage sag condition lasts until the fault is cleared by a protective device. In the plant, this will typically be a fuse or a plant feeder breaker. In the utility system, the fault could be cleared by a branch fuse or a substation breaker. If reclosing is used by the utility, the voltage sag condition can occur multiple times.

Utility system faults can transpire on a distribution system or on a transmission system. Fig. 2 illustrates a typical distribution system configuration with a number of feeders supplied from a common bus. A fault on Feeder F1 will cause an interruption, which will affect the customers on that particular feeder. However, most of the customers on the other three parallel feeders will also experience voltage sag while the fault is actually occurring on the system.

Faults on a transmission system can affect an even greater amount of customers. Customers' miles away from the fault location can still experience voltage sags resulting in equipment malfunction when the fault is on the transmission system.

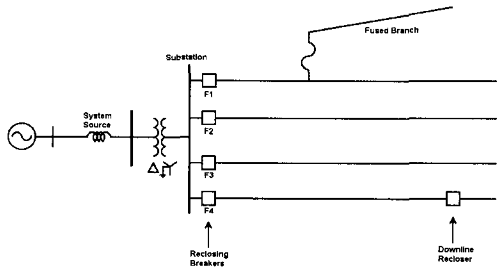

Fig. 2 Typical distribution system configuration

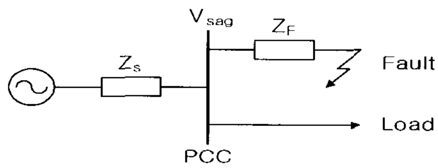

Fig. 3 Voltage divider model for voltage sag

To quantify sag magnitude in radial systems, the voltage divider model, illustrated in Fig. 3 can be used. This might appear to be a rather simplified model, especially for transmission systems. In Fig. 3, there are two impedances: Z_S is the source impedance at the point-of-common coupling (PCC); and Z_F is the impedance between the PCC and the fault. The point-of-common coupling is the point from which both the fault and the load are fed. In other words, it is the place where the load branches are off from the fault current. In the voltage divider model, the load current before as well as during the fault is neglected. There is thus no voltage drop between the load and the PCC, and thus the voltage at the equipment terminals can be found from equation (1).

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{1}$$

If the pre-event voltage is exactly 1 pu, then E = 1. This results in the equation (2) for the sag magnitude.

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} \tag{2}$$

Any fault impedance should be included in the feeder impedance Z_F. We see from equation (2) that the sag becomes deeper for faults electrically closer to the customer (when Z_F becomes smaller), and for systems with a smaller fault level (when Z_S becomes larger). Note that a single-phase model has been used here, whereas in reality the system is three-phase. That means that this equation strictly speaking only holds for three-phase faults.

4. Simulation and Results

4.1 System model studied

The model system of the distribution network for simulation is presented in Fig. 4. The model system has 5 buses, 3 transformers, and 3 loads. Total simulation time is 1.5[sec], and sampling frequency is 3840[Hz].

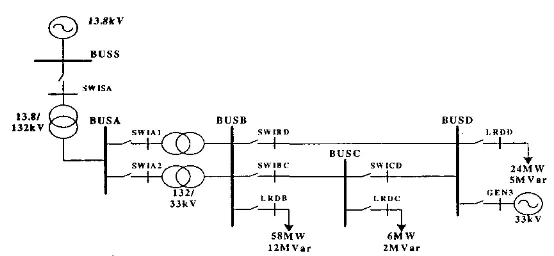

Fig. 4 System diagram for maximum load

The model system is introduced by reference [4]. BUSS has been chosen as the slack bus and this generator will supply the active power required to balance the system. So, BUSS is taken as an ideal source. Table 1 indicates system parameters.

Table 1 System parameters for networks

From bus	To bus	Type	Resistance	Reactance
BUSS	BUSA	transformer	0.0	0.06670
BUSA	BUSB	transformer	0.00994	0.20880
BUSA	BUSB	transformer	0.00921	0.21700
BUSB	BUSC	line	0.04460	0.19170
BUSB	BUSD	line	0.21460	0.34290
BUSC	BUSD	line	0.23900	0.41630
BUSD	BUSE	transformer	0.00994	0.20880

Simulation was performed in 3 types of system conditions.

(1) Maximum load, no distributed generation (DG)
(2) Maximum load, synchronous generator at BUSD
(3) Maximum load, synchronous generator at BUSE

As well, the fault condition is simulated for analyzing the system impact of the distributed generation under fault conditions. Table 2 illustrates fault types and fault locations. Fault starting time is 0.25[sec].

Table 2 Fault types and locations

Fault type	Single line-to-ground (SLGF) 3-phase fault
Fault location	BUSA, BUSC, LineBD (line between BUSB and BUSD)

Load as shown in Fig. 4 is maximum load. Fig. 5 presents different types of systems. The distributed generation has been moved to BUSE.

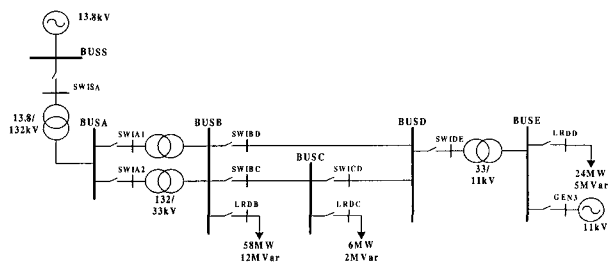

Fig. 5 System diagram for minimum load

4.2 No distributed generation system

At each bus and line, voltages and currents can be obtained, so RMS values are calculated. Per unit quantities are introduced, and baseMVA is 50MVA.

Fig. 6 indicates waveforms of voltages at each bus under normal conditions. As shown in Fig. 6, because voltages were dropped by loads and line impedances, a bus which was far from the source has a lower voltage than 1[pu]. For example, voltage at bus BUSD is about 0.98[pu].

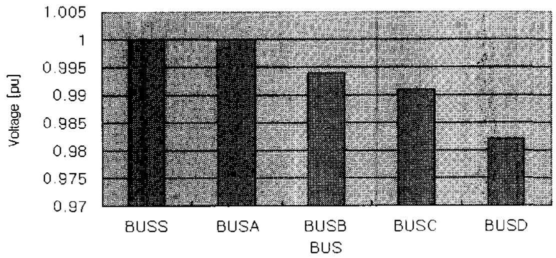

Fig. 6 Voltages for each bus under normal condition, no DG

Fig. 7 presents waveforms of voltages of phase A at each bus under single line-to-ground fault and 3-phase fault at bus BUSC.

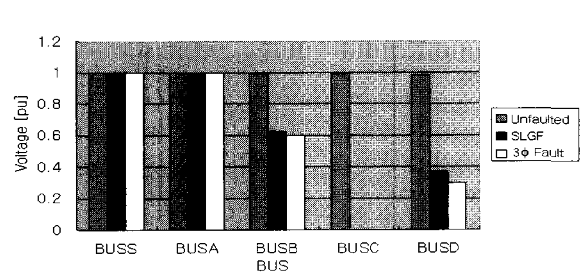

Fig. 7 Voltages at each bus under SLGF (BUSC)

After a fault occurrence, voltage at faulted bus BUSC is dropped to 0.0 [pu], and voltage sag occurs in other buses, i.e. BUSB, BUSD.

4.3 Maximum load, synchronous generator at BUSD

Figs. 8~9 show waveforms of voltage and current at each bus in systems connected with a synchronous generator (capacity: 10MVA) as distributed generation at bus BUSD.

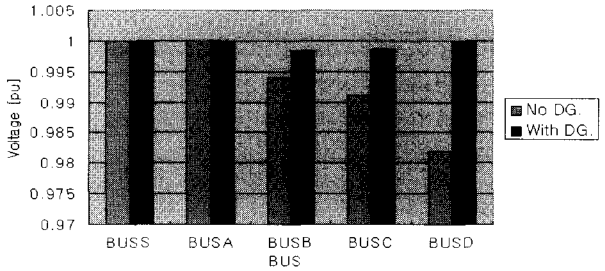

Fig. 8 Voltages at each bus

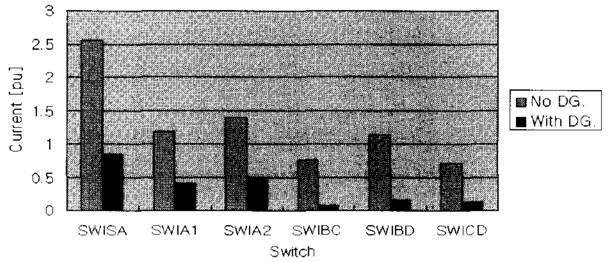

Fig. 9 Currents through each switch with DG (BUSD)

As shown in Figs. 8~9, voltages connected with synchronous generators at bus BUSD are 1.0[pu], and currents through each switch are small values against the case of no distributed generation.

Fig.s 10 and 11 demonstrate the variation of bus voltage in a system connected with distributed generation under single line-to-ground and 3-phase fault, respectively. As seen in Fig. 10, we can observe a small variation of voltage at bus BUSD by synchronous generator in comparison with Fig. 8. This variation is made by a speed regulator in the synchronous generator, and it is large at the bus connected with distributed generation.

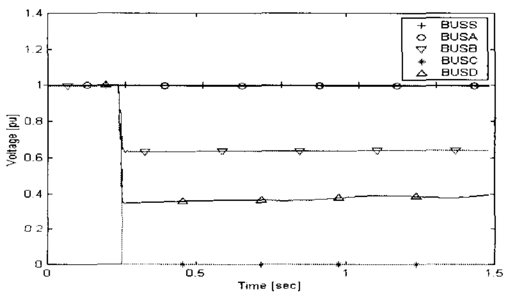

Fig. 10 Voltages at each bus under SLGF (BUSC) with DG

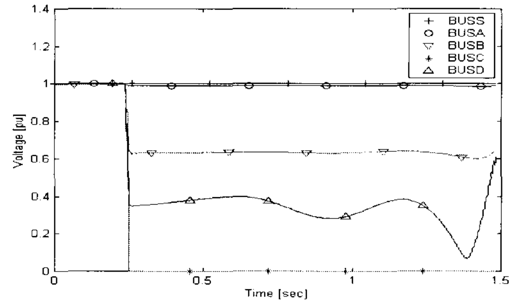

Fig. 11 Voltages at each bus under 3-phase fault with DG

As shown in Fig. 11, voltage at BUSD is increasing in fluctuation. We can show phase angle of the generator in Fig. 12. Magnitude of the phase angle is increasing. This means that the generator is losing synchronism.

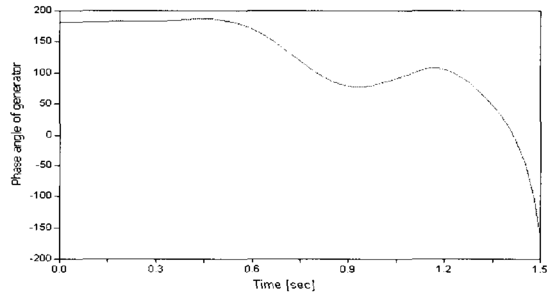

Fig. 12 Phase angle of synchronous generator

4.4 Maximum load, synchronous generator at BUSE

For analysis of impacts on distributed generation connected with a low level bus, the system in Fig. 5 is simulated. In this case, voltage at bus BUSE connected with distributed generation maintains 1.0[pu] under normal conditions, but also observe that voltage at bus BUSD is 0.92[pu] in Fig. 13. Fig. 14 indicates waveforms of voltages under single line-to-ground fault at bus BUSC.

After a fault, the synchronous generator loses synchronism at 0.45[sec]. Voltage at bus BUSC connected with the synchronous generator fluctuates between 0.6[pu] and 1.8[pu], thereby affecting voltages at other buses, i.e. BUSB, BUSD.

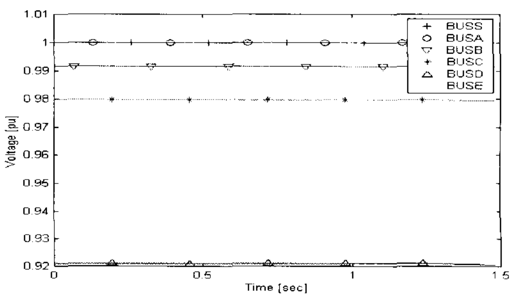

Fig. 13 Voltages at each bus with DG (BUSE)

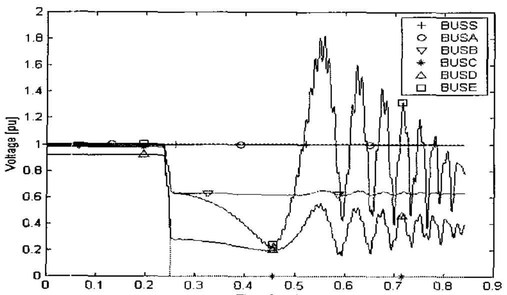

Fig. 14 Voltages at each bus under SLGF with DG (BUSE)

Fig. 15 shows waveforms of voltages of phase A at bus BUSE under various capacities of distributed generation. The different capacities of each generator has been simulated and the results summarized in Fig. 15.

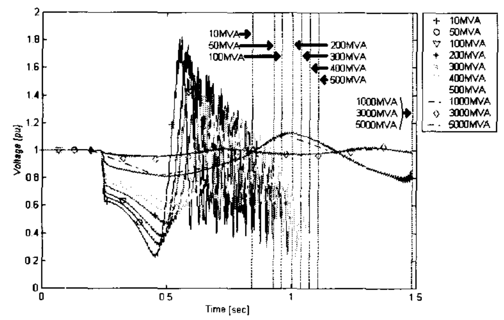

Fig. 15 Voltages of phase A at BUSE under various capacities of distributed generation

As shown in Fig. 15, if capacity of the generator is larger, the distribution system can withstand voltage sag or fault. When the speed of the generator is very low, EMTP ends simulation. The horizontal lines in Fig. 15 indicate the simulation completion time. There exist several facts in this instance. When the capacity of the generator is large, first, fluctuation of voltage is small, second, simulation time increases. Fig. 16 shows waveforms of voltages at each bus under single line-to-ground faults in systems connected with synchronous generators at bus BUSE.

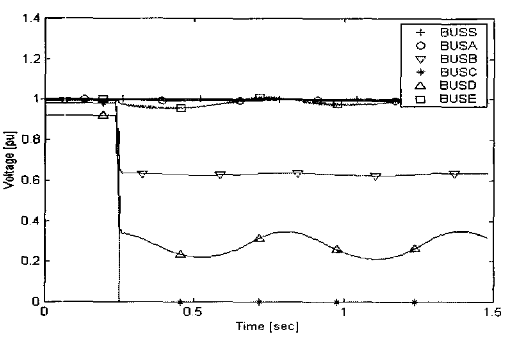

Fig. 16 Voltages at each bus under SLGF (BUSC) with DG (BUSE, 5000MVA)

As presented in Fig. 16, if the capacity of the generator is sufficient to supply fault current, then the synchronous generator doesn't loss synchronism. However, the fault still remains, so, voltages of other buses are small in value.

4.5 Summary

Voltage sags by SLGF on the BUSB and BUSD are shown in Fig. 17. When the DG is connected with the distribution system, voltages will have a slight increment at each bus during a fault. The magnitude of voltages on the BUSB and BUSD have increased under various capacities of DG, and are shown in Fig.s 18 and 19.

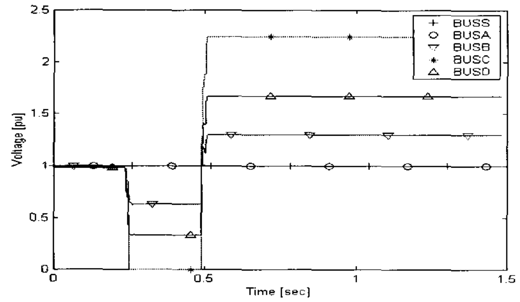

Fig. 17 Voltages at each bus under transient fault without DG

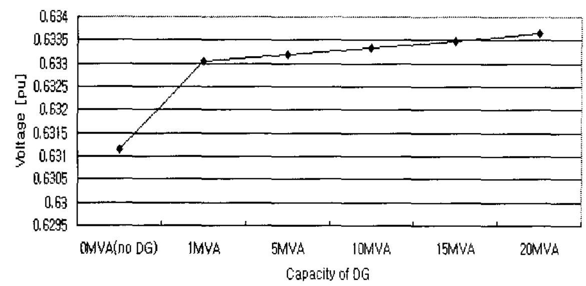

Fig. 18 Voltage at BUSB by various capacity of DG

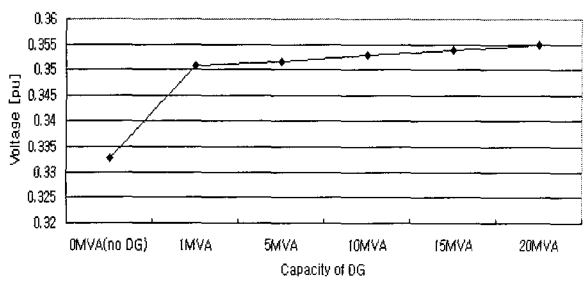

Fig. 19 Voltage at BUSD by various capacity of DG

Because the capacity of DG is smaller than in the central power plant, voltage increment is small. Nevertheless each bus still suffers from voltage sag.

As depicted in Fig. 20, in the system connected with distributed generation, post-fault voltage approaches to pre-fault voltage at each bus.

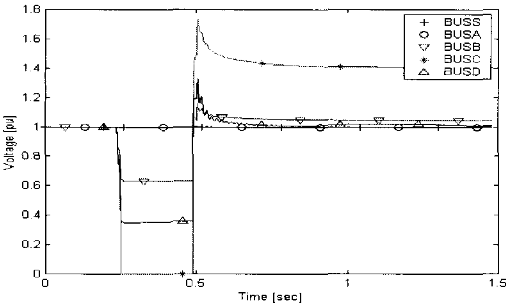

Fig. 20 Voltages at each bus with DG (10MVA)

The distributed generation is affected with voltage sag. If the magnitude of the voltage sag is very great, the system is unstable and the synchronous generator loses synchronism. As shown in Fig. 15, when the synchronous generator has a large capacity, the system well endures voltage sag. Moreover, if voltage sag has a short duration, the generator will only be slightly affected. Therefore, if not prepared for voltage sag, the synchronous generator loses synchronism and suffers damage during voltage sag. Furthermore, the synchronous generator induces over-voltage when the generator loses synchronism, so it can lead to serious damage of the power system equipment. Fig. 21 shows waveforms of voltages at bus BUSD for various fault locations.

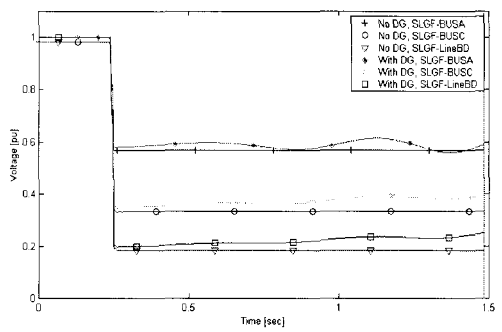

Fig. 21 Voltages for various conditions

As presented in Fig. 21, the magnitude of voltage sag at the bus connected with distributed generation is in inverse proportion to distance from the fault position. However, power swing exists by synchronous generator and when voltage sag is severe, synchronous generator loses synchronism.

5. Conclusion

Voltage sag impacts on various system components, such as the generator, motor, power electronic devices, computer, etc. When the system is operating under normal conditions, distributed generation is able to maintain system voltage efficiently.

The distribution network with/without distributed generation is simulated by using EMTP in order to analyze system impact. When the system is stable, the synchronous generator has good effect on system voltage, but once fault or voltage sag occurs, the synchronous generator becomes unstable. This simulation demonstrates the serious impact of distributed generation under a fault, such as loss of synchronism.

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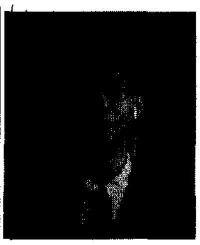

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