Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

ANALYSIS OF VOLTAGE SAGS DUE TO UNBALANCED FAULTS IN DISTRIBUTION SYSTEMS IN THE PRESENCE OF AC GENERATORS

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ABSTRACT
This paper presents a preliminary analysis on the impact of ac generators on voltage sags in distribution systems cause by unbalanced short-circuits. The analysis is conducted through numerous electromagnetic transient simulations. Distributed generation systems composed by synchronous and induction machines are considered. The results show that the voltage sags in different system buses are affected due to the presence of ac generators.

KEY WORDS
Distributed generation, distribution systems, synchronous generators, induction generators, voltage sags, unbalanced short-circuits.

1. Introduction

One of main cause of voltage sags in distribution networks, which is a very important power quality problem facing many industrial customers, is unbalanced short-circuits [1]. Modern variable speed drivers, for example, are very susceptible to voltage sags and, in some extreme cases, these equipments may be tripped when the voltage drops bellow 80%, leading to serious financial issues.

In addition, in recent years, the usage of distributed generators in electric power distribution systems has significantly increased [2]-[4]. Despite the fact that considerable attention has been paid to new generation technologies, *e.g.* fuel cells and photovoltaic arrays, nowadays, most distributed generation sites employ synchronous and induction machines [4]. It is well recognized that these machines can supply short-circuit currents to unbalanced faults.

Based on the above facts, it is important to determine and understand the impact of ac generators on voltage sags due to unbalanced faults. In this case, it is necessary to verify the impact on the voltage sag at the producer bus as well as at buses of other consumers. Therefore, this paper presents some preliminary results on this topic. The analysis is conducted by investigating several cases simulated through an electromagnetic transient program, as suggested in [5]. The results can be useful for industrial consumers and power producers.

This work is organized as follows. Section II describes the models of the diverse network components adopted to conduct this investigation. Section III explains the voltage sag characterization approach used to compare different cases. The main simulation results are presented in Section IV. Finally, the preliminary conclusions are summarized in Section V.

2. Network Component Models

The electromagnetic transient simulation package adopted was the SimPowerSystems version 4.0 for use with Matlab/Simulink, [6]. In this work, all network components were represented by three-phase models. The distribution network feeders were represented by a series *RL* impedance, because they can be considered short-lines, and the transformers were modeled through the *T* circuit. In the studies, active power loads were represented by constant current models and reactive power loads were represented by constant impedance models, as recommended in [7] to dynamic studies.

2.1 Induction Generators

Although most induction generators in operation are employed in wind power plants [4], [8], such machines have also been used in medium size hydro and thermal plants [4], [9]-[11]. Therefore, in order to keep the results as generic as possible, the mechanical torque was considered constant, *i.e.* the speed regulator and prime mover dynamics were neglected. In addition, the speed regulator and prime mover, indeed, have practically no influence on voltage sags since its response times are quite long. The squirrel-cage rotor induction generator was represented by a sixth-order model [6]. In all cases simulated, part of the reactive power consumed by the generator was locally supplied by capacitors installed at the terminal of the machine, whose compensation capacity was adopted equal to 1/3 of the machine capability, as is usual in this case [4].

2.2 Synchronous Generators

At present, most distributed generation systems employ synchronous generators, which can be used in thermal, hydro or wind power plants [4]. In the electromagnetic transient simulations, the synchronous generators were represented by an eight-order model [6]. Usually, synchronous generators connected to distribution networks are operated as constant active power sources, so that they do no take part in the system frequency control [4]. Therefore, in this work, the mechanical power was considered constant, *i.e.* the speed regulator and prime mover dynamics were neglected. Moreover, as previously mentioned, the time constants of typical speed regulators and prime movers are quite high so that they have practically no impact on voltage sags. In addition, typically, there are two different modes of controlling the excitation system of distributed synchronous generators. One aims to maintain constant the terminal voltage (voltage control mode) and the other one aims to maintain constant the power factor (power factor control mode) [4], [12]. Power factor control mode is usually adopted by independent producers to maximize the active power production [4]. In consequence, unitary power factor operation is adopted. Thus, both forms of control are employed in this study. In the voltage regulator cases, the controller set point was fixed at 1 pu. Whereas, in the power factor regulator cases, the controller set point was fixed at 1 (unitary power factor). A functional description of excitation systems acting as a voltage or power factor regulator is provided in [12].

2.3 Test System

The test systems used in this work is shown in Fig. 2. Such network comprises a 133 kV, 60 Hz, subtransmission system with short-circuit level of 1500 MVA, represented by a Thevenin equivalent (Sub), which feeds a 33 kV distribution system through two 132/33 kV, Δ/Yg transformers. An ac generator with capacity of 30 MVA is connected at bus 6, which is connected to the network through a 33/6.9 kV, Δ/Yg transformer. This machine can represent one generator in a thermal generation plant as well as an equivalent of various generators in a wind or small-hydro generation plant. In some cases, such machine was simulated as an induction generator and in other ones as a synchronous generator.

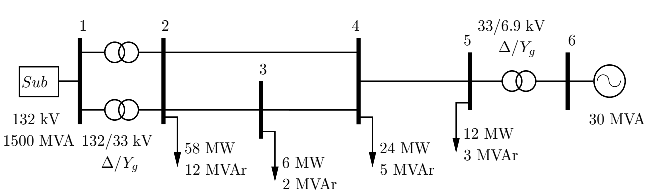
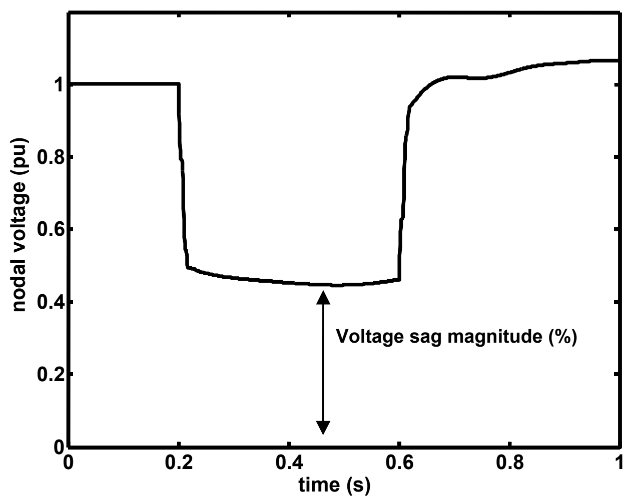


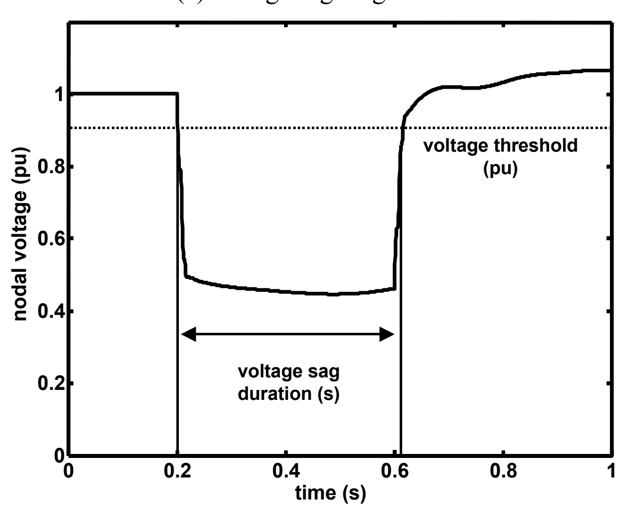
Fig. 1. Single-line diagram of the system.

3. Voltage Sag Characterization

When analyzing voltage sag related issues, it is necessary to use some factors that can characterize or quantify the voltage sag. Although, just magnitude and duration are not enough to conduct a complete and detailed investigation [5], these factors are used in this work, since these parameters are easily determined and calculated. In this paper, voltage sag magnitude refers to the remaining rms voltage, as recommended in [13]. This factor can be better understood through Fig. 2(a). On the other hand, the voltage sag duration is defined as the total period that the rms voltage is lower than a determined threshold, as indicated in Fig. 2(b). The threshold value adopted here is 0.85 pu. As a comparison tool, these factors can be applied to the rms voltage per phase or to the positive sequence voltage.



(a) voltage sag magnitude.



(b) voltage sag duration.

Fig. 2. Definition of voltage sag magnitude and duration.

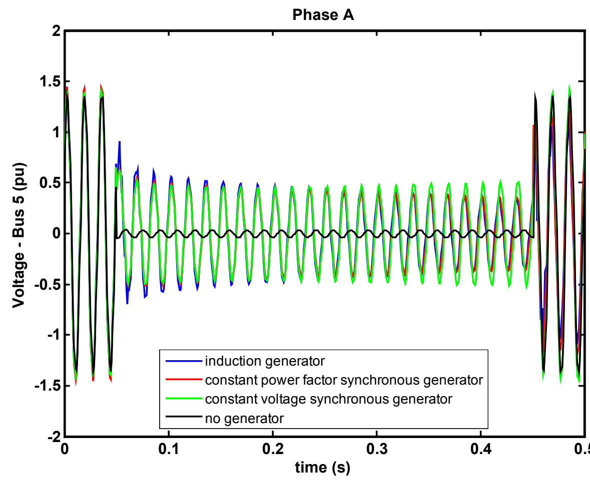
4. Simulation Results

In this section, some simulation results are presented and discussed. Fig 3 presents the dynamic behavior of phase-A voltage in different system buses for a phase-A-to-ground fault applied at bus 4 at t = 50 ms, which is eliminated in 400 ms. Moreover, the voltage variation in the faulted phase is shown considering the presence of different generators and for the case without any generator.

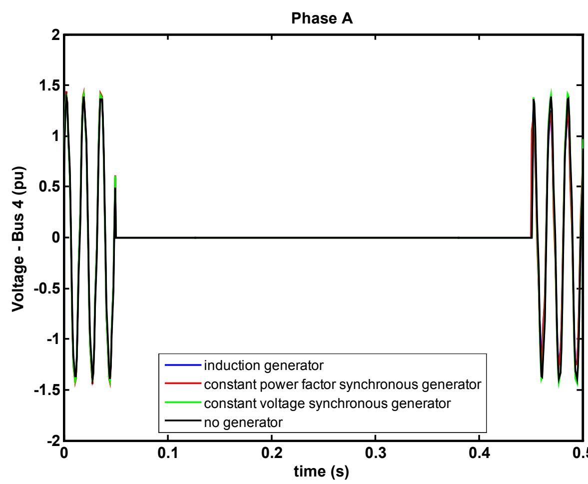
As one can see, from Fig 3(a), the voltage sag at bus 5 is less severe in the presence of the distributed generator, since it helps to sustain the voltage during the fault. This bus is the closest one to the generator. In the case of bus 4, as shown in Fig 3(b), the voltage goes to zero for all cases, since the fault is applied at this bus. On the other hand, at bus 3, the voltage sag is aggravated by the presence of the induction generator, as can be verified from Fig. 3(c). However, for the other generators there is no difference when compared with the case without generator. Based on these results, one can argue that the installation of an induction generator at bus 5 leads to a more severe voltage sag at bus 3 in the case of occurrence of phase-to-ground faults in the system.

To facilitate the comparison, Fig. 4 presents the dynamic responses of the positive sequence voltages of buses 3, 4 and 5 for the same previous fault. Analyzing the voltage of bus 4 and 3, one can verify that the voltage sag magnitude (minimum value of voltage) is smaller in the presence of the generators, *i.e.* the voltage sag problem is aggravated by the installation of the generators. It occurs because the generators increase the system short-circuit level. On the other hand, analyzing the voltage of bus 5, one can see that in the presence of the constant voltage synchronous generator, the voltage sag magnitude is larger, *i.e.* the voltage sag problem is improved by the generator. In the case of the constant power factor synchronous generators, there is practically no difference between the situation with and without generator considering the voltage sag magnitude of bus 5. Whereas the voltage sag of bus 5 is adversely affected by the induction generator.

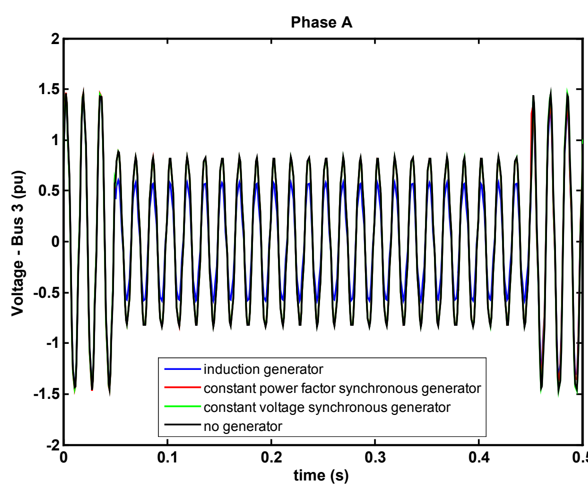
In order to obtain a better understanding of the influence of each type of generation on voltage sags, many repeated simulations were carried out considering different clearance times of the fault described previously. As discussed, voltage sags can be characterized by their magnitude (minimal value of voltage) and duration (period that the voltage remains below a determined value). In addition, these factors can be applied to the positive sequence voltage. By using these factors, the results are summarized in TABLE , where the voltage sags of buses 4 (where the fault is applied) and 5 (where the generator is installed) are shown.



(a) voltage at bus 5.



(b) voltage at bus 4



(c) voltage at bus 3.

Fig. 3. Voltage behavior due to a phase-A-to-ground fault at bus 4.

Analyzing the behavior of bus 5 voltage, one can confirm that the usage of the constant voltage synchronous generator improves the voltage performance from sag magnitude viewpoint. In the case of constant power factor synchronous generator, for some situations, the voltage sag magnitude is improved. However, when the fault clearance time increases, the presence of the generator affects negatively the response of bus 5 voltage. On the other hand, in the case of the induction generator, independent of the fault clearance time, both the magnitude and the duration of the voltage sag are adversely affected when compared with the case without generators. Such differences can be partially explained through the dynamic behavior of the reactive power exchanged between the generators and the network. In the case of bus 4 voltage, independent of the type of the generator employed, in all cases, the voltage sag is aggravated by the installation of the generators due to the increase in the system short-circuit level.

Therefore, it can be verified that, typically, the installation of a generator in an industry plant can reduce the voltage sag at this bus. However, the voltage supplied to the other consumers may be adversely affected by this installation.

5. Conclusion

This paper presented some preliminary results on voltage sags in distribution systems due to unbalanced faults in the presence of synchronous and inductions generators. The results show that these generators can have an important impact on the voltage sag magnitude and duration. Moreover, the installation of these generators can usually alleviate the voltage sag in the producer bus but, on the other hand, it may adversely affect the voltage sag at buses of other consumers. The results presented here are not definitive and more research must be done to completely understand the influence of different types of generators on voltage sags.

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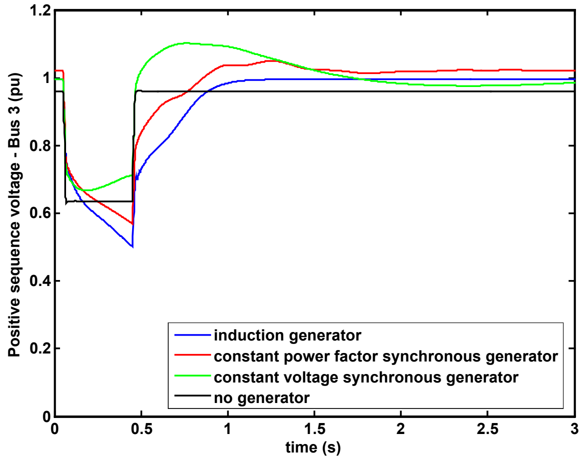
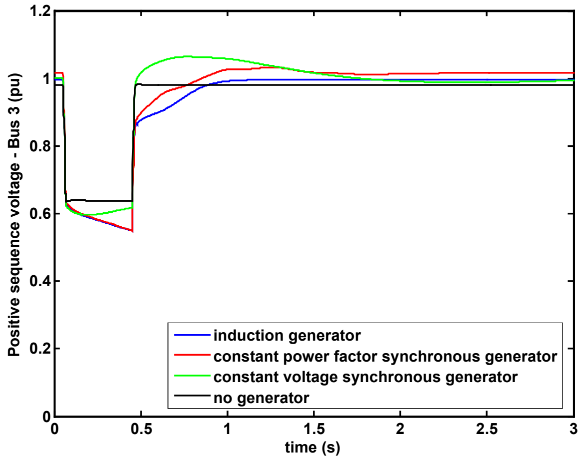
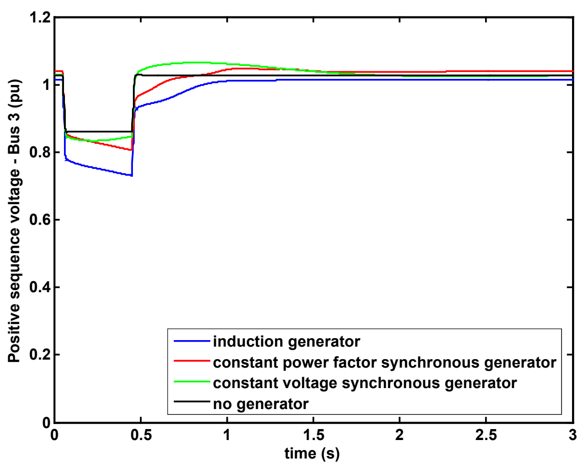


(a) positive sequence voltage of bus 5.



(b) positive sequence voltage of bus 4.



(c) positive sequence voltage of bus 3.

Fig. 4 Response of the nodal voltage of bus 4 and 5 for a phase-A-to-ground short-circuit applied at bus 4.

Table 1
Voltage sags due to a phase-to-ground short-circuit

	fault duration = 200 ms			
	bus 5		bus 4	
generator type	magnitude (pu)	duration (ms)	magnitude (pu)	duration (ms)
no generators	0.623	207	0.632	206
constant voltage synchronous generator	0.640	203	0.585	207
constant power factor synchronous generator	0.644	204	0.585	207
induction generator	0.5445	236	0.550	212
	fault duration = 300 ms			
	bus 5		bus 4	
generator type	magnitude (pu)	duration (ms)	magnitude (pu)	duration (ms)
no generators	0.612	307	0.632	306
constant voltage synchronous generator	0.649	302	0.585	307
constant power factor synchronous generator	0.620	306	0.570	307
induction generator	0.503	434	0.529	315
	fault duration = 400 ms			
	bus 5		bus 4	
generator type	magnitude (pu)	duration (ms)	magnitude (pu)	duration (ms)
no generators	0.612	407	0.632	406
constant voltage synchronous generator	0.649	401	0.585	406
constant power factor synchronous generator	0.596	414	0.558	411
induction generator	0.466	705	0.512	442
	fault duration = 500 ms			
	bus 5		bus 4	
generator type	magnitude (pu)	duration (ms)	magnitude (pu)	duration (ms)
no generators	0.612	507	0.632	506
constant voltage synchronous generator	0.649	500	0.585	506
constant power factor synchronous generator	0.578	525	0.551	512
induction generator	0.438	1241	0.501	1011