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Voltage Magnitude Analysis Considering Load Curtailment Minimization in Sub-Transmission Networks with Distributed Generators

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Abstract

Most of distribution generation and smart grid research works are dedicated to the study of network operation parameters, reliability among others. However, many of this research works usually uses traditional test systems such as IEEE test systems. This work proposes a voltage magnitude study in presence of fault conditions considering the realistic specifications found in countries like Brazil. The methodology considers a hybrid method of fuzzy set and Monte Carlo simulation based on the fuzzy-probabilistic models and a remedial action algorithm which is based on optimal power flow. To illustrate the application of the proposed method, the paper includes a case study that considers a real 12 bus sub-transmission network.

Keywords: Distribution generation, Optimal power flow, Reliability, Sub-transmission network.

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1. Introduction

Minimizing the unserved power by minimization of load curtailment leads to a reliability maximization in electrical systems. Thus, an important monetary loss due to undelivered power, economic damage and inconvenience to the power system user is avoided. The reliability criteria used to support decision making in electrical power system can be deterministic or probabilistic. In both cases, it is necessary to make use of a consistent database and to undertake an exhaustive statistical analysis of all the available information, such as failure rates (λ) and average repair times (r) of each distribution system component.

The new structure of the electrical network, after the implementation of concepts such as distributed generation (GD) and smart grid, consists of various subsystems or networks of different levels which belong to the same power system. In reality, the structure of such networks varies; it depends on the area and on the policy that guide the energy planning.

The IEEE test systems are used to analyze and simulate methodologies. However, depending on the network characteristic, such circuits sometimes don't give a reasonable description of reality. Taking Brazil as an example, the huge size of the power system as well as the territory makes it possible to exploit several levels of voltage where it is suitable to use high voltage in distribution or sub-transmission networks (69 kV) through the extensive usage of distributed generation [1, 2]. Thus, it is necessary to characterize and analyze the sub-transmission networks.

The present work proposes a voltage magnitude study in presence of fault conditions considering the realistic specifications found in countries like Brazil. The methodology proposed is based on statistical failure and repair data of the sub-transmission power system components and uses fuzzy-probabilistic modeling for system component outage parameters. To catch both randomness and fuzziness of component outage parameters, a hybrid method of fuzzy set and Monte Carlo simulation based on the fuzzy-probabilistic models is presented. A remedial action algorithm, based on optimal power flow is used to minimize the total load curtailment [3, 4].

This paper is organized as follows: Section 2 explains the proposed methodology. Section 3 presents the case study and the discussion of the obtained results. Finally, in section 4 the most relevant conclusions are presented.

2. Methodology

Figure 1 presents the idea of the proposed methodology. This methodology is intended only for independent forced outages and has five main aspects: database creation, network characterization, fuzzy models for repair time, failure rate and unavailability, selection of system states and remedial actions.

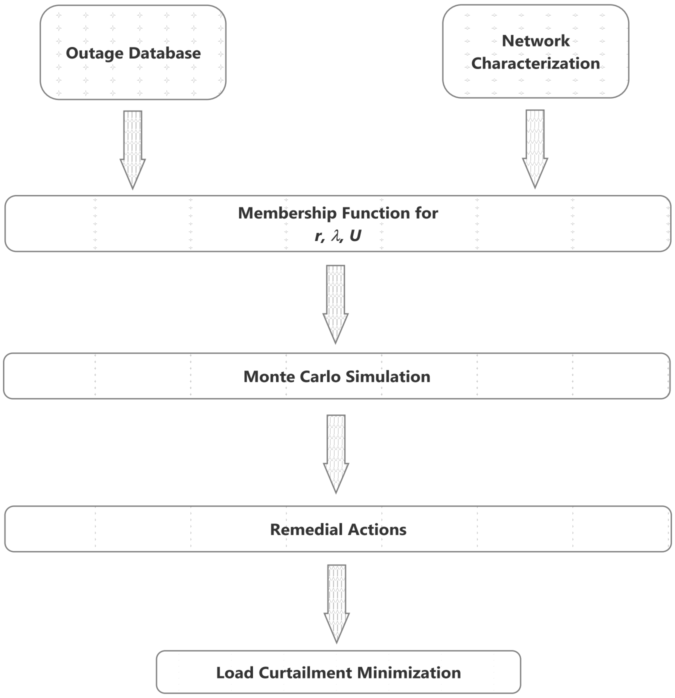

Fig. 1. Proposed methodology scheme

2.1. Outage database

A creation of a consistent database an exhaustive statistical analysis of all available information are the main basis for the proposed methodology.

2.2. Network characterization

The test network with intensive usage of distributed generators take into account with electrical characteristics, such as topology, load level, generation power, voltage magnitude and angle, etc.

2.3. Fuzzy membership functions for repair time, failure rate and unavailability

It is extremely difficult to distinguish precisely the effects of the weather conditions, and environment and operational conditions on the outage data of individual components using a probability model. The failure frequency or probability of sub-distribution power systems are directly impacted by these conditions. It is also very common that a large number of utilities do not have sufficient statistical records of outage parameters. Thus, the fuzzy model is an appropriated method to represent the uncertainty. Fuzzy models for repair time, failure rate and unavailability can be found in [3, 4].

2.4. Monte Carlo simulation

In general, sub-transmission components are represented using the two-state (up and down) model. The two-state models for generating units and transmission components are created by Nonsequential Monte Carlo Simulation [3] in order to obtain a sample of all possible transmission power system states:

$$S_i = \begin{cases} (success) & if \quad R_i > Q_i \\ (failure) & if \quad 0 \leq R_i \leq Q_i \end{cases} \tag{1}$$

The system state containing N components is depicted by vector S:

$$S = (S_1, \dots, S_i, \dots, S_N) \tag{2}$$

where S_i denotes the state of the ith component and Q_i its failure probability (unavailability) for the ith component. R_i is a random number uniformly distributed between [0, 1] for the ith component.

2.5. Remedial actions

A remedial action algorithm, based on optimal power flow (OPF) (see equations (3–14)) is used to reschedule generation and alleviate constraint violations and, at the same time, to avoid any load curtailment, if possible, or, otherwise, to minimize the load curtailment. The objective function of the OPF model minimizes the total load curtailment.

$$min \sum_{i \in LG} Scut_i \tag{3}$$

$$PGEN_i^{min} \leq PGEN_i \leq PGEN_i^{max} \quad i \in GN \tag{4}$$

$$QGEN_i^{min} \leq QGEN_i \leq QGEN_i^{max} \quad i \in GN \tag{5}$$

$$Pcut_i \leq Lp_i \quad i \in LG \tag{6}$$

$$Qcut_i \leq Lq_i \quad i \in LG \tag{7}$$

$$PGEN_i - Lp_i - P_i(v, \delta) + Pcut_i = 0 \quad i \in GN \tag{8}$$

$$QGEN_i - Lq_i - Q_i(v, \delta) + Qcut_i = 0 \quad i \in GN \tag{9}$$

$$P_i(v, \delta) + Lp_i - Pcut_i = 0 \quad i \in LN \tag{10}$$

$$Q_i(v, \delta) + Lq_i - Qcut_i = 0 \quad i \in LN \tag{11}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad i \in N \tag{12}$$

$$\delta_i^{min} \leq \delta_i \leq \delta_i^{max} \quad i \in N \tag{13}$$

$$S_k(v, \delta) \leq S_k^{max} \tag{14}$$

3. Case study

A Brazilian 12 bus sub-transmission network (Figure 2) with 69kV, 1 substation and 11 load points is used for the application of the proposed methodology. In this case study were considered three load levels referred as light, moderate and heavy load. Eight capacitor banks are located in buses 2, 5, 6, 7, 9, 10, 11 and 12. The MVA base is 100.

Simulations were carried out in order to determine the response of the Brazilian 12 bus sub-transmission network with addition of distributed generators (DG) (they can be located at buses 2, 5, 6, 7, 9, 10, 11, 12) considering steady state and fault state in the network. The data network are presented in tables 1 and 2.

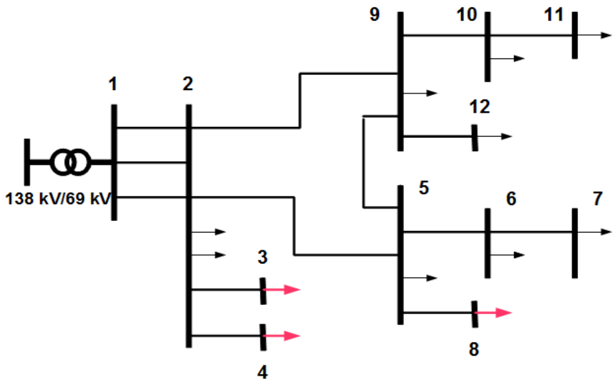

Fig. 2. Sub-Transmission network topology

The DG characteristics are:

- Size - 1, 3, 5, 7, 10 for steady state and additional 20, 30 MVA in failure analysis;
- Power factor - 0.9.

Table 1. Line data

Bus Out	Bus In	R (pu)	X (pu)	Thermal Limit (MVA)
1	2	0.0644	0.1527	71
1	2	0.0146	0.0617	106
1	2	0.0265	0.1164	106
2	3	0.0099	0.0417	34
2	4	0.0024	0.0058	71
2	5	0.0128	0.0544	106
5	6	0.1481	0.3593	72
6	7	0.1346	0.3264	72
5	8	0.0038	0.0089	72
2	9	0.0561	0.2460	106
9	10	0.1996	0.4842	72
10	11	0.2472	0.5995	72
9	12	0.6579	0.5562	34
5	9	0.0449	0.1972	106

Table 2. Load data

Bus	Heavy Active Load [pu]	Moderate Active Load [pu]	Light Active Load [pu]	Heavy Reactive Load [pu]	Moderate Reactive Load [pu]	Light Reactive Load [pu]	Capacitor [pu]
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.3045	0.2284	0.1218	0.1544	0.1003	0.0463	0.1836
3	0.1150	0.0863	0.0460	0.0378	0.0246	0.0113	0.0000
4	0.2320	0.1740	0.0928	0.0763	0.0496	0.0229	0.0000
5	0.3099	0.2324	0.1240	0.1494	0.0971	0.0448	0.0918
6	0.0751	0.0563	0.0300	0.0426	0.0277	0.0128	0.0406
7	0.0708	0.0531	0.0283	0.0322	0.0210	0.0097	0.0204
8	0.0310	0.0233	0.0124	0.0102	0.0066	0.0031	0.0000
9	0.1210	0.0908	0.0484	0.0353	0.0230	0.0106	0.0714
10	0.0771	0.0578	0.0309	0.0329	0.0214	0.0099	0.0306
11	0.0343	0.0257	0.0137	0.0131	0.0085	0.0039	0.0204
12	0.0166	0.0125	0.0066	0.0107	0.0070	0.0032	0.0306

3.1. Voltage analysis for steady state

As an example figures 3 and 4 presents the voltage results for steady and fault state in each bus considering the DG in bus 6.

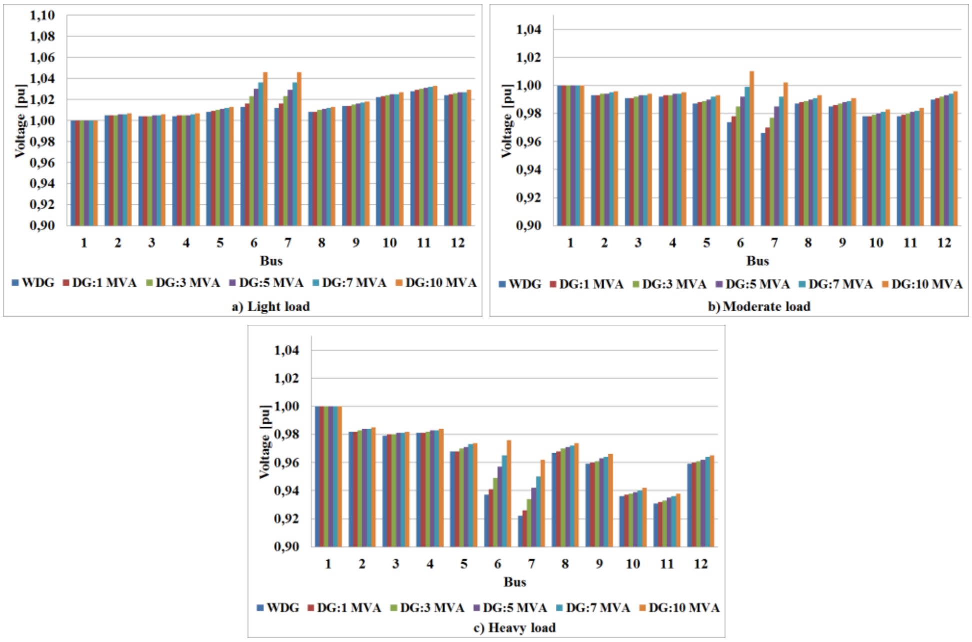

Fig. 3. Bus voltage in steady state: DG in bus 6

As can be seen in Figure 3 a strong impact in voltage magnitude occurs when heavy load is considered, mainly in buses 6, 7, 10, and 11. These four buses belongs to radial structure in the network and are very sensible to load growth.

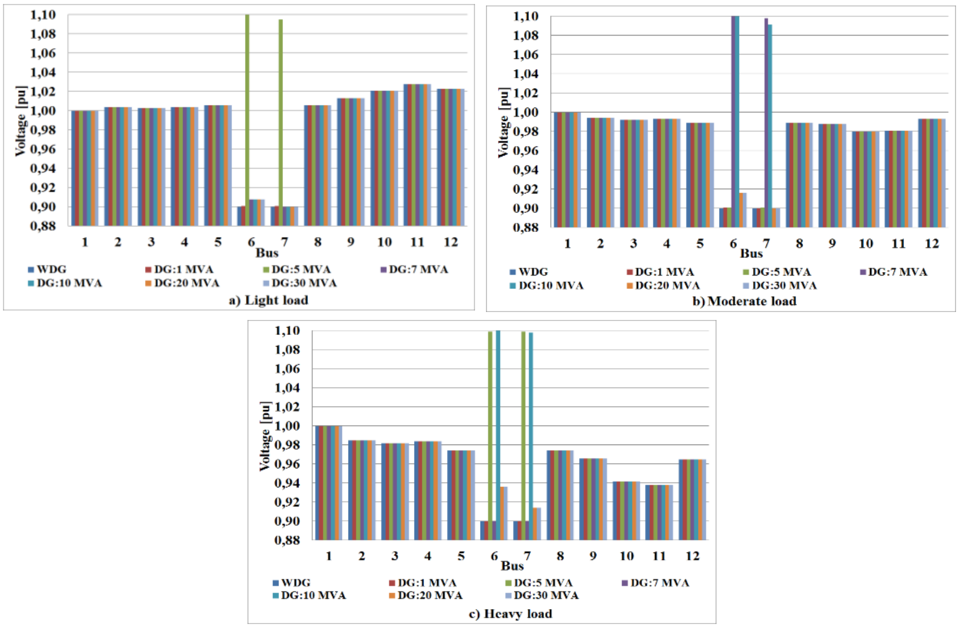

Fig. 4. Bus voltage in fault state: DG in bus 6

Monte Carlo simulation shows that line 5-6 presents the highest fault probability (0.17%). Thus, the simulation in fault condition considers line 5-6 in down sate. It is possible to seen through Figure 4 that buses 6 and 7 are the most affected. There are two reasons for this situation; these two buses are close to the fault and are in radial lines. Buses 10 and 11 are also strongly affected with the load increasing (heavy load).

Table 3 presents the active load curtailment for a fault in line 5-6 considering three load levels and six different DG capacities in bus 6.

Table 3 Total load curtailment for a fault in line 5-6

DG (MW)	Light Load Curtailment		Moderate Load Curtailment		Heavy Load Curtailment	
	(p.u.)	(%)	(p.u.)	(%)	(p.u.)	(%)
1	0.036	6.49	0.1	9.61	0.137	9.88
5	0.013	2.34	0.064	6.15	0.101	7.28
7	0	0	0.046	4.42	0.083	5.98
10	0	0	0.02	1.92	0.056	4.04
20	0	0	0	0	0	0
30	0	0	0	0	0	0

Through table 1 it is possible to see that load curtailment doesn't exceed 10% of total system load and can be observed that the DG contributes to the reliability increasing.

4. Conclusions

This paper presents a voltage magnitude study in presence of fault conditions considering the realistic specifications found in countries like Brazil. As can be seen, the load influence and network topology are essential factors in sub-transmissions network studies. Fault conditions in radial lines, like 5-6 leads to a considerable variation in voltage magnitude in buses that proceeds that line (buses 6 and 7). It was verified a strong contribution in reliability increasing in fault condition when DG is present on the network.

Nomenclature

$Scut_i$	Load curtailment at bus i in p.u.
$PGEN_i$	Generated active power at bus i in p.u.
$PGEN_i^{max}$	Upper limit of generated active power at bus i in p.u.
$PGEN_i^{min}$	Lower limit of generated active power at bus i in p.u.
$QGEN_i$	Generated reactive power at bus i in p.u.
$QGEN_i^{max}$	Upper limit of generated reactive power at bus i in p.u.
$QGEN_i^{min}$	Lower limit of generated reactive power at bus i in p.u.
$Scut_i$	Apparent load curtailment at bus i in p.u.
Lp_i	Active load at bus i in p.u.
Lq_i	Reactive load at bus i in p.u.
$P_i(v,\delta)$	Active power injections at bus i in p.u.
$Q_i(v,\delta)$	Reactive power injections at bus i in p.u.
V_i	voltage magnitude at bus i in p.u.
V_i^{max}	Upper limit of voltage magnitude at bus i in p.u.
V_i^{min}	Lower limit of voltage magnitude at bus i in p.u.
δ_i	Voltage angle at bus i in p.u.
δ_i^{max}	Upper limit of voltage angle at bus i in p.u.
δ_i^{min}	Lower limit of voltage angle at bus i in p.u.
$S_k(v,\delta)$	Apparent power flow on line k in p.u.
S_k^{max}	Rating power limit of line k in p.u.
LG	Set of buses with loads (generator bus and load bus that contain loads)
GN	Set of generator buses
LN	Set of load buses
N	Total number of buses

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