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Impact of Distributed Generation in Steady State, Voltage and Transient Stability–Real Case

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Abstract— **This paper investigates the influence of a synchronous distributed generation on a Brazilian real network. The distributed generation represents a small hydro power plant with total capacity of 30MW. The model of the network is developed in a professional computer software package. Simulations are carried out considering voltage dependency of static loads and different DG penetration levels. The technical aspects analyzed are steady-state voltage profile, electrical power losses, voltage and transient stability. Also, some adequacy aspects are analyzed, related to national and international standards. It was found that the distributed generation enhanced the overall system performance.**

Index Terms— **Distributed generation, synchronous machine, steady-state voltage profile, transient stability, voltage stability.**

I. INTRODUCTION

IN recent years, many distributed generators (DG) have been installed in power systems worldwide, and many more units are expected to be installed in the near future because of their advantages over conventional generation. The European Union goal is a 22% production from renewable energy sources in 2010 [1]. This scenario is motivated by the increasing concern over environment impact and the need for eliminating the unnecessary transmission and distribution costs.

Examples of renewable energy sources are wind turbines, photovoltaic systems, biomass, fuel cells and small hydro power plants. In particular, small hydro power plants have obtained increasing interest due to their acceptable prices for generating electrical power without producing harmful pollution and green-house gases and their relatively low environmental impact compared to large hydro power plants.

However, the connection of the DG has both benefits and drawbacks of the technical, economical and environmental aspects [2]. A high DG penetration level may influence the whole system operation and control, leading to technical impacts that must be identified [3, 4]. Then, such aspects must be analyzed to prevent instability problems and assure adequate system voltage and frequency levels, regarding customers and utility interests.

In this context, this paper presents a complete investigation of DG penetration level influence on system technical aspects such as: steady-state voltage profile and losses, voltage and transient stability. Also, some adequacy aspects are analyzed, related to national and international standards. These aspects are analyzed in an existing Brazilian system with real data by using load flow program, continuation method and non-linear time-domain dynamic simulations.

This paper is organized as follows. Section II describes the system and models used to represent the main networks components. The methodology used to carry out the simulations is also explained in this Section. Section III presents and discusses the simulation results. Finally, the conclusions are summarized in Section IV.

II. NETWORK TOPOLOGY AND MODELING

A. System Description

The test system used in this paper is part of a real power system sited at the North region of Brazil, and is interconnected with the main transmission Brazilian system. Its one-line diagram in presented in Fig. 1.

The main system is composed by 230kV and 138kV transmission lines and has two hydroelectric: TUC, the main generation with total capacity of 8.1 GW, and CUNA, a distributed generation with total capacity of 30MW. The main load points, which are indicated in the figure and represent small cities, are: TUC, ALT, RUR, ITA, TAP and STA. The system was divided in three different areas for clarity purposes, as shows Fig. 1.

Table 1 presents system active power demand to each area for different load pattern. Since the more pessimist situation is the high load, the studies presented in this paper were conducted to the high load pattern.

TABLE I
SYSTEM DEMAND (MW)

Area	**Area 1**	**Area 2**	**Area 3**
Light load	19.0	28.2	89.0
Medium load	27.1	40.7	92.4
High Load	29.0	43.6	100.4

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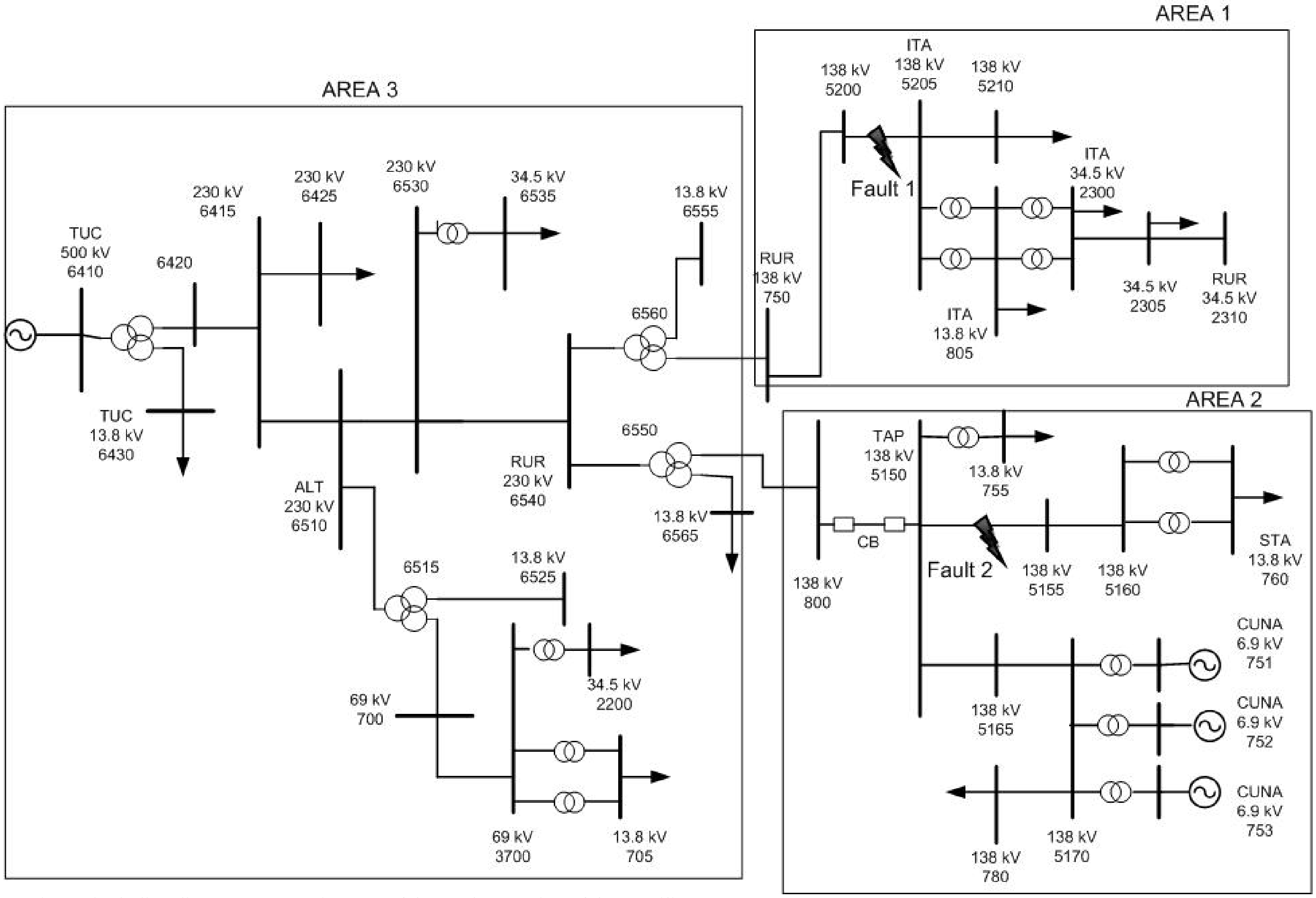


Fig.1. Single-line diagram representing part of the northern region of the Brazilian system.

B. Distributed Generator Modeling

The small hydro power plant (CUNA) is modeled as synchronous salient pole generators with 2 machines of 12.5MVA and 1 machine of 10.84MVA, represented by a sixth-order model in the electromagnetic transient simulations [5]. The generator nominal voltage is 6.9kV with nominal frequency of 60Hz.

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) [2]. Power factor control mode is usually adopted by independent producers to maximize the active power production. In this paper, the voltage control mode is adopted following the utility practices. Voltage regulators are included and modeled with an IEEE type 1 simplified model [5] and speed regulators according to [6].

C. Simulations

The DG penetration level (PL) can be calculated as a function of the total DG power generation over the total load demand:

$$PL(\%) = \frac{P_{DG}}{\sum P_L} \times 100 \qquad (1)$$

To avaliate the impact of the DG penetration level, the following cases are considered:

- Case 1: PL = 15.6% (DG = 27 MW);
- Case 2: PL = 12.1% (DG = 21 MW);
- Case 3: PL = 8.6% (DG = 15 MW);
- Case 4: PL = 0% (DG = 0 MW).

In all cases, both active and reactive power demand of the loads are kept constant. Thus, the power required from the main generator TUC decreases with the increase of the DG penetration level.

The simulations are performed by using the softwares ANAREDE for power flow and PV curves analysis and ANATEM for electromechanical transients analysis, both developed by CEPEL [7,8].

The PV curves are obtained by varying the active and reactive loads (with constant power factor) and keeping the active power injected by the DG at the nominal level [9]. The active and reactive power supplied by the generator was kept constant because, usually, such generators are not rescheduled by the system operator. Different load models were considering during the simulations.

For transients analysis, voltage dependency of static loads is considered. System active power loads at 13.8kV buses are considered as 60% constant impedance loads, and reactive power loads are considered as 100% constant impedance loads as suggests the ONS (Brazilian System National Operator) [10]. Two protections schemes were considered in the simulations, as shows Table 2. The undervoltage protection acts when voltage becomes lower than 0.9 pu. This circuit breaker is indicated in Fig. 1 as CB.

TABLE II
PROTECTION SCHEMES

protection type	**clearing time (s)**
distance protection	80 ms
undervoltage protection	60 ms

III. SIMULATION RESULTS

A. Steady-State Analysis

In this section, both voltage drop and active power loss are analyzed. Fig. 4 shows system voltage profile to high load for the main buses in the corridor between the main generator (bus 6420) and the DG (bus 5170). The results show that as the DG penetration level increases, system voltage profile also increases. This fact is reflected in system losses. Since the DG is connected close to a huge consumer center (STA), at low DG penetration level system losses increases for all load profiles, as shows Fig. 5.

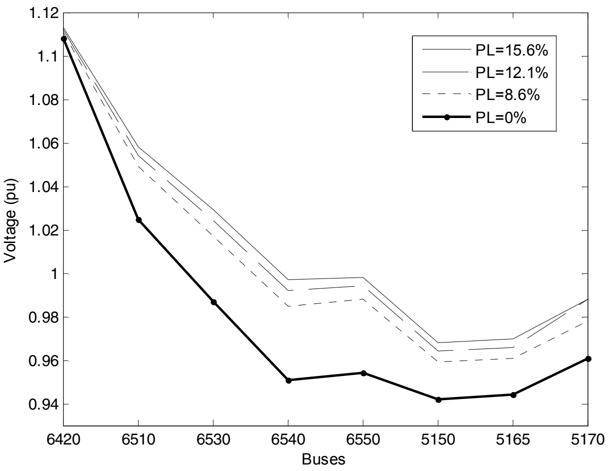


Fig.4. Steady-state voltage profile for different DG penetration levels.

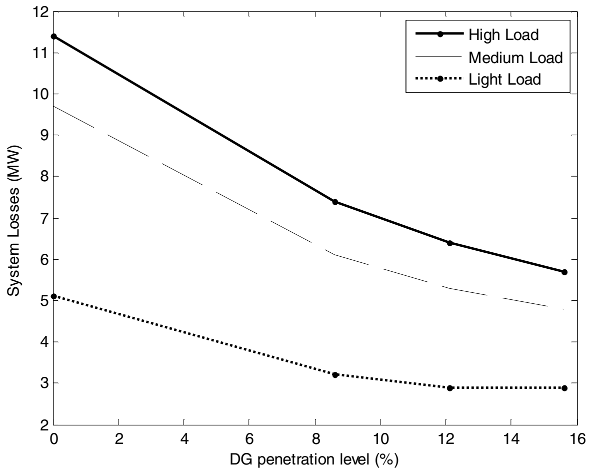


Fig.5. Active power losses for different DG penetration levels.

B. Voltage Stability Analysis

The voltage stability margin measures the distance from the initial operation point to the maximum loading point in the PV curve, and can be expressed in MW or in percentage [5].

In order to study the impact of DG on the voltage stability, three scenarios with different DG penetration levels are investigated: case 1, case 2 and case 3. Fig. 6 shows the voltage stability PV curve at bus 5210 (138kV) for different DG penetration levels to high demand, considering constant power loads. Although the active and reactive power supplied by the DG was kept constant during the simulations, what means that only the main generation assumes the increase in system demand, the results show that the presence of the DG improves the system voltage stability margin. It can be explained because the DG provides active and reactive power to local loads, decreasing system losses and increasing system voltage stability limit.

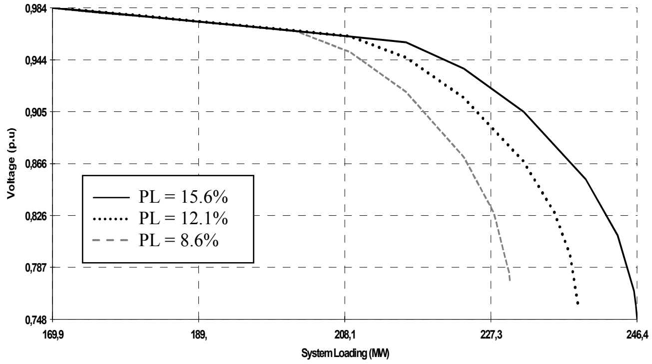


Fig.6. PV curves for different DG penetration levels considering constant power load.

Simulations were also performed considering the others ZIP load models: constant impedance (Z), constant current (I) and constant power (P) [5]. The constant power load model is the most pessimist situation for static loads, with lower voltage stability margin as shows Table III. Another simulation was conducted replacing 60% of the static loads modeled as constant power with dynamic loads (induction motors). This brings the system to a voltage stability margin even worst, of 39.6%. However, for all cases, simulations results considering different DG penetration levels show that the presence of the DG always increased the voltage stability margin.

TABLE III
LOAD MODEL AND SYSTEM VOLTAGE STABILITY MARGIN

Load Model	**Voltage Stability Margin**
Static - costant impedance	64.80%
Static - constant current	56.94%
Static - constant power	45.02%
60% of dynamic loads	39.60%

C. Transient Analysis

Although many simulations were analyzed, this paper presents only the results analyzed for two faults, which are indicated in Figure 1.

- Fault 1: three phase fault applied at 1 second at 40% of line 5200 - 5205 (area 1), which is eliminated by tripping this branch.

Fig. 7 presents the voltage sag at bus 751 close to the DG, occasioned by this fault for different DG penetration levels. The results show that the increase in the DG penetration level results only in a slightly increase in voltage sag magnitude during the transient, which is not significant. The DG slightly increases the current in the branch 5170–751, as shows Fig. 8.

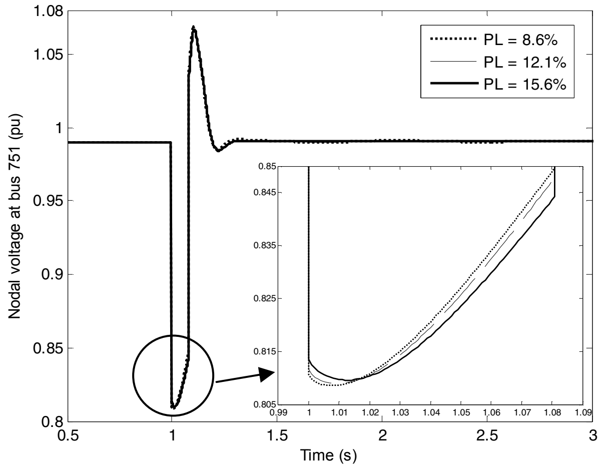
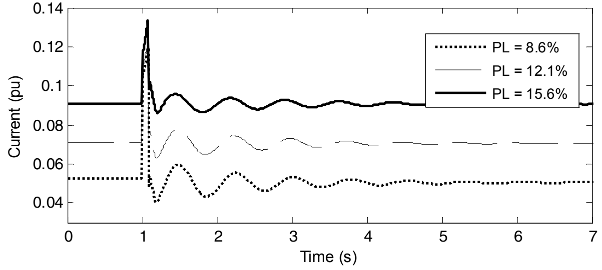


Fig.7. Nodal voltage at bus 751 for different DG penetration levels.


(a)Simulation

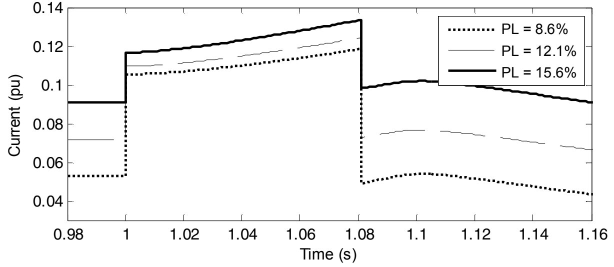
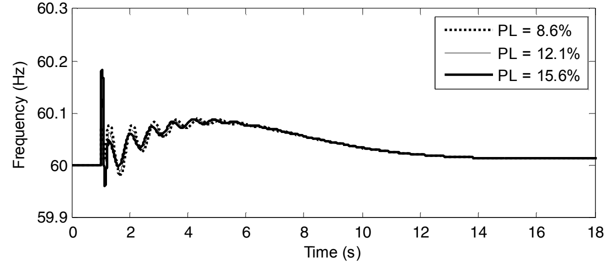

(b)Transient Details

Fig.8. Current in the branch 5170-751 during fault 1 for different DG penetration levels.

Since the DG plants do not participate in system frequency regulation, one can see from Fig. 9 that frequency excursions are larger when DG penetration level is bigger.

Fig. 10 shows the active power generation in CUNA (DG) and TUC (main generation). The demand of 29MW from area 1 is not supplied due to the short circuit. Then, the TUC decreases its generation to meet the demand after the fault, since CUNA output generation remains constant after the transient.


(a)Simulation

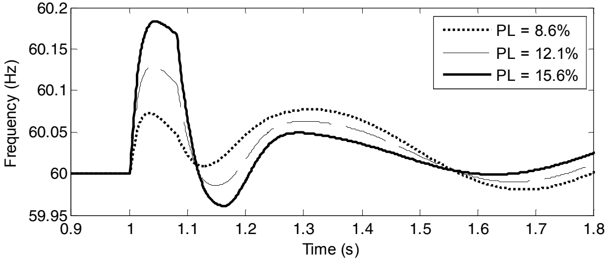

(b)Transient Details

Fig.9. Frequency behavior during fault 1 for different DG penetration levels.

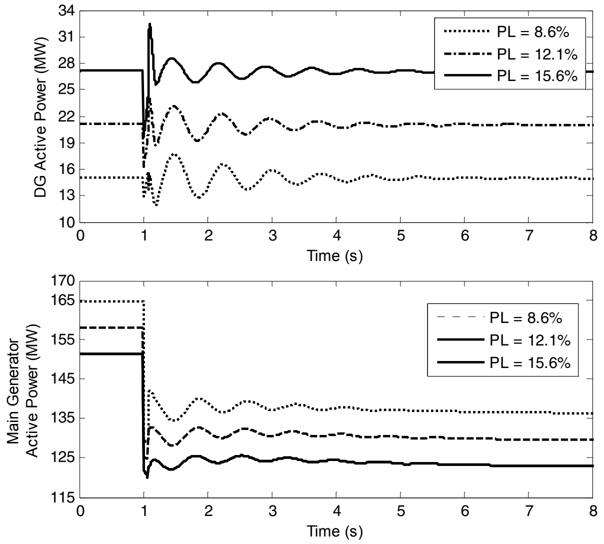


Fig.10. Active power during fault 1 for different DG penetration levels.

- Fault 2: three phase fault at 40% of line 5150 - 5155 (area 2), which is eliminated by tripping this branch;

Fig. 11 presents the voltage sag at bus 751 close to the DG, occasioned by this fault for different DG penetration levels. Since this fault is much closer to the monitored bus, this voltage sag is more severe than the one occasioned by fault 1. Also, the increase in the DG penetration level does not affect significantly the voltage sag magnitude.

Differently from fault 1, to this fault the increase in the DG penetration level results in a slightly decrease in voltage sag magnitude. This can be explained by the current in branch 5170-751 during the fault, which also decreases, as shows Fig. 12.

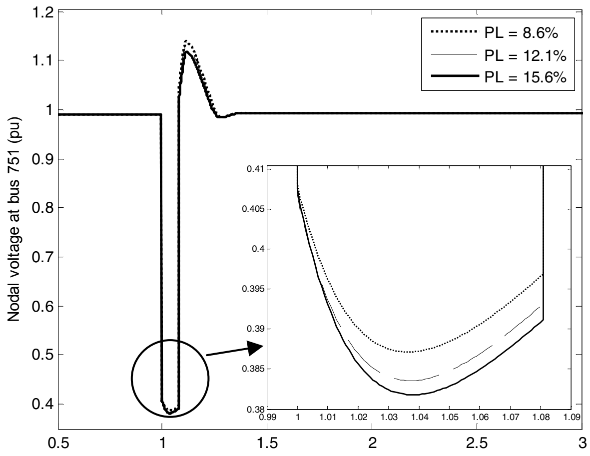
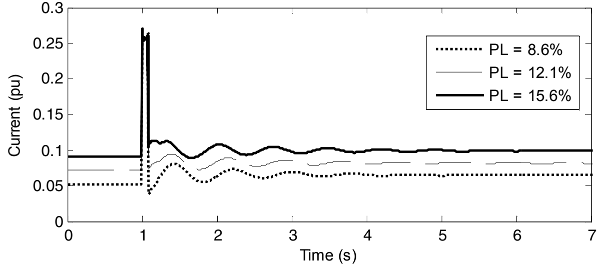


Fig.11. Nodal voltage at bus 751 for different DG penetration levels.

(a)Simulation



(b)Transient Details

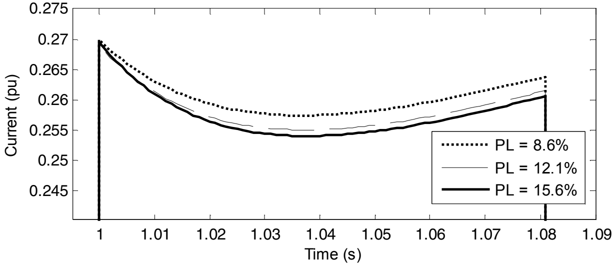
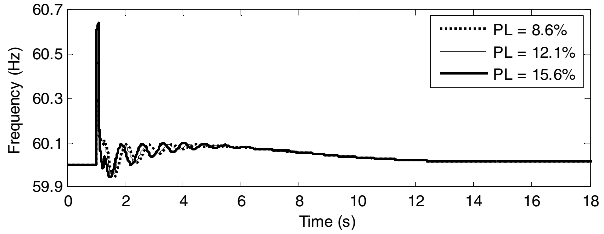


Fig.12. Current in branch 5170-751 during fault 2 for different DG penetration levels.

Fig. 13 shows frequency behavior when the system is subjected to fault 2. The same performance is observed: frequency excursions are larger when DG penetration level is bigger.

Fig. 14 shows the active power generation in CUNA (DG) and TUC (main generation). Again, the demand not supplied due to this fault is compensated with the decrease of the main generation.

(a)Simulation



(b)Transient Details

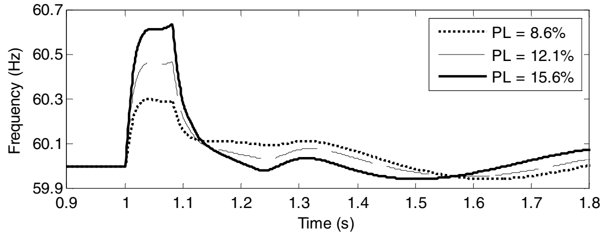


Fig.13. Frequency behavior during fault 2 for different DG penetration levels.

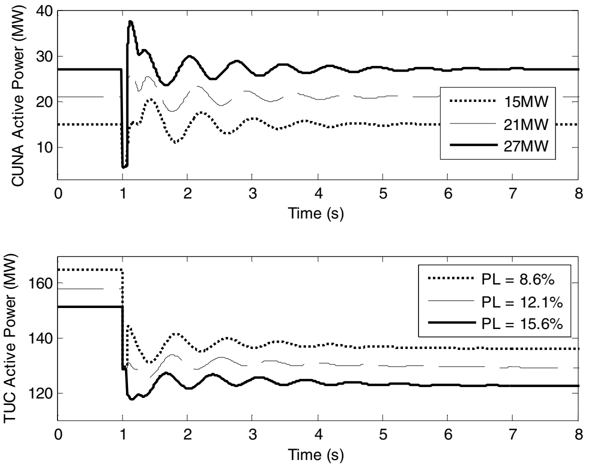


Fig.14. Active power during fault 2 for different DG penetration levels.

D. Standards Adequacy Analysis

During short circuits, synchronous generators usually accelerate, and may become unstable due to the loss of synchronism. The stability of synchronous generators can be determined by analyzing the dynamic response of the rotor angle. In order to evaluate this question, the critical clearing time was determined. The critical clearing time is the maximum actuation time of the protection system such that the power system is transiently stable. The contingency simulated was fault 2 since it is more severe. The distributed generation is considered to supply 27MW (PL = 15.6%). Fig. 15 presents the rotor angle behavior to the critical clearing time, which is 0.24sec. This time is considerable superior than the clearing time adopted by the utility (t = 80ms) and the maximum clearing time of 150ms imposed by the Brazilian System National Operator for 138kV transmission lines [11].

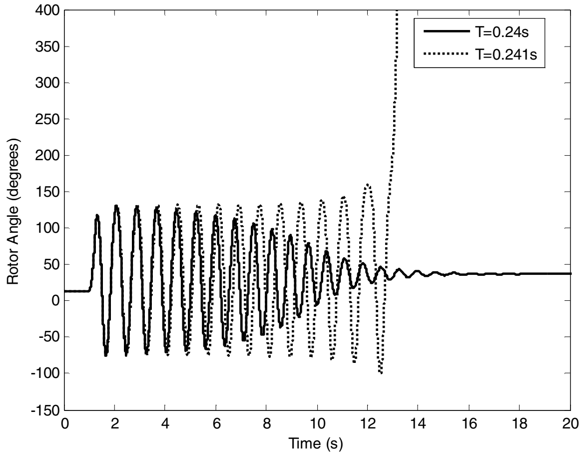


Fig.15. DG rotor angle for a three-phase short circuit.

The ONS establishes a voltage sag tolerance curve for generators (ride through capability) as shows Fig. 16 [12]. Generators which do not meet this tolerance curve must be disconnected and pay fine. The results show that these voltage sags does not imply in generator disconnection. Only faults in lines 5150-5165 and 5165-5170 will cause the generator disconnection.

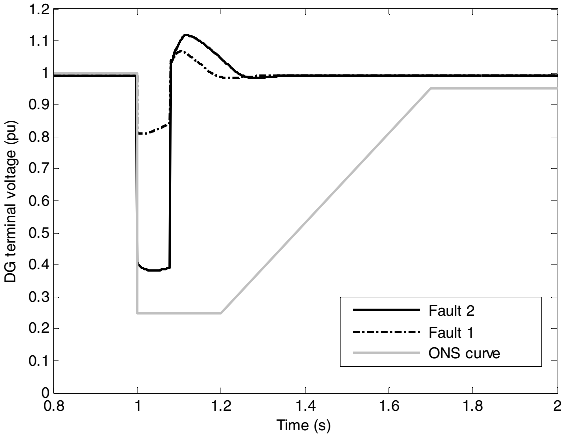


Fig.16. DG terminal voltage during fault 1 and fault 2.

IV. CONCLUSIONS

This paper addresses the impact of DG with different penetration levels on steady-state voltage profile, losses, voltage and transient stability of power systems. A real network is simulated with two hydro power plants: one representing the main generation and the other the DG. The analyses are conducted using load flow program, continuation method and non-linear time-domain dynamic simulations. For voltage stability analysis, the demand is considered as constant power loads. However, for transients analysis, voltage dependency of static loads is considered.

Regarding the steady-state analysis, the utilization of DG improves voltage profile and decreases active power losses. With more power from the DG units, the voltage stability margin is also improved, giving the system more active power transfer capacity. Since the DG plants do not participate in system frequency regulation, frequency excursions are larger when DG penetration level is bigger. However, the DG penetration levels do not impact voltage at DG terminals.

The critical clearing time evaluated is superior to the clearing time currently adopted by the utility (t = 80ms) and the maximum clearing time of 150ms imposed by the Brazilian National Operator for 138kV transmission lines. Also, only faults in lines next to the DG will cause the generator disconnection by severe voltage sags. Based on the results and discussion, it can be concluded that DG can improve the steady-state and stability performance of power system.

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