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Analysis of transient stability in distribution systems with distributed generation

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ABSTRACT

Transient stability in distribution systems has gained special interest due to the continuous increase of distributed generation connected to the grid. Besides the dynamic behavior of the generation system, distribution networks have extensive branches and unbalanced loads, with a specific set of equipment, increasing the complexity of the numerical analysis of transient stability. In this context, this work proposes a new methodology for transient analysis in distribution networks with distributed generation, divided in three major steps: the representation of the network model through a simplified model; the selection of disturbances types and buses for application, and the adjustment of stability control systems. The methodology is suitable for unbalanced networks and a demonstration of a single-pole switching is presented. Case studies are simulated and analyzed for a real network model.

1. Introduction

The analysis of transient stability is essential in transmission systems, and it has been addressed in many researches over the last decades. The impact of a large perturbation in a transmission line may lead to a widespread energy blackout and, therefore, efforts have been concentrated on modeling and analyzing the generation, protection and transmission systems subjected to this situation. Some of the well-established methods for these studies include Lyapunov stability, input-output stability, stability of linear systems, and partial stability [1,2].

Dynamic phasors and direct method of Lyapunov are the studied methods for application in power systems. For real systems, however, time domain simulation is widely used [3].

In the time domain, several works use the simplified network, reduced to the substation and the line that interconnect the generation [4,5]. It is representative only when studying the generation stability, however, for the distribution systems analysis, where besides the machines it is also desired to evaluate the reflection on the voltage and frequency imposed to the loads, this model is not satisfactory.

With the recent advances in renewable energy technologies, the increase of distribution generation (DG) directly connected to distribution networks is remarkable. In this case, distribution systems with a significant amount of DG may also be subjected to unstable operation in the event of a large perturbation in the grid [2].

Networks in the transmission systems are traditionally considered balanced, and an equivalent network between the substation and the DG is sufficient for a transient stability analysis.

The peculiarity of distribution systems is an important feature in this scenario, which operates in a predominance of unbalanced loads [6] and limited control devices. For Volt-Var control, some important devices include capacitors banks and automatic voltage regulators (AVR), and for network protection, reclosers and fuses are worthy to be mentioned.

These conditions, combined with abrupt and unpredictable variations of DG, bring a concern on their dynamic behavior and, consequently, the impact on power quality due to the diversity of sources [7].

In transmission systems, the small signal of stability and transient stability are essential studies, that show, through analytical methods or simulations in the time domain, the dynamics of the generators and the responses of the controls over events in the system [6–10]. However, this type of analysis is not suitable for direct use in distribution systems, since the characteristics are not the same [6,11].

There are few researches that explore transient stability studies in distribution systems, and most of them focus on the response of synchronous machines subject to load unbalance [12–14] with a generator-load model, without inclusion of the distribution networks. Recent studies consider the analysis applied only in hypothetical networks, and do not contemplate events in branches, which are significant for this kind of analysis [3,6].

The main contribution of this work is the proposal of a methodology

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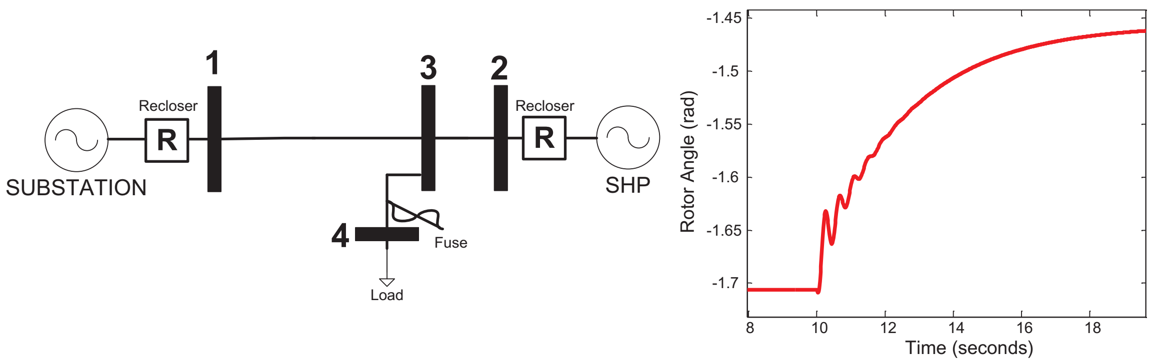

(a) Distribution network (b) SHP generator rotor angle

Fig. 1. Simulation of a branch fault in a distribution network.

Table 1
Operational limits.

Variable	Acceptable values	Description
δ_i	$<\delta_{critical}$	Rotor angle of the machine in continuous operation
ΔP	$\leqslant 0.5$ p.u.	Torsional stress
TV	0.80 p.u. $\leq$ TV $\leq$ 1.10 p.u.(normalize to TV in 10 s)	Level voltage in transient state
SV	0.95 p.u. $\leq$ SV $\leq$ 1.05 p.u.	Level voltage in steady state
TF	56.5 Hz $\leq$ TF $\leq$ 66.0 Hz(normalize to SF in maximum 30 s)	Frequency in transient state
SF	59.9 Hz $\leq$ SF $\leq$ 60.1Hz	Frequency in steady state

Where: P: Active power; TV: Transient Voltage; SV: Steady state Voltage; TF: Transient frequency; SF: Steady state frequency.

for global stability analysis in distribution systems, which highlights:

(a) Network simplification technique for transient stability studies, by creating a representative model for dynamic analysis;
(b) A selection criteria establishment of main branches with potential impact in the angular stability, by considering the protection devices characteristic of distribution systems;
(c) Dynamic models representation with specific parameters for DG in distribution networks;
(d) Evaluation of single-pole disturbances in distribution systems;
(e) Control system adjustment in conditions of instability.

In order to demonstrate the application and effectiveness of the methodology, case studies of a real network model are presented and discussed.

2. Problem formulation

For a specific initial operating condition, an electric power system can be classified as stable if it is able to “regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact” [15].

The primary concern in the stability analysis is to verify the synchronism of the generator machines in a short period of time after the occurrence of a disturbance, during which the actions of the controllers do not have a significant effect [9].

The increase in the DG penetration in a distribution system does not significantly affect the speed of the machines regarding the synchronous speed, but it causes an increase on the oscillation frequency after a fault [15]. Synchronous generators connected to distribution systems present small rated power and have low inertia, what results in a system with a higher probability of losing synchronism and hence stability

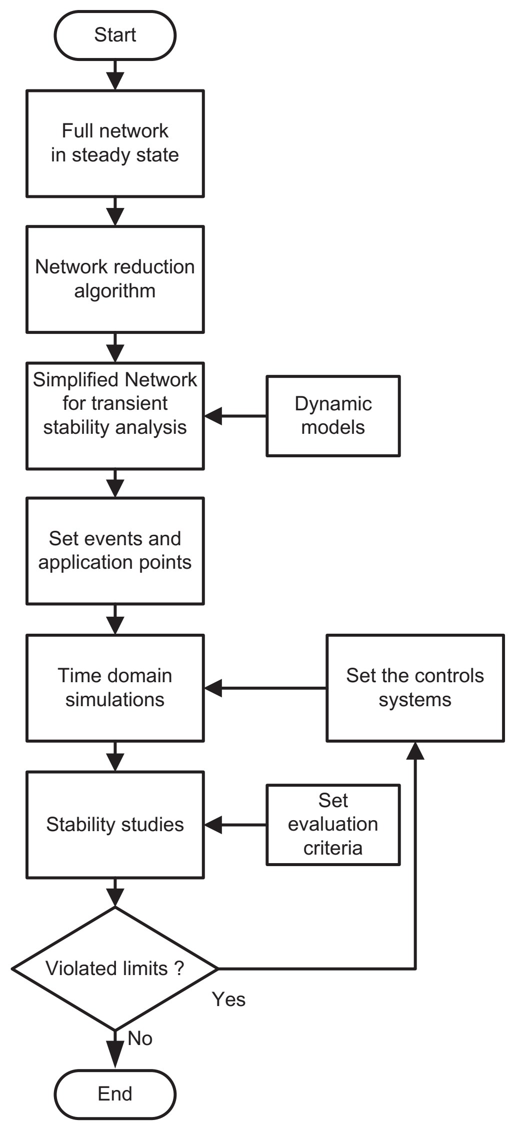

Fig. 2. Methodology flowchart.

[10,16]. For this reason, especial attention to protection systems should be given, avoiding overvoltage, overcurrent and unintentional islanding.

In distribution networks, load unbalance and branches with large extension shall be considered in transient simulations, as they may cause interference in the responses of the generator machines and in the quality of power supply when a fault occurs. For example, in a phase-ground short-circuit, a single-phase simulation does not show the overvoltage in remaining phases.

In addition, large branches of distribution networks are predominantly protected by fuses, which require a specific analysis of events in these network segments. As an example, Fig. 1(a) shows a reduced distribution network with four buses and a Small Hydro Power Plant (SHP) generator connected to Bus 2. At the instant t = 10 s, a three-phase short circuit is applied to Bus 4, which is protected by a fuse. Figure (b) shows the rotor angle of the SHP generator, which losses the synchronism and stability after the fault.

The power system transient stability problem with *n* machines can be modeled by a set of oscillation equations, one for each machine of the system. These equations can be deployed in first order differential equations systems, according to Eqs. (1) and (2).

$$M_i \cdot \frac{d_{\omega i}}{dt^2} + D_i \cdot \omega_i = P_{m_i} - P_{e_i} \tag{1}$$

$$\frac{d_{\delta_i}}{dt} = \omega_{i(t)} - \omega_s \tag{2}$$

where M_i: Inertia constant of the ith machine in [p.u. s^2]/rad; t: time in seconds; D_i: Damping constant of the ith machine in [p.u. s]/rad; ω_i: Angular velocity at each instant in [rad/s]; P_{m_i}: Mechanical input power of the ith primary machine in [p.u.]; P_{e_i}: Active electric power injected into the network by the ith machine in [p.u.]; δ_i: Angular position of the axis of the ith machine with respect to an axis rotating at synchronous speed in [rad]; ω_s: Synchronous speed in [rad/s].

The solution of the equations system (1) and (2) allows to evaluate the transient stability of power systems. In this study, as an evaluation criteria of the transient stability of distribution systems, it is expected that the various DG reach a stable point of operation after a disturbance event. In addition, the power quality is expected to remain within acceptable limits of operation and safety, which are:

(i) voltage and frequency levels in all buses systems must not exceed the limits set for transient and steady state, and
(ii) distributed generators must not be subjected to harmful torsional effects.

These conditions will be fulfilled when the variables limits shown in Table 1 are met, where the limits adopted are typical for distribution networks [19,20]. The system frequency adopted is 60 Hz.

The operation critical angle is obtained when the derivative of the synchronizing power is zero, i.e., at the point of maximum power transfer. The torsional stress is obtained by the difference of the active power generated immediately before and immediately after the contingency, and the difference must not exceed 0.5 p.u. to safeguard the shaft of the generator-turbine systems due to the switches in the grid [19]. Voltage and frequency values in transient and steady state are defined by regulatory agencies [17,18].

3. Proposed methodology

The purpose of this work is to develop a methodology for global analysis of transient stability in distribution systems with the presence of DG. The models and techniques proposed include the peculiarities of distribution systems that provide a representative analysis of transient stability.

Fig. 2 shows the flowchart of the proposed methodology, which is detailed in the following sections:

3.1. Network simplification

The first step of the proposed methodology consists in performing a network simplification. In general, the distribution networks may have an expressive number of branches and equipment, unbalanced loads and dynamic controls. The simulation of the entire network could lead to convergence problems and expressive computational requirement.

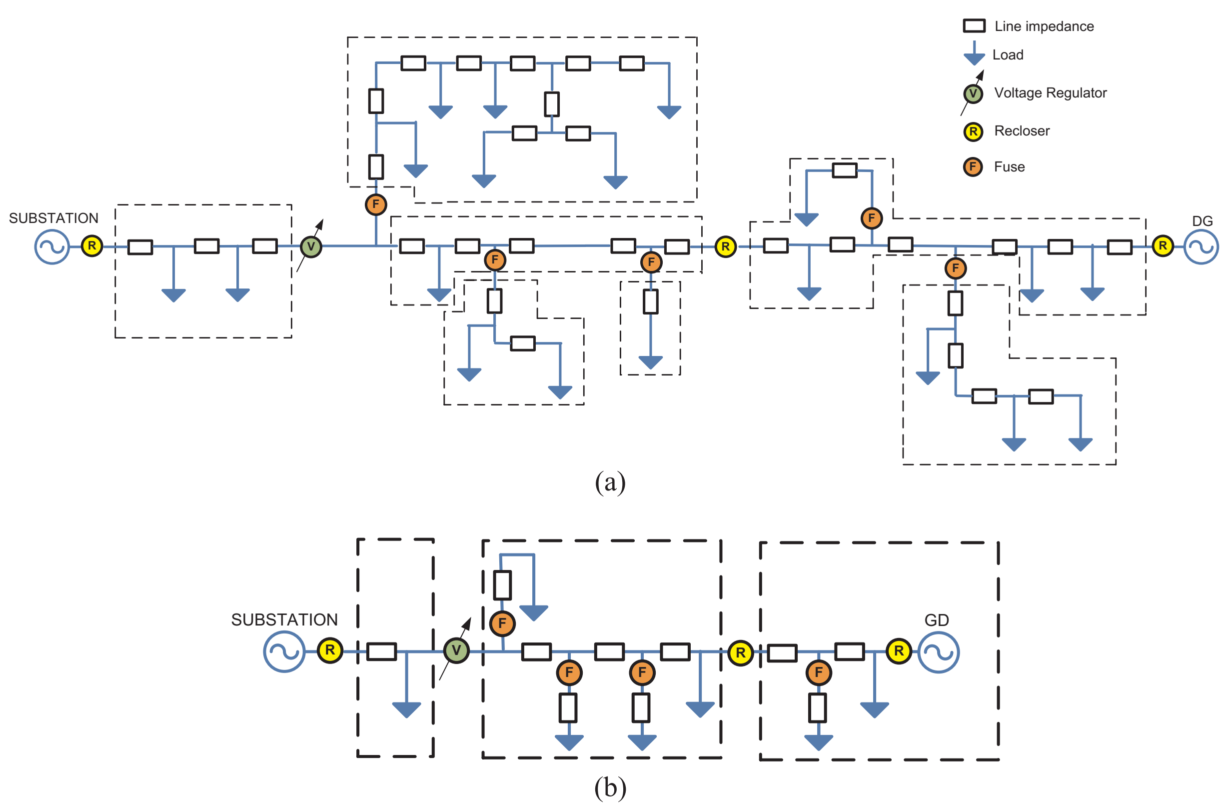

Fig. 3. Example of network simplification: (a) Original network. (b) Simplified network.

With the proposed simplification, the network model contains only the representative elements in steady state.

The final representation of the network is obtained with the following steps:

(1) Identify and maintain in the model the equipment in main feeder: distributed generators (DG), fuses (F), reclosers (R), and voltage regulators (VR). These devices will define the areas where the reduction algorithm will be applied.
(2) Divide the feeder into small areas among each identified element in the previous step.
(3) Calculate the total line impedance among each equipment (impedance of the section), and the total line impedance of each branch that derives from the main line. For convenience of calculation, all line impedances in each section or branch are concentrated.
(4) In each area, the number of branches should be reduced. Branches that have the following characteristics will be preserved in the simplified network: (a) Branch with lower accumulated impedance at its most extreme point. This branch will present a shorter short circuit; (b) Branch with higher accumulated impedance just after the fuse of the main feeder branch. This branch has the largest short-circuit current; (c) Branch with higher rated current fuse at the main feeder outlet. This fuse will have the longest time of operation.
(5) Calculate the concentrated load from each section or branch. The loads are modeled as constant impedance, where the equivalent impedance per phase is calculated by considering the voltage obtained with the power-flow of the full network in steady state, keeping the original voltage drops in the simplified network, according to (3):

$$Z_i = \frac{V_{rms_i}^2}{S_i^*} \tag{3}$$

where Z_i is the equivalent impedance of load of phase i (Ω); V_{rms_i} is the RMS voltage of phase i (V); and S_i is the apparent power of phase i (VA).

Fig. 3 illustrates the application of the proposed methodology in a hypothetical network. In this example, the complete network is reduced to seven loads in 9 buses.

The number of branches to be analyzed may be significantly reduced using the proposed methodology, while the simplified model preserves the branches and fuses more relevant for the analysis.

In addition, in order to obtain to the network reduction, the model must include the representation of the distributed generators and their respective stability controls. This work suggests the standardized IEEE controls [20–22]; with specific definitions of gains and time constants for distribution networks, which allows the dynamic models to respond in a representative manner to the characteristics of this type of network. In the following sections the models and parameters used in this work are detailed.

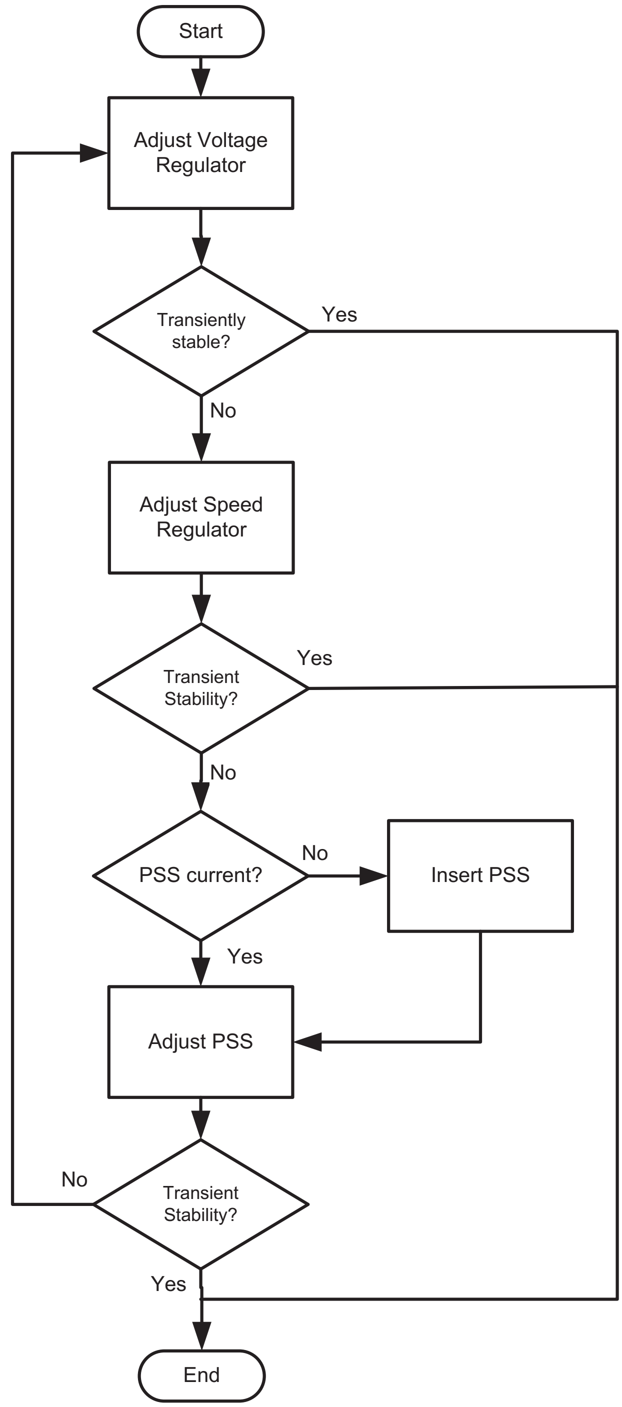

Fig. 4. Control system adjustment flowchart.

3.2. Definition of the set of events

In the second step of the methodology, it is defined the set of events for transient stability evaluation in distribution systems that represent the main scenarios of studies for different operating conditions, which reduces the number of analysis.

The main events to be analyzed are short-circuits and loss of load in critical buses for the stability. The machines transient responses, the substation connections and the power quality of loads are the main interests in the study. Changes in the load are defined to evaluate the dynamic in small signal. Transient stability is assessed by short circuits simulations in the main feeder and branches.

The analysis evaluates the critical fault clearing time for synchronous machines, the torsional effect on the shafts of the generators, the frequency of the system and the voltage levels per phase, as previously defined in Table 1.

The critical buses for application of disturbance faults are selected according to the following criteria:

(i) The bus closest to each substation;
(ii) The bus closest to each distributed generator;
(iii) An intermediate bus, between each DG and substation;
(iv) The bus downstream of the protection fuse in each branch;
(v) The last bus of each branch, i.e., at the point of the greatest

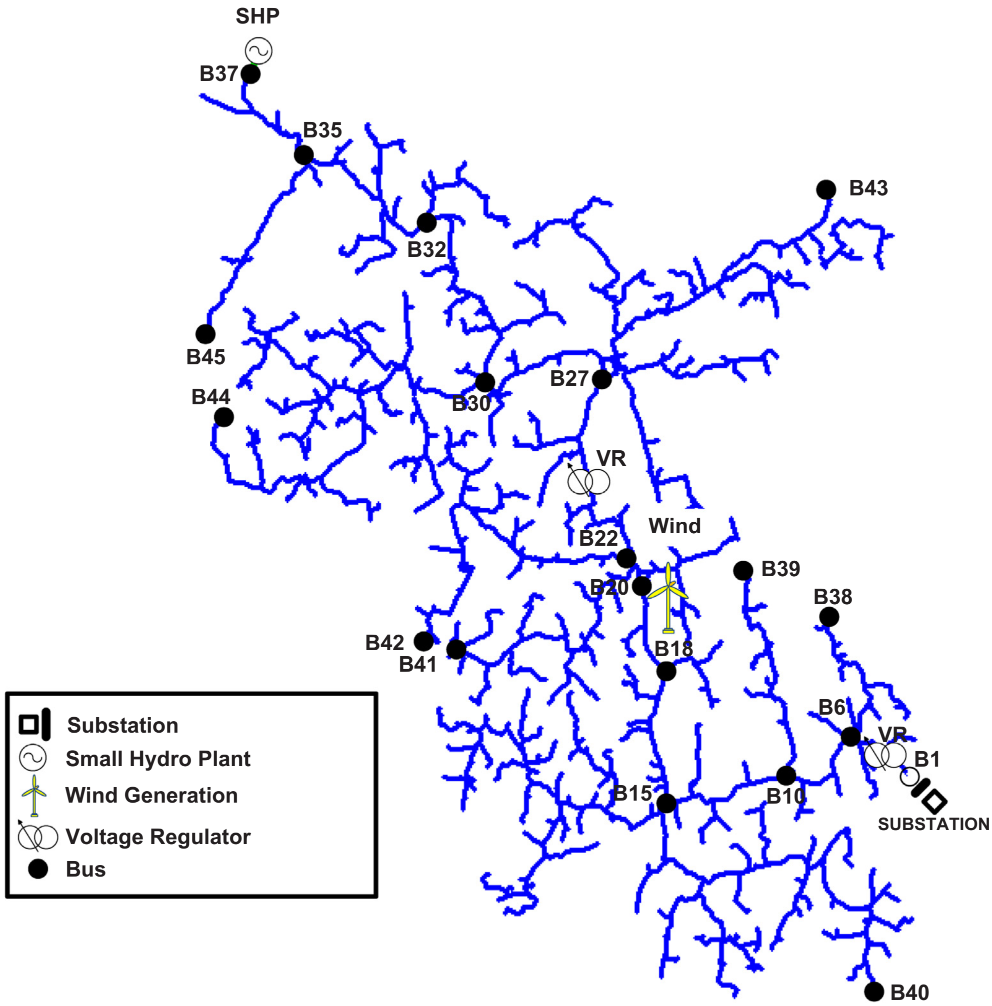

Fig. 5. Distribution network used in the case study.

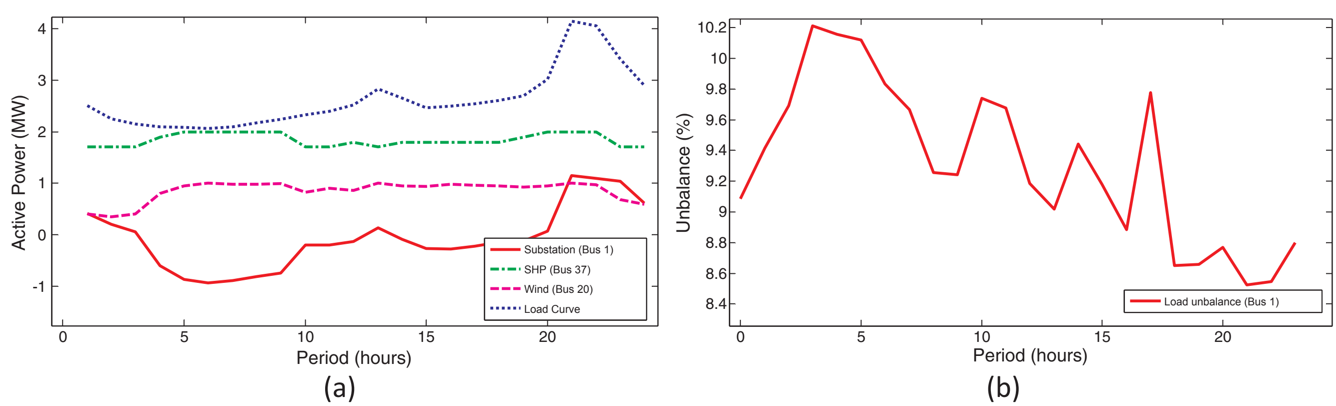

Fig. 6. Feeder load curves. (a) Active power. (b) Unbalance load.

accumulated impedance.

(vi) The events in the branches may cause transient instability in the DG, although they are not generally analyzed in distribution networks. This work demonstrates some situations where this is verified.

The following faults are applied to selected branches in each area:

(a) A load rejection event, where the search algorithm defines the branch with the highest sum of loads;
(b) Application of three-phase and phase-to-ground short-circuits immediately downstream of fuse protection;
(c) Application of three-phase and phase-to-ground short-circuits in the branch with higher impedance accumulated.
(d) Application of three-phase and phase-to-ground short-circuits in the branch with lower impedance accumulated downstream of branch fuse of the main feeder.

Initially, the default operating time values for the protective equipment are adopted. After the simulations, if there is transient instability, an optimization algorithm will adjust the controls and their respective times.

The use of reclosers in the three-phase operation mode is traditional in distribution networks. Although it is not common for distribution networks, for applications with DG, single-phase reclosing demonstrates a fundamental role in transient stability, as it will be demonstrated in this paper. Thus, this paper makes a comparative analysis between single-phase and three-phase reclosers operations.

It is worth emphasizing that when an event in distributions system occurs, it is expected that the synchronous DG maintain their synchronism after temporary elimination of the fault, keeping the operation limits within pre-established values.

Thus, this paper makes a comparative analysis between single-phase and three-phase reclosers operations.

3.3. System control adjustment

Applying single-phase auto-reclosers for distribution networks is not common, but it has a fundamental role in transient stability with DG, as it will be demonstrated in this paper. Thus, this paper makes a comparative analysis between single-phase and three-phase reclosers operations.

The use of PSS in DG connected in distribution systems has been growing, mainly due to the dynamic characteristics of these systems [25–28].

The initial adjustments may not meet the quality criteria or the transient stability condition. In this case, an algorithm is applied to voltage regulator, speed regulator and controllers of power system stabilizer (PSS), as indicated in the flowchart of Fig. 4 [23].

The control system adjustment is not object of this work; in the simulations, it was used a meta-heuristic to adjust the controls, based on Ziegler and Nichols [29] method.

Transient instability typically occurs in the first oscillation, that implies in the need of faster voltage regulators, which in turn hamper the inherent damping of the machines, and instability may occur in subsequent oscillations [11]. The proposed sequence prioritizes the voltage regulator adjustment, followed by the speed regulator and the PSS. If after adjusting the voltage and speed regulators, stability is not achieved, the PSS is adjusted or inserted into the control system. If the control system is changed, all simulations will be performed again.

4. Case study

A real distribution system was considered as a case study, with 44.8 km of main feeder, 6309 buses and a SHP. To evaluate the diversification of DG sources, a wind generation was introduced. In Fig. 5 it show the distribution system unifilar diagram. The software Power Factory – DigSilent [24] was used as simulation tool in time domain.

The SHP generation curves, wind generation, load curves, as well as substation power equivalent are shown in Fig. 6(a). Fig. 6(b) shows the load unbalance curve.

The period of low load of the distribution system is typically the most critical, because the DG power generated exceeds the load, and there will be export of energy to the substation, which leads the system to have the lowest damping coefficient. In this case study, the period of analysis will be around 5 h:00 min, that is the time with the lowest load.

The information about the equipment used in the study is presented below:

4.1. Small Hydro Power Plant (SHP) with synchronous generator

A SHP model represented by synchronous generators of salient poles was considered, with total rated power of 3.125 MVA and average generation of 2.0 MW, operating with constant power and unity power factor.

Table 2 shows the main parameters of the machines.

Table 2
SHP generators parameters.

Parameter	Value
Rated apparent power (MVA)	1.562
Number of poles	10
Rotor type	Salient
Nominal speed (rpm)	720
Inertia time constant (s)	0.7557
Armature resistance ra (p.u.)	0.0100
Stator reactance X′ (p.u.)	0.1000
Unsaturated d axis synchronous reactance – Xd (p.u.)	0.9106
Unsaturated q axis synchronous reactance – Xq (p.u.)	0.4659
Unsaturated d axis synchronous transient reactance – Xd′ (p.u.)	0.4365
Unsaturated d axis synchronous subtransient reactance – Xd″ (p.u.)	0.2950
Unsaturated q axis synchronous subtransient reactance – Xq″ (p.u.)	0.3782
Zero-sequence reactance – X0 (p.u.)	0.1346
Negative-sequence reactance – X2 (p.u.)	0.3366
d axis transient open circuit time constant – T′d0 (s)	1.7582
d axis subtransient open circuit time constant – T″d0 (s)	0.0127
q axis subtransient open circuit time constant – T″q0 (s)	0.0200

Table 3
SHP voltage regulator parameters.

Variable	Value	Unit	Description
Tr	0.02	[s]	Measurement delay
Tb	0.02	[s]	Filter delay time
Tc	0.1	[s]	Filter derivative time constant
Ka	150	[p.u.]	Controller gain
Ta	0.015	[s]	Controller time constant
Te	0.5	[s]	Exciter time constant
Ke	0.96	[p.u.]	Exciter constant
E1	3.13	[p.u.]	Saturation factor 1
SE1	0.10	[p.u.]	Saturation factor 2
E2	4.18	[p.u.]	Saturation factor 3
SE2	0.50	[p.u.]	Saturation factor 4
Kf	0.01	[p.u.]	Stabilization path gain
Tf1	1.00	[s]	Stabilization path time constant
Vrmin	− 20	[p.u.]	Controller minimum output
Vrmax	20	[p.u.]	Controller maximum output

4.2. SHP voltage regulator

The basic function of an excitation system is provide DC current to the synchronous machine field winding and determine the terminal voltage control and the reactive power generation, besides specific functions to increase system stability [10]. The voltage regulator used was DC1 type of IEEE [8]. Table 3 shows the used settings:

4.3. SHP speed regulator

The primary regulation aims to maintain the frequency deviations to a minimum without stability loss [11]. The used speed regulator was

Table 4
SHP speed regulator parameters.

Variable	Value	Unit	Description
R	0.300	[p.u.]	Temporary droop
Tr	5.000	[s]	Governor time constant
Tf	0.100	[s]	Filter time constant
Tg	0.002	[s]	Servo time constant
At	1.000	[p.u.]	Turbine gain
Dturb	0.010	[p.u.]	Frictional losses factor p.u.
Qnl	0.010	[p.u.]	No load flow
R	0.050	[p.u.]	Permanent droop
Velm	0.150	[p.u.]	Gate velocity limit
Gmin	0	[p.u.]	Minimum gate limit
Gmax	1	[p.u.]	Maximum gate limit

Table 5
Parameters of the SHP PSS.

Variable	Value	Unit	Description
T1	0.05	[s]	Lead-lag 1st derivate time constant
T2	0.30	[s]	Lead-lag 2nd delay time constant
T3	1.20	[s]	Lead-lag 3nd derivate time constant
T4	1.00	[s]	Lead-lag 4nd delay time constant
T5	1.00	[s]	Stabilizer derivative time constant
T6	1.00	[s]	Stabilizer time constant
Ks	−50	[p.u.]	Stabilizer gain
A1	0.00	[s]	Filter 1st time constant
A2	0.00	[s]	Filter 2nd time constant
A3	0.50	[s]	Filter 3nd time constant
A4	1.00	[s]	Filter 4nd time constant
A5	2.00	[s]	Filter 5nd time constant
A6	1.00	[s]	Filter 6nd time constant
Lsmin	−0.10	[p.u.]	Controller minimum output
Lsmax	0.10	[p.u.]	Controller maximum output

the HYGOV of IEEE [21]. Table 4 presents the main speed regulator parameters.

4.4. SHP power system stabilizer

The best dynamic response of the system is obtained by adding an additional signal stabilizer. The PSS added is a IEEE standard, whose parameters are shown in Table 5.

4.5. Wind generator

The wind generator was modeled as a directly connected induction generator (SCIG), operating in super synchronous speed. This choice was motivated by the fact that this type of connection presents characteristics that influence the quality of supply in certain operational conditions, such as wind variation.

Table 6
Comparative data between complete network and simplified network.

	Complete network	Simplified network	Variation %
Substation power flow	0.11 + j0.50 MVA	0.10 + j0.52 MVA	3.43%
SHP power flow	2.00 + j0.00 MVA	2.00 + j0.00 MVA	0.00%
SHP voltage	1032 p.u.	1034 p.u.	0.19%

4.6. Network simplification

The proposed methodology reduces the original network with large number of branches and unbalanced loads into a simplified network with compatible dynamic response. The equivalent model of the network was reduced from 6309 buses to 45 buses, as shown in Fig. 7.

Firstly, the buses that would be preserved were defined, which were the ones with reclosers, voltage regulators and DG. Among each of these elements, the simplification method was applied, where the preserved branches were determined. The other branches were converted into connected loads in the main feeder bus.

The simplified distribution network was compared, in a permanent regime, to the real network. It was done by comparing mainly the power flows in the trunk and the voltage in remarkable and important segments. Table 6 shows the calculated powers and voltages in the complete network and in the simplified network.

4.7. Selection of events

In the case study of this work, 39 events were simulated. They are distributed as shown in Table 7.

The events in the main feeder are applied in the buses near to the sources, in order to simulate severe events for DG. The branch load rejection consists in the disconnection of the branch with higher aggregate load, which aims to provide a power step and to evaluate the response of the DG control systems.

Events on branches are aimed to assess possible transient loss of

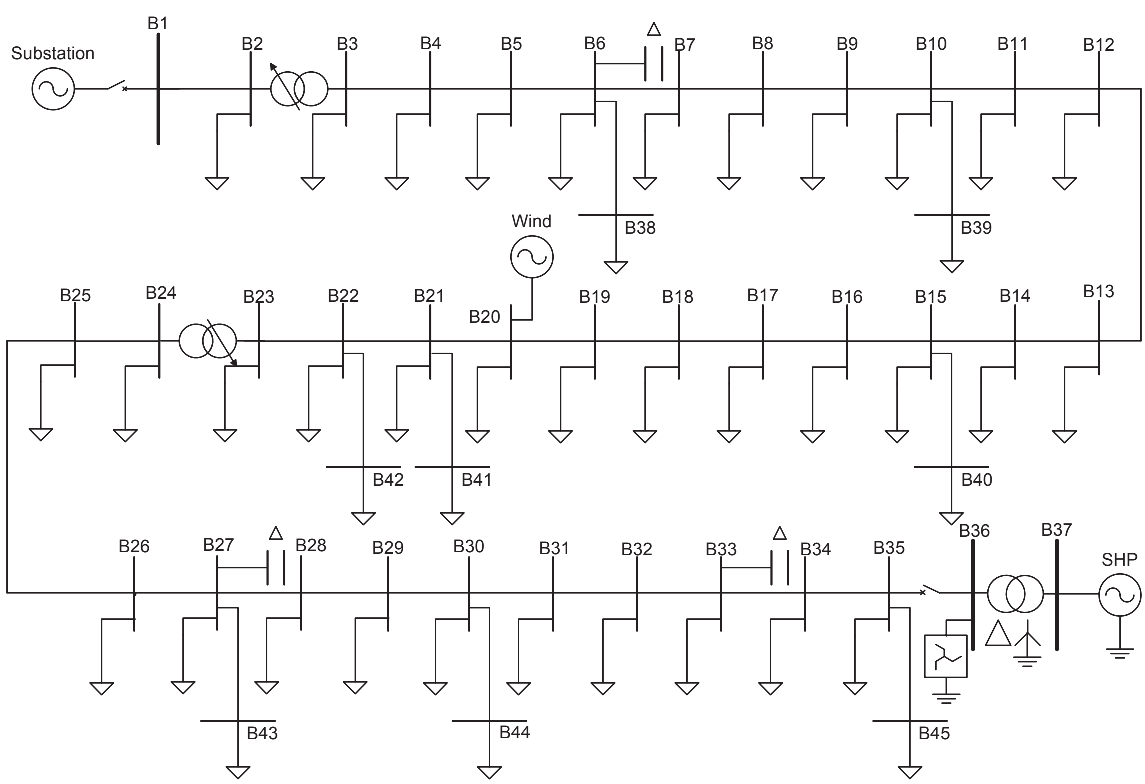

Fig. 7. Simplified network used in the case study.

Table 7
Events and application buses.

Segment	Short-circuit	Buses
Main feeder	Three-phase	1, 20 and 35
	Phase-to-ground	1, 20 and 35
Branches	Load rejection	41
	Three-phase	6, 10, 15, 20, 22, 27, 30, 35, 38, 39, 40, 41, 42, 43, 44 and 45
	Phase-to-ground	6, 10, 15, 20, 22, 27, 30, 35, 38, 39, 40, 41, 42, 43, 44 and 45

stability due to the time of operation of the protections for branches.

Distribution systems traditionally have reclosers operating in three-pole switching mode, i.e., even if the fault is single-phase, there is a three-phase interruption. That mode of operation results in a large reduction of load power, which can lead to instability of the synchronous DG. In this study, an evaluation of the single-pole switching operation of the reclosers is performed, where the advantage over three-pole operations, for phase-to-ground faults, is evidenced.

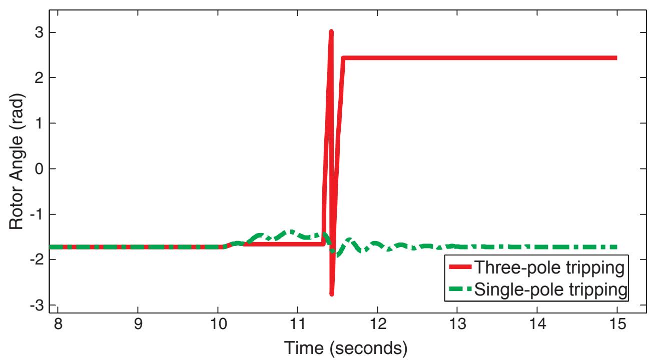

Fig. 8. SHP rotor angle.

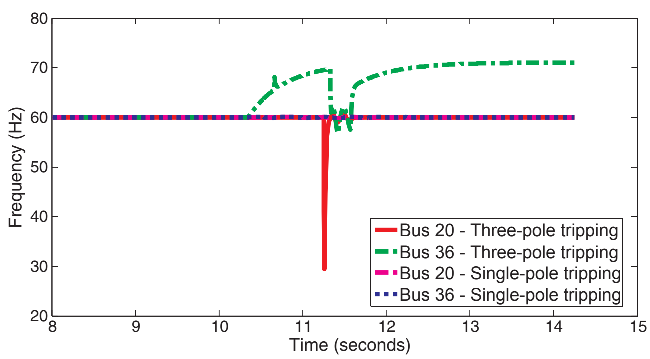

Fig. 9. Frequency in the buses with generation.

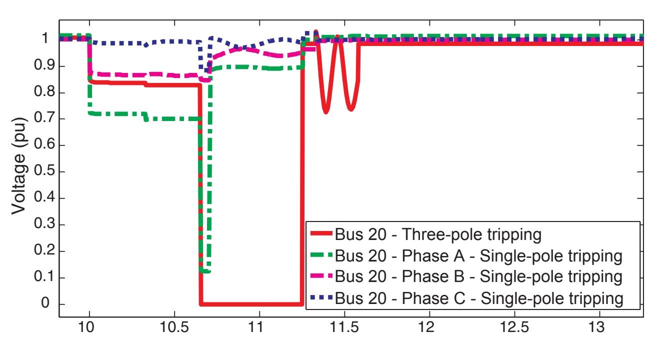

Fig. 10. Voltages in the main buses of the network.

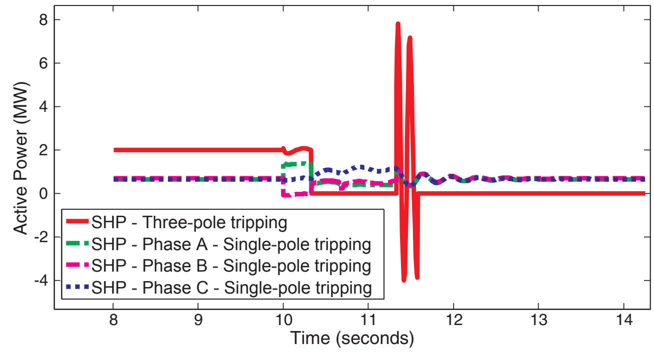

Fig. 11. Active power of the SHP.

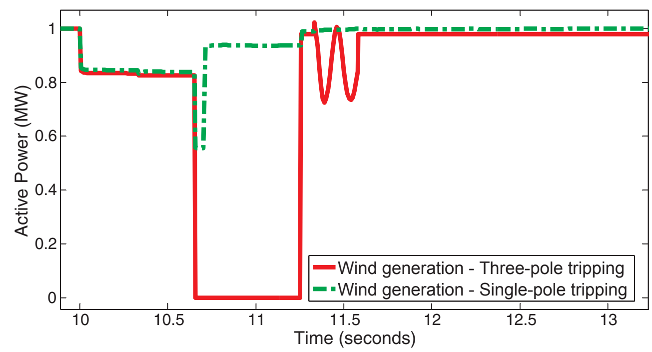

Fig. 12. Active power of wind generation.

4.8. Case Study 01: Comparison between single-pole and three-pole switching in a phase-to-ground fault in the main feeder

This scenario applied a short circuit phase-to-ground in bus 35, near to SHP. For traditional analysis the operation of protection elements is three-pole tripping and reclosing. The proposed method considers the tripping and reclosing as single-pole.

The system fault occurs at 10 s of simulation, and the SHP circuit breaker is the first equipment to operate, opening the circuit at 10.328 s. At 10.650 s, the substation circuit breaker operates by clearing all current sources. At 11.25 s the substation breaker closes its contacts and at 11.328 s the SHP breaker is closed. Fig. 8 shows the transient response for synchronous machine with three-pole tripping and for tripping single-pole, in the proposed method. Three-pole opening and reclosing tripping cause the SHP loss of stability, which does not happen in single-pole operations.

The traditional method causes the SHP shutdown while the single-pole reclosing keeps the connected generation. Fig. 9 presents the frequency in buses with generation.

Fig. 10 illustrates the voltages on the bus 20, where it can be seen that the phase analysis of single-pole reclosing provides less severe voltage sags in the system.

Fig. 11 illustrates the SHP active power generated, where the high values achieved in the loss of synchronism can be seen in the traditional method.

For the traditional operation, the active power supplied by the wind generator is also stopped during the disconnection system. It happens because the voltage is lower than the minimum allowed by the converter. This limit is not reached in a single-pole tripping. Fig. 12 shows the active power produced by the wind generator. In traditional methods, with single-phase analysis, the wind farm is disconnected because there is a reduction in the voltage on the connection bus.

4.9. Case Study 02: Three-phase fault in branch

This study evaluates the stability transient for an event occurred in

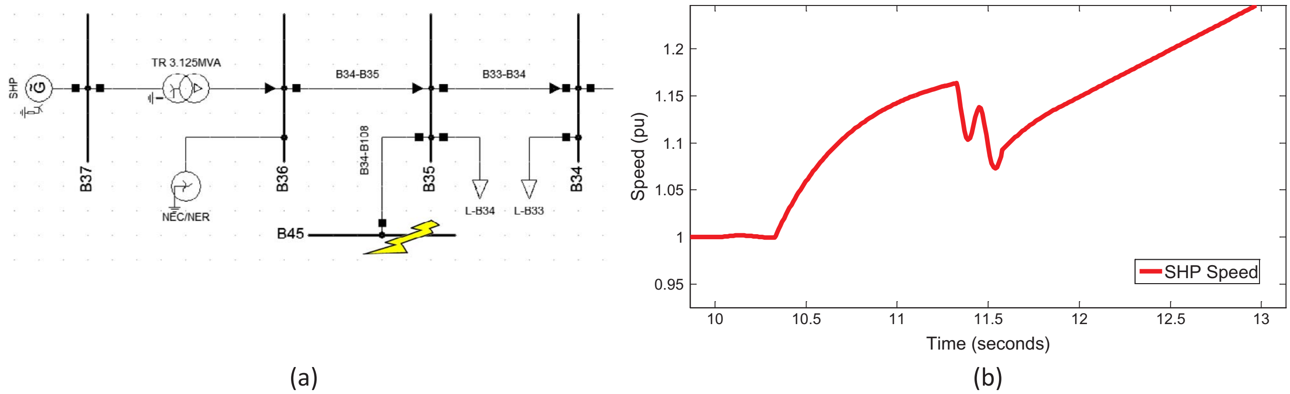

Fig. 13. SHP rotor speed.

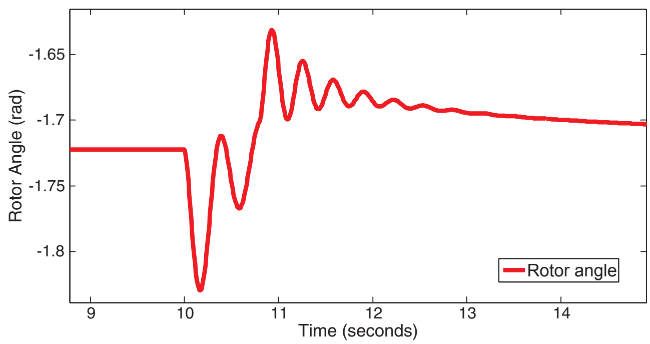

Fig. 14. SHP rotor angle with new adjustment.

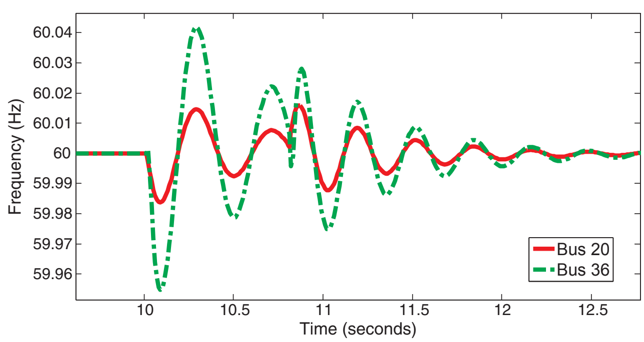

Fig. 15. Frequency in the buses with generation.

branches, which is not evaluated in traditional studies using a simplified model with substation and DG. The primary protection for faults in branches are fuses, in which the operating times depend on the level of short-circuits of the system.

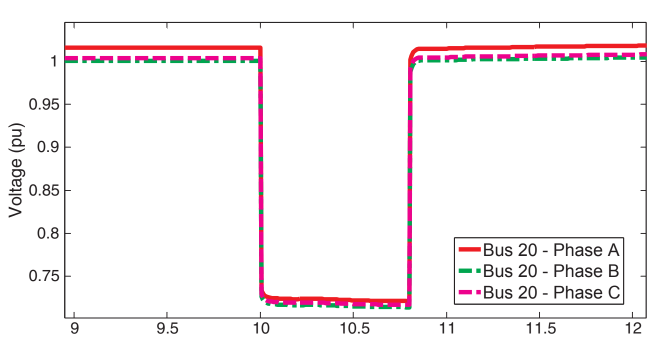

Fig. 16. Bus voltage in the wind generation.

A three-phase short-circuit was applied to bus 43, that derives from bus 27 of the main feeder. The short-circuit is of the order of 400 A and the fuse time response is around 680 ms. Fig. 13 presents the synchronous machine rotor speed, where an oscillation is observed, which makes the generator lose synchronism with the distribution network.

Fig. 13(a) illustrates a short stretch of the distribution network in which a three-phase short-circuit was applied to the bus 45, which derives from the bus 35 of the main feeder. The short-circuit is from 400 A order and the fuse operation is about 680 ms. Fig. 13(b) presents the rotor speed of the synchronous machine for the applied event, which shows the loss of synchronism with the distribution network, even after the operation of the fuse element.

In traditional evaluation, this condition would not be taken into consideration, because branches events are not simulated. In this work, when the loss of synchronism is detected, an adjustment algorithm of the control system proposes new settings, searching for stability for all simulated events.

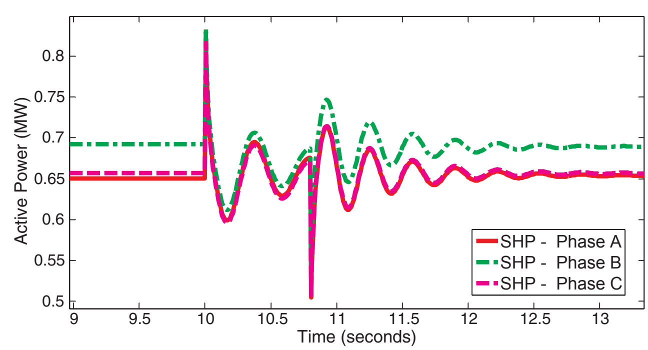

Fig. 17. SHP active power.

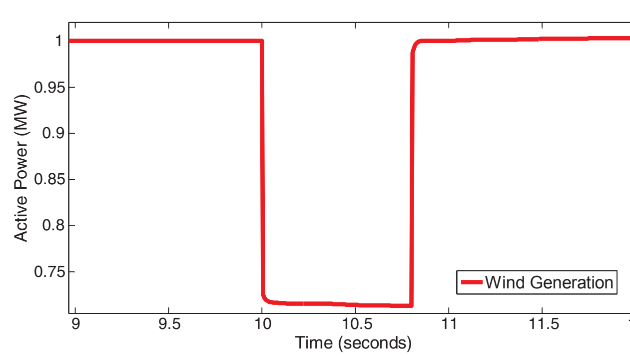

Fig. 18. Active power of wind generation.

Table 8
Summary of simulation results.

Segment	Short-circuit	Three-pole tripping		Single-pole tripping	
		Stable	Unstable	Stable	Unstable
Main feeder	Three-phase		1, 20 and 35	1, 20 and 35	
	Phase-to-ground		1, 20 and 35	1, 20 and 35	
Branches	Load rejection	41		41	
	Three-phase	6, 10, 15, 20, 22, 38, 39, 40, 41 and 42	27, 30, 35, 43, 44 and 45	6, 10, 15, 20, 22, 27, 30, 35, 38, 39, 40, 41, 42, 43, 44 and 45	
	Phase-to-ground	6, 10, 15, 20, 22, 27, 30, 38, 39, 40, 41, 42 and 44	35 and 45	6, 10, 15, 20, 22, 27, 30, 35, 38, 39, 40, 41, 42, 43, 44 and 45	

4.10. Case Study 03: Three-phase fault in branch after the controls adjustment

It was seen that a three-phase short-circuit applied to the bus 43 leads to the loss of the plant synchronism due to the fuse operation time. In a distribution system, it is often not possible to change the fuse to reduce the operating time without having great interference in the protections coordination.

This work proposes a methodology where a heuristic adjustment of the control system is applied in case of transient instability. For the case studied, the PSS had the time constants changed, leading the system to stability. Fig. 14 shows the SHP rotor angle after the new adjustment of the control system.

Fig. 15 shows the frequency oscillating within the operating limits imposed. With the new settings of the SHP control system, these variations are within the technical limits.

Fig. 16 it is shown a momentary voltage sag, caused by short-circuit. The duration of this sag is linked to the operation time of the fuse, which will isolate the defaulted portion.

In Fig. 17 it is presented the variation of active power generated per phase. The same events in branches cause swings in generations, what is not evaluated in the traditional method.

Fig. 18 illustrates the active power provided by the wind generator, which also suffers variation with the verified voltage sag.

Table 8 shows a summary of the simulations results for the case study.

These results show the importance of the branch faults study for transient stability. In a simplified analysis where the branches are not considered, these failures will not be detected. The effectiveness of single-pole switching is also observed, which keeps the system stable in all disturbances. For the events where the system became unstable, the adjustment system of the controls readjusted the parameters and succeeded in the simulations.

5. Conclusions

This paper presented a global methodology to evaluate the transient stability in distribution systems with DG. The analysis included the study grid reduction to a representative network on a smaller scale, with dynamic response compatible with the original network. The main protections devices and voltage regulators have been preserved, with their original models and controls, as well as the impedance of the sections along the feeder. A set of events is proposed and the results obtained are compared with acceptable limits. The work demonstrates the importance on considering the branches representation in a distribution system, as well as the advantages of applying single-pole switching for reclosers in distribution systems. Simulations show success of single-pole switching in the transient stability of generators in the event of single-phase short circuits, which are predominant in distribution systems. Single-pole tripping and reclosing allow the DG to remain in synchronism with the electrical system during the fault clearing, contributing to the support of power at the time of system oscillation, thereby increasing the quality of the electricity supplied.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijepes.2018.01.039.

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