Received: 20 June 2017 | Revised: 25 January 2018 | Accepted: 13 February 2018

DOI: 10.1002/etep.2567

RESEARCH ARTICLE

WILEY

A new methodology for transient stability in distribution systems with distributed generation

Ederson Pereira Madruga[1] | Daniel Pinheiro Bernardon[1] | Rodrigo Padilha Vieira[1] | Luciano Lopes Pfitscher[2]

[1] UFSM—Federal University of Santa Maria, Santa Maria, Rio Grande do Sul, Brazil

[2] UFSC—Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

Correspondence
Daniel Pinheiro Bernardon, UFSM—Federal University of Santa Maria, Santa Maria, RS, Brazil.
Email: epmadruga@gmail.com

Summary

Transient stability in distribution systems has gained special interest because of the continuous increase of distributed generation connected to the grid. Besides the dynamic behavior of the generation system, the distribution networks present extensive branches and unbalanced loads with a specific set of equipment, what increases 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, which is divided in 3 major steps: (1) the representation of the network model through a simplified model, (2) the selection of disturbances types and buses for application, and (3) and the adjustment of stability control systems. The methodology is suitable for unbalanced networks and a demonstration of a single-pole switching is presented. Some case studies were simulated and analyzed for a real network model.

KEYWORDS

distributed generation, distribution network, synchronous generation, transient stability, unbalanced loads

1 | INTRODUCTION

The analysis of transient stability is essential in transmission systems, so 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, the efforts are 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. However, for real systems, the 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 only representative when studying the generation stability; however, in 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.

List of Abbreviations: ANEEL, Brazilian Electricity Regulatory Agency; ATP, analysis transient program; AVR, automatic voltage regulator; DFIG, doubly-fed electric machine; DG, distributed generation or distributed generations; IEEE, Institute of Electrical and Electronics Engineers; A, Core cross-section area; ONS, National System Operator—Brazil; PRODIST, Procedures for Distribution of Electric Energy in the National Electric System—Brazil; PSS, power system stabilizer; SHP, small hydropower plant

With the recent advances in renewable energy technologies, the increase of distributed generation (DG) directly connected to the 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 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, 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 its dynamic behavior and, consequently, the impact on power quality due to the diversity of sources.[7]

In transmission systems, the small signal stability and transient stability are essential studies, which 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.[8-10] However, this type of analysis is not suitable for direct use in distribution systems, since the characteristics are not the same.[11]

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

The main contribution of this work is the proposal of a methodology 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 for the establishment of main branches with potential impact on 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.

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 of the 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 in relation to 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.[10] For this reason, a special attention in order to protect the 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-to-ground short circuit, a single-phase simulation does not show the overvoltage in the 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, Figure 1A shows a reduced distribution network with 4 buses and a small hydropower plant (SHP) generator connected to bus 2. At the instant $t = 10$ seconds, a 3-phase short circuit is applied to bus 4, which is protected by a fuse. Figure 1B shows the rotor angle of the SHP generator, which losses the synchronism and stability after the fault.

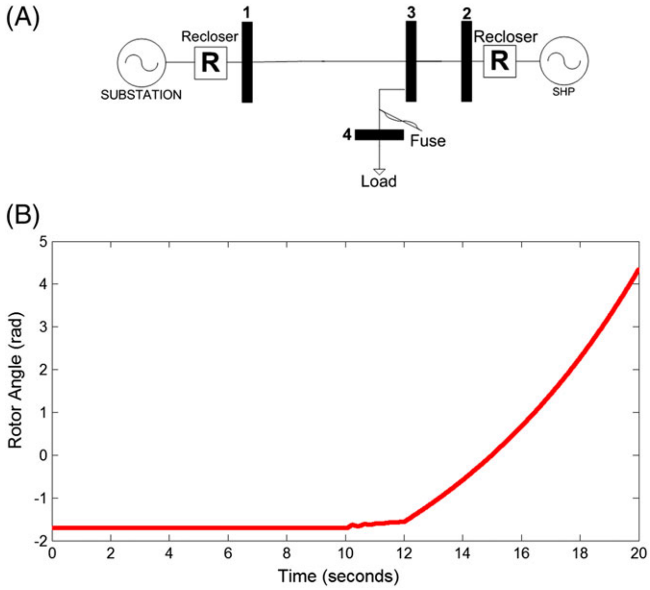

FIGURE 1 Simulation of a fault in a distribution network: A, distribution network with a secondary branch (bus 4) protected by a fuse with large response time; B, effect of a short circuit in the secondary branch on the small hydropower plant (SHP) generator rotor angle

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

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

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

where M_i is the inertia constant of the ith machine (pu·s^2/rad); t, time (s); D_i, damping constant of the ith machine (pu·s/rad); ω_i, angular velocity at each instant (rad/s); P_{m_i}, mechanical input power of the ith primary machine (pu); P_{e_i}, active electric power injected into the network by the ith machine (pu); δ_i, angular position of the axis of the ith machine with respect to an axis rotating at synchronous speed (rad); ω_s, synchronous speed (rad/s).

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

1) Voltage and frequency levels in all buses systems must not exceed the limits set for transient and steady state.
2) 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.[16,17] The system frequency adopted is 60 Hz.

The critical angle of operation is obtained when the derivative of the synchronizing power is 0, ie, 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 pu to safeguard the shaft of the generator-turbine systems because of the switches in the grid.[16] Voltage and frequency values in transient and steady state are defined by regulatory agencies.[18,19]

TABLE 1 Operational limits

Variable	Acceptable Values	Description
δ_i	$<\delta_{\text{critical}}$	Rotor angle of the machine in continuous operation
ΔP	$\leq$0.5 pu	Torsional stress
TV	0.80 pu $\leq$ TV $\leq$ 1.10 pu (normalize to TV in 10 s)	Level voltage in transient state
SV	0.95 pu $\leq$ SV $\leq$ 1.05 pu	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 $\leq$ 60.1 Hz	Frequency in steady state

Abbreviations: *P*, active power; *SF*, steady-state frequency; *SV*, steady-state voltage; *TF*, transient frequency; *TV*, transient voltage.

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.

Figure 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. 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 the main feeder: distributed generators, fuses, reclosers, and voltage regulators. These devices will define the areas where the reduction algorithm will be applied.
2) Divide the feeder into small areas among each equipment identified 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 shall be preserved in the simplified network: (*a*) the branch with lower accumulated impedance. This branch will present the lowest short circuit; (*b*) the branch with higher accumulated impedance just after the fuse of the main feeder branch. This branch has the largest short-circuit current; and (*c*) the branch with higher rated current fuse at the main feeder derivation. This fuse will have the longest time of operation.
5) Calculate the concentrated load of 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):

$$Z_i = \frac{V_{\text{rms}_i}^2}{S_i^*} \tag{3}$$

where Z_i is the equivalent impedance of load of phase i in ohms, V_{rms_i} is the root mean square voltage of phase i in volts, and S_i is the apparent power of phase i in volt-amperes.

Figure 3 illustrates the application of the proposed methodology in a hypothetical network. In this example, the complete network is reduced to 7 loads in 9 buses.

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

In addition, in order to obtain 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[17,20,21] with specific

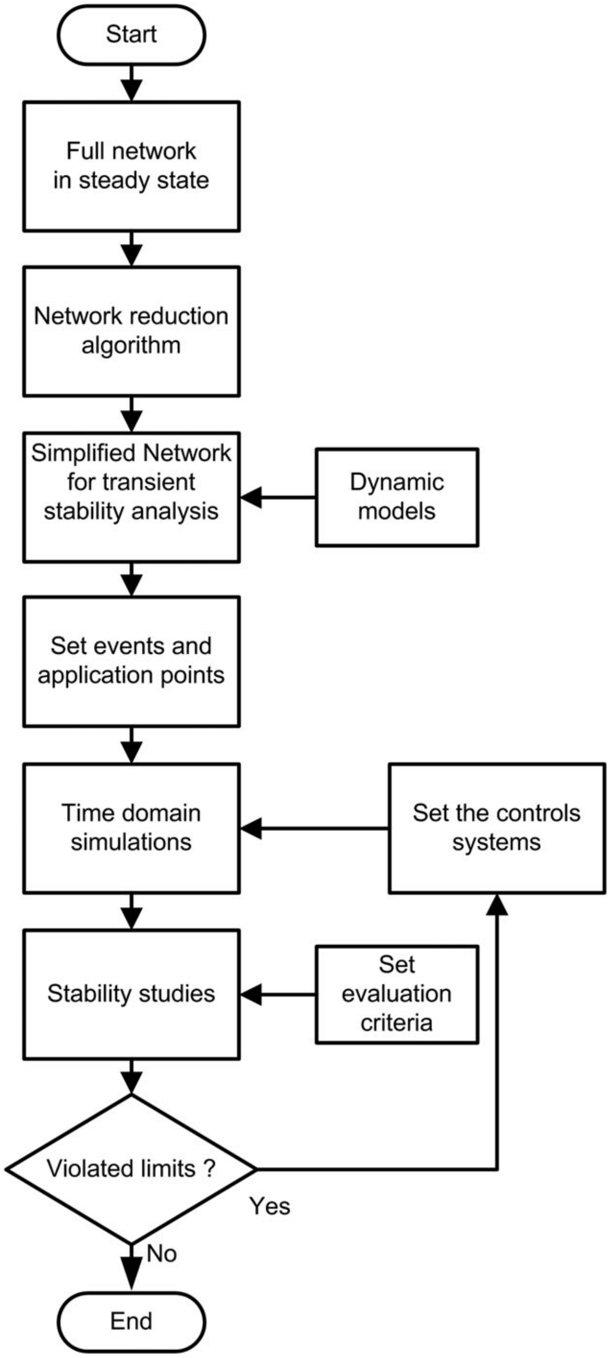

FIGURE 2 Methodology flowchart

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.

3.2 | Definition of the set of events

In the second step of the methodology 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 selected buses. The main interests in the study are the transient responses of the machines, the substation connections, and the power quality of loads. Changes in the

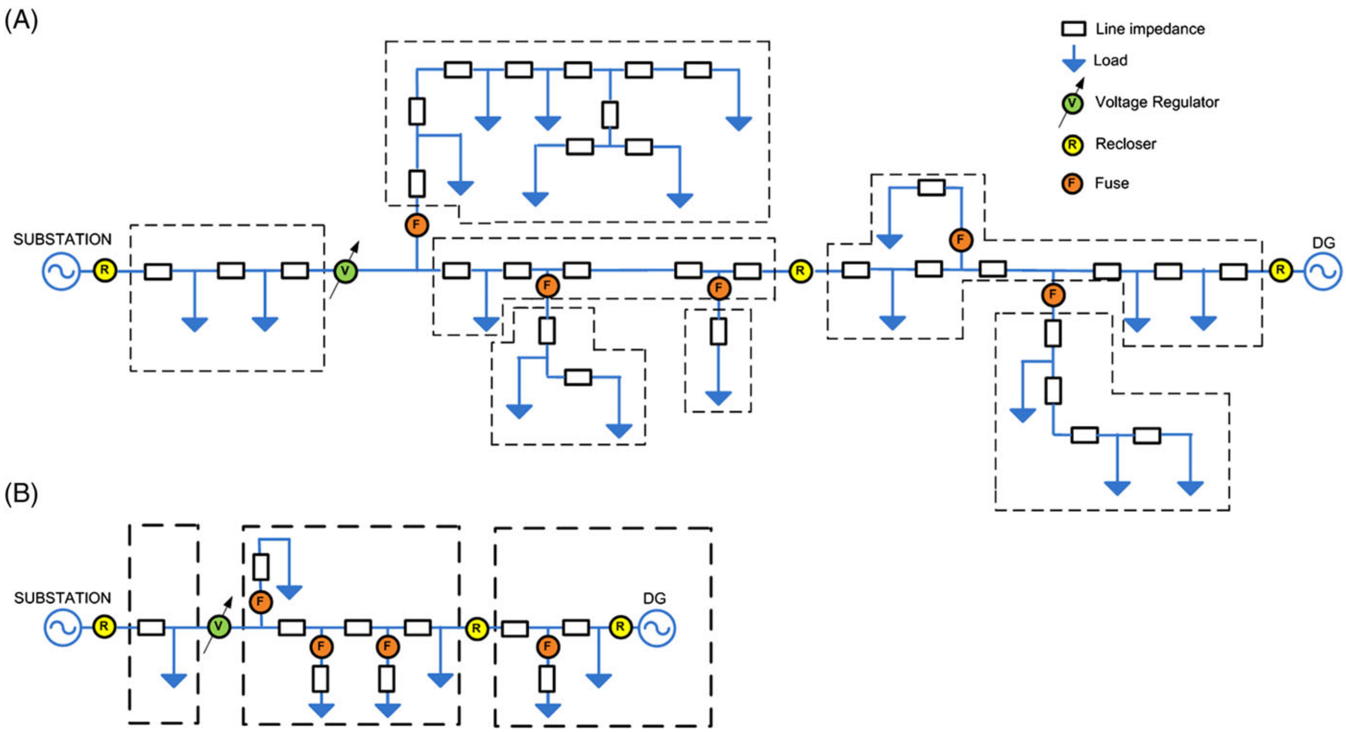

FIGURE 3 Example of network simplification: A, original network; B, simplified network

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 time of the fault clearing 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 buses for application of disturbance faults are selected according to the following criteria:

1) the closest bus to each substation
2) the closest bus to each distributed generator
3) an intermediate bus among each distributed generator and substation
4) the bus downstream of the protection fuse in each branch
5) the last bus of each branch, ie, at the point of the greatest accumulated impedance

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 it is verified.

The following faults are applied to the 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 3-phase and phase-to-ground short circuits immediately downstream of fuse protection;
c) application of 3-phase and phase-to-ground short circuits in the branch with higher impedance accumulated;
d) application of 3-phase and phase-to-ground short circuits in the branch with lower impedance accumulated downstream of the 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 3-phase operation mode is traditional in distribution networks, but 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 3-phase reclosers operations.

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

Thus, this paper makes a comparative analysis between single-phase and 3-phase reclosers operations.

3.3 | System control adjustment

In transient stability analysis of distribution system is common to adjust the controllers of speed, voltage and stabilizing signal (power system stabilizer [PSS]). The use of PSS in distributed generator connected to distribution systems has been increasing, mainly because of the dynamic characteristics of these systems.[22-24]

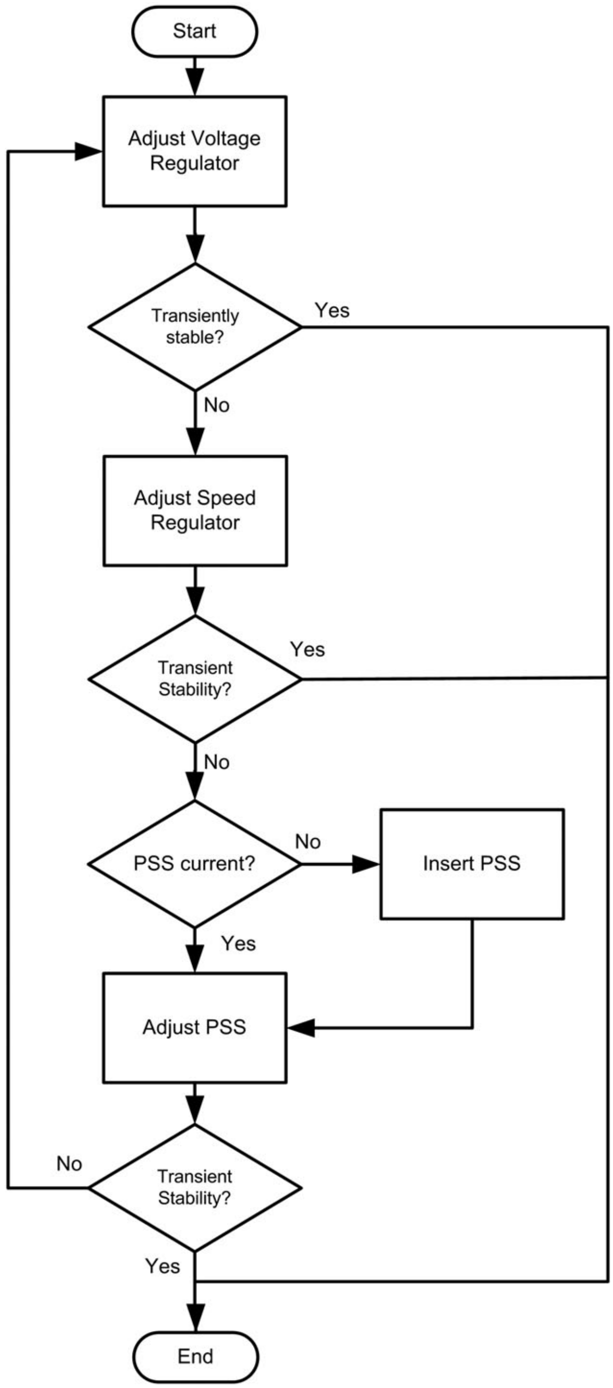

FIGURE 4 Control system adjustment flowchart. PSS, power system stabilizer

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 PSS,[25] as indicated in the flowchart of Figure 4.

The control system adjustment is not the object of this work. In the simulations, a meta-heuristic to adjust the controls on the basis of Ziegler and Nichols's[26] method was used.

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 the instability may occur in subsequent oscillations.[11] The proposed sequence prioritizes the voltage regulator adjustment, followed by the speed regulator and the PSS. If the stability is not achieved after adjusting the voltage and speed regulators, 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 Figure 5, it shows the distribution system unifilar diagram. The software DIgSILENT PowerFactory[27] was used as simulation tool in time domain.

The SHP generation curves, wind generation, load curves, and substation power equivalent are shown in Figure 6A. Figure 6B shows the percentage unbalance among the 3-phase loads.

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 an 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 hours 0 minutes, that is, the time with the lowest load.

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

Small hydropower plant with synchronous generator: An SHP model represented by synchronous generators of salient poles was considered, with a total rated power of 3.125 MVA and an average generation of 2.0 MW, operating with constant power and unity power factor.

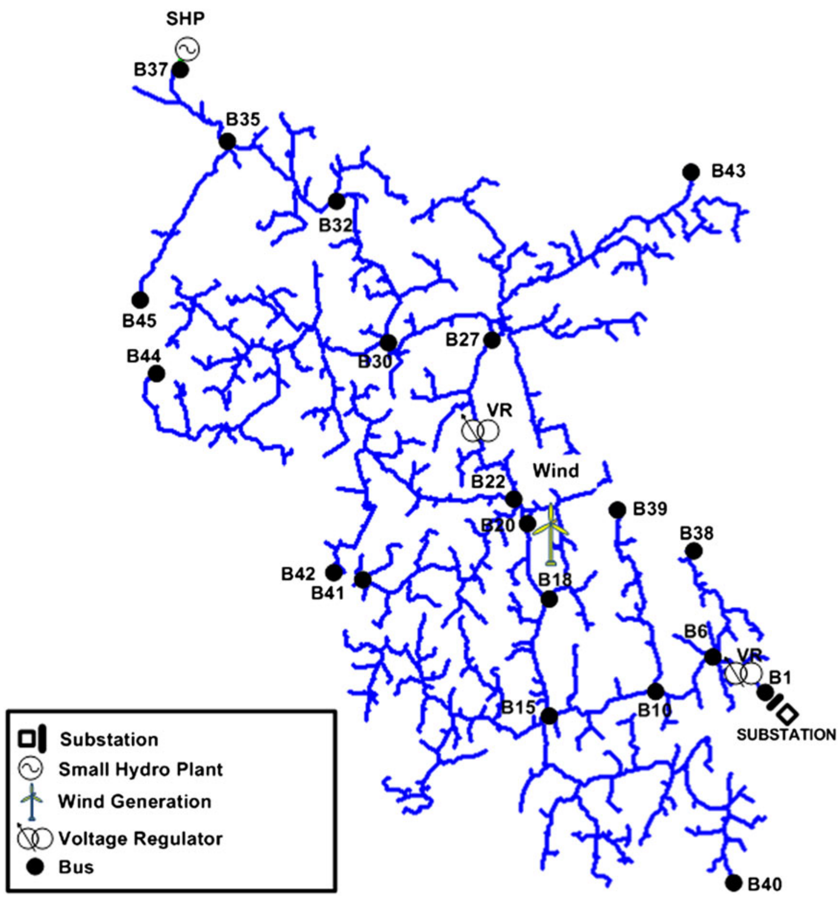

FIGURE 5 Distribution network used in the case study

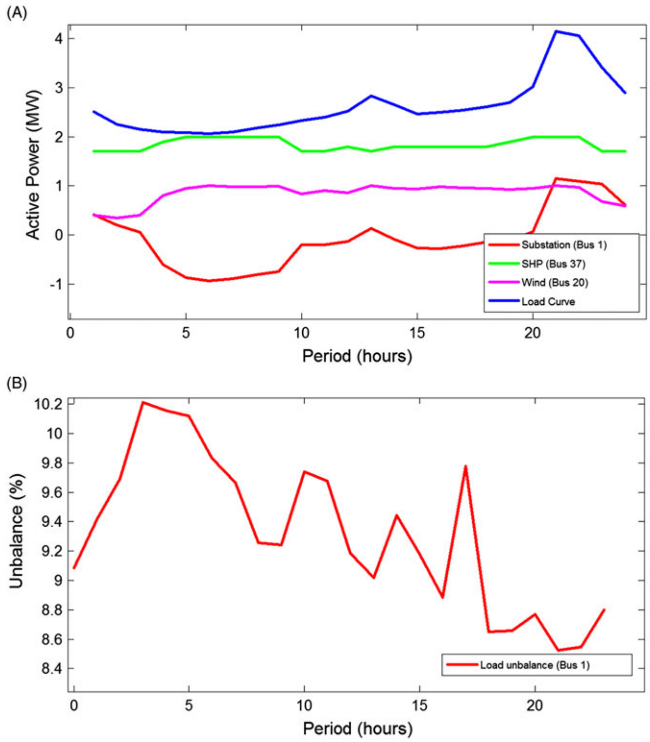

FIGURE 6 Feeder load curves: A, active power; B, unbalance load. SHP, small hydropower plant

Table 2 shows the main parameters of the machines.

Small hydropower plant voltage regulator: The basic functions of an excitation system are to 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:

Small hydropower plant speed regulator: The primary regulation aims to maintain the frequency deviations to the minimum without stability loss.[11] The used speed regulator was the HYGOV of IEEE.[20] Table 4 presents the main speed regulator parameters.

Small hydropower plant power system stabilizer: The best dynamic response of the system is obtained through the addition of an additional signal stabilizer. The PSS added is an IEEE standard, which parameters are shown in Table 5.

Wind generator: The wind generator was modeled as a directly connected Squirrel Cage 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

4.1 | 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 Figure 7.

First, the buses that would be preserved were defined, which were the ones with reclosers, voltage regulators, and distributed generators. 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.

Table 6 shows the calculated powers and voltages in the complete network and in the simplified network.

4.2 | Selection of events

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

TABLE 2 Small hydropower plant 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*, pu	0.0100
Stator reactance X', pu	0.1000
Unsaturated *d* axis synchronous reactance *Xd*, pu	0.9106
Unsaturated *q* axis synchronous reactance *Xq*, pu	0.4659
Unsaturated *d* axis synchronous transient reactance Xd', pu	0.4365
Unsaturated *d* axis synchronous subtransient reactance Xd'', pu	0.2950
Unsaturated *q* axis synchronous subtransient reactance Xq'', pu	0.3782
Zero-sequence reactance *X*0, pu	0.1346
Negative-sequence reactance *X*2, pu	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 Small hydropower plant voltage regulator parameters

Variable	Value	Unit	Description
T_r	0.02	s	Measurement delay
T_b	0.02	s	Filter delay time
T_c	0.1	s	Filter derivative time constant
K_a	150	pu	Controller gain
T_a	0.015	s	Controller time constant
T_e	0.5	s	Exciter time constant
K_e	0.96	pu	Exciter constant
E_1	3.13	pu	Saturation factor 1
SE_1	0.10	pu	Saturation factor 2
E_2	4.18	pu	Saturation factor 3
SE_2	0.50	pu	Saturation factor 4
K_f	0.01	pu	Stabilization path gain
T_{f1}	1.00	s	Stabilization path time constant
V_{rmin}	−20	pu	Controller minimum output
V_{rmax}	20	pu	Controller maximum output

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

TABLE 4 Small hydropower plant speed regulator parameters

Variable	Value	Unit	Description
R	0.300	pu	Temporary droop
T_r	5.000	s	Governor time constant
T_f	0.100	s	Filter time constant
T_g	0.002	s	Servo time constant
A_t	1.000	pu	Turbine gain
D_{turb}	0.010	pu	Frictional losses factor
Q_{nl}	0.010	pu	No load flow
R	0.050	pu	Permanent droop
V_{elm}	0.150	pu	Gate velocity limit
G_{min}	0	pu	Minimum gate limit
G_{max}	1	pu	Maximum gate limit

TABLE 5 Parameters of the SHP PSS

Variable	Value	Unit	Description
T_1	0.05	s	Lead lag 1st derivate time constant
T_2	0.30	s	Lead lag 2nd delay time constant
T_3	1.20	s	Lead lag 3rd derivate time constant
T_4	1.00	s	Lead lag 4th delay time constant
T_5	1.00	s	Stabilizer derivative time constant
T_6	1.00	s	Stabilizer time constant
K_{s}	−50	pu	Stabilizer gain
A_1	0.00	s	Filter 1st time constant
A_2	0.00	s	Filter 2nd time constant
A_3	0.50	s	Filter 3rd time constant
A_4	1.00	s	Filter 4th time constant
A_5	2.00	s	Filter 5th time constant
A_6	1.00	s	Filter 6th time constant
L_{smin}	−0.10	pu	Controller minimum output
L_{smax}	0.10	pu	Controller maximum output

Distribution systems traditionally have reclosers operating in 3-pole switching mode, ie, even if the fault is single phase, there is a 3-phase interruption. This mode of operation may result in a large reduction of load power, which can lead to the instability of the synchronous distributed generator. In this study, an evaluation of the single-pole switching operation of the reclosers is performed, where the advantage of phase-to-ground operation over 3-pole operation is evidenced.

4.3 | Comparison between single-pole and 3-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 3-pole tripping and reclosing. The proposed method considers the tripping and reclosing as single pole.

The system fault occurs at 10 seconds of simulation, and the SHP circuit breaker is the first equipment to operate, opening the circuit at 10.328 seconds. At 10.650 seconds, the substation circuit breaker operates by clearing all current

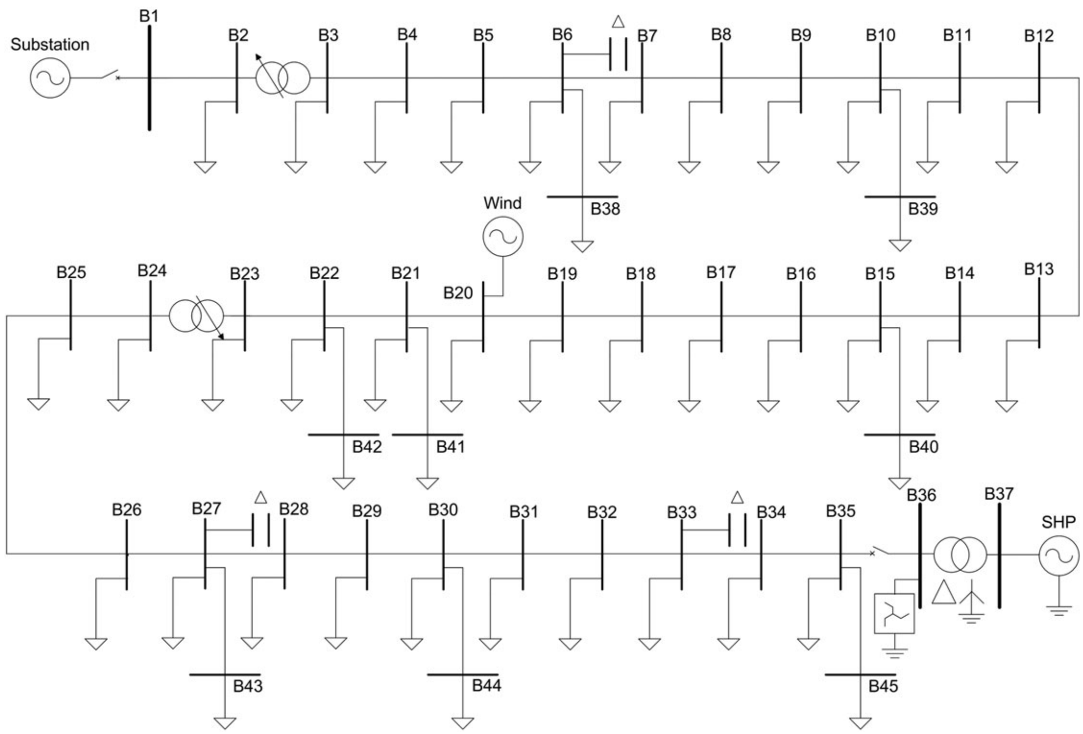

FIGURE 7 Distribution network used in the case study. SHP, small hydropower plant

TABLE 6 Comparative data between complete network and simplified network

	Complete Network	Simplified Network	Variation, %
Substation power flow	0.10 + 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	1.032 pu	1.034 pu	0.19

Abbreviation: SHP, small hydropower plant.

TABLE 7 Events and application buses

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

sources. At 11.25 seconds, the substation breaker closes its contacts, and at 11.328 seconds, the SHP breaker is closed. Figure 8 shows the transient response for synchronous machine with 3-pole tripping and for single-pole tripping, 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. Figure 9 presents the frequency in buses with generation.

Figure 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.

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

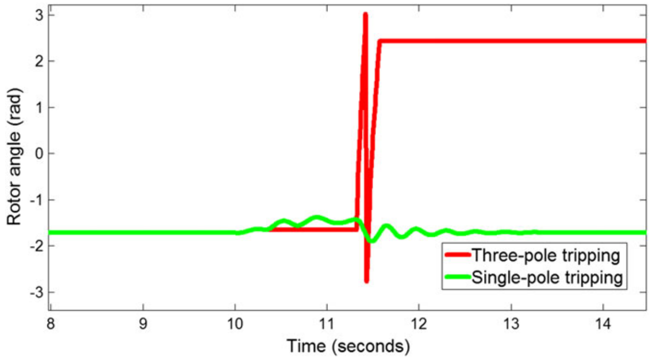

FIGURE 8 Small hydropower plant rotor angle

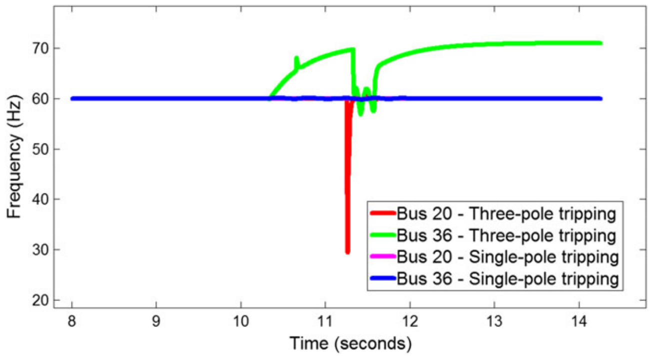

FIGURE 9 Frequency in the buses with generation

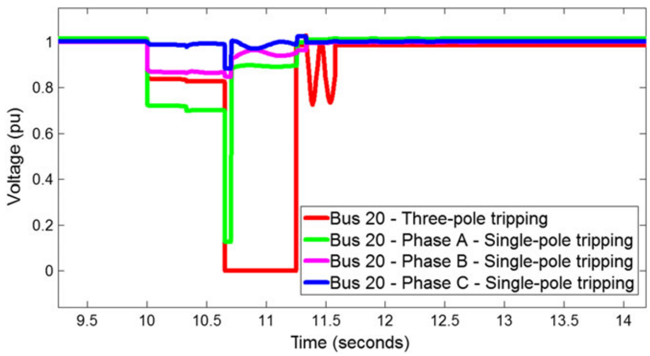

FIGURE 10 Voltages in the main buses of the network

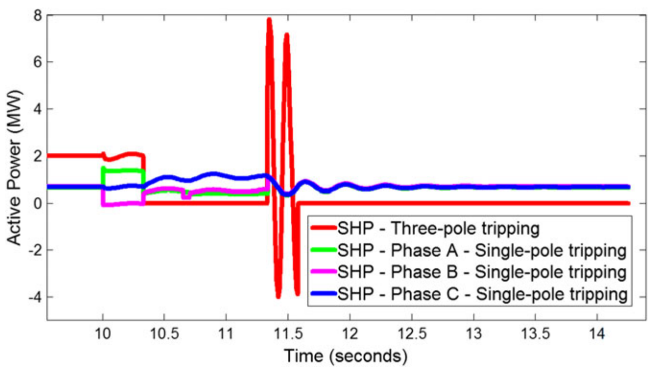

FIGURE 11 Active power of the small hydropower plant

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. Figure 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.

4.4 | Three-phase fault in branch

This study evaluates the stability transient for an event occurred in branches, which is not evaluated in traditional studies using a simplified model with substation and distributed generator. The primary protection for faults in branches are fuses, in which the operating times depend on the level of short circuits of the system.

A 3-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. Figure 13 presents the synchronous machine rotor speed, where an oscillation is observed, which makes the generator lose synchronism with the distribution network.

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.

4.5 | Three-phase fault in branch after the controls adjustment

It was seen that a 3-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. Figure 14 shows the SHP rotor angle after the new adjustment of the control system.

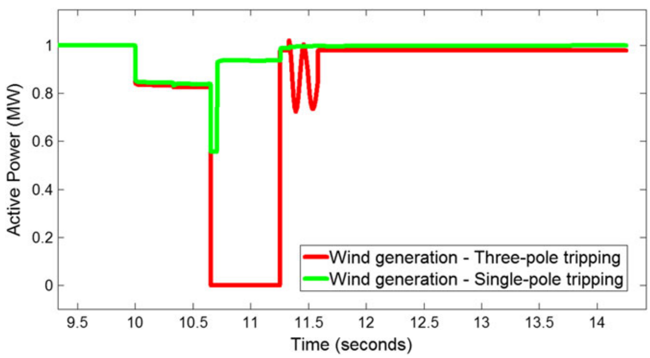

FIGURE 12 Active power of wind generation

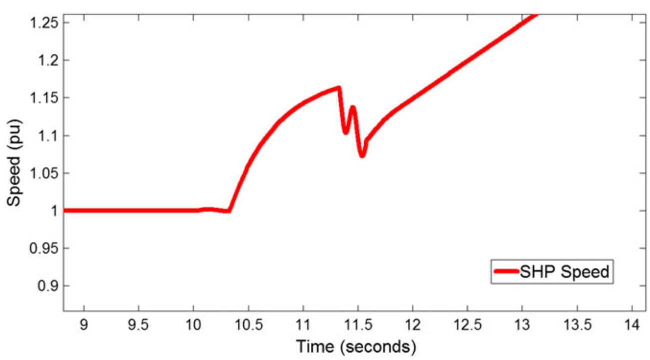

FIGURE 13 Small hydropower plant (SHP) rotor speed

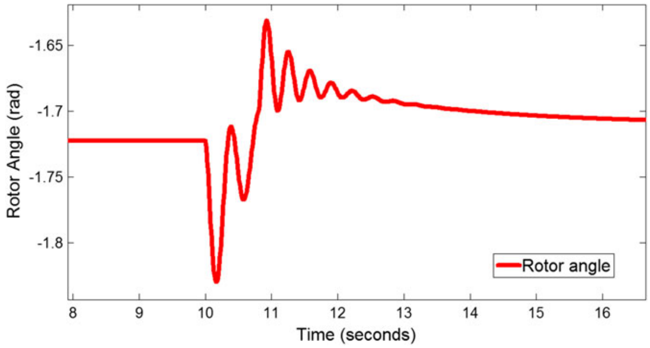

FIGURE 14 Small hydropower plant rotor angle with new adjustment

Figure 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.

Figure 16 shows the 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 Figure 17, the variation of active power generated per phase is presented. The same events in branches cause swings in generations, what is not evaluated in the traditional method.

Figure 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.

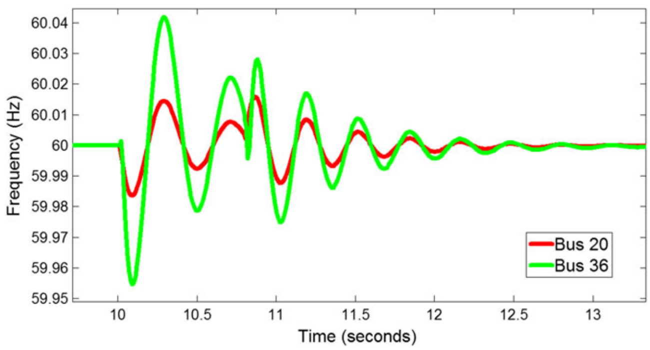

FIGURE 15 Frequency in the buses with generation

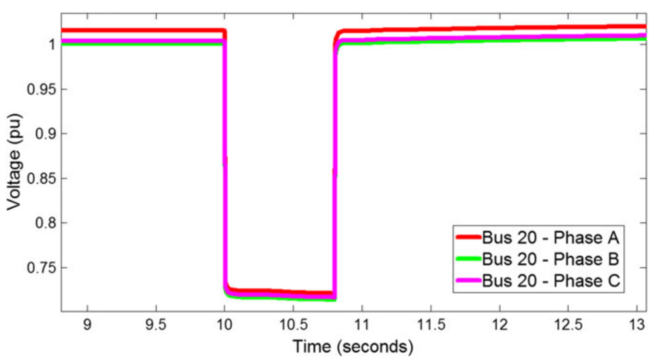

FIGURE 16 Bus voltage in the wind generation

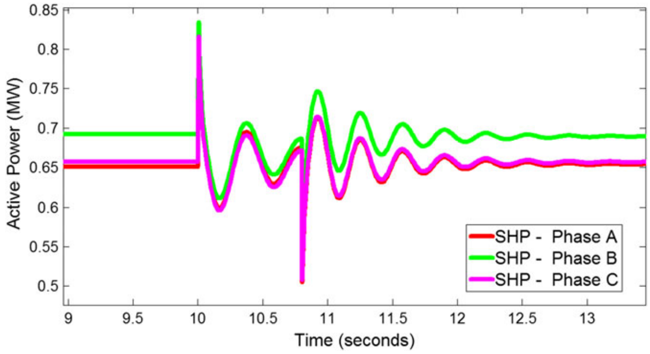

FIGURE 17 Small hydropower plant (SHP) active power

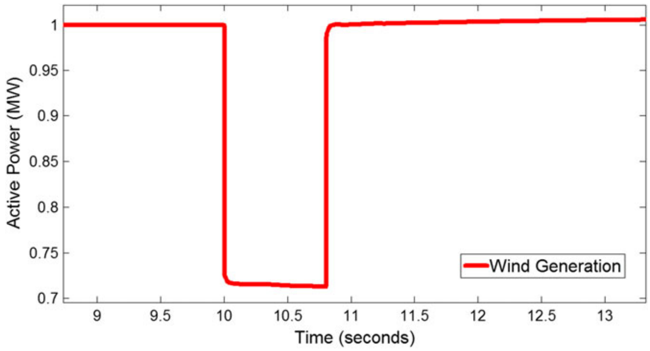

FIGURE 18 Active power of wind generation

TABLE 8 Summary of simulation results

		Three-Pole Tripping		Single-Pole Tripping	
Segment	**Short Circuit**	**Stable**	**Unstable**	**Stable**	**Unstable**
Main feeder	Three phases		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 phases	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	

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.

ACKNOWLEDGEMENT

The authors would like to thank the technical and financial support of Brazilian power utility and agencies: CERTAJA ENERGIA, CAPES, CNPq, FAPERGS and INCT-GD UFSM.

ORCID

Ederson Pereira Madruga http://orcid.org/0000-0003-0476-4772

REFERENCES

1. Ackermann T, Andersson G, Söder L. Distributed generation: a definition. *Electr Pow Syst Res*. 2001;57(3):195-204.
2. Stankovic AM, Aydin T. Analysis of unbalanced power system faults using dynamic phasors. *IEEE Trans Power Syst*. 2000;15(3):1062-1068.
3. Dias IC, Resener M, Canha LN, Pereira PR. Transient stability study of an unbalanced distribution system with distributed generation. IEEE 2014.
4. Zhou N, Wang P, Wang Q, Loh PC. Transient stability study of distributed induction generators.
5. Boemer JC, Gibescu M, Kling WL. Dynamic models for transient stability analysis of transmission and distribution systems with distributed generation: an overview. IEEE Bucharest power tech conference. Romania 2009; Using an Improved Steady-State Equivalent Circuit Method, IEEE, 2014.
6. Nasr-Azadani E, Cañizares CA, Olivares DE, Bhattacharya K. Stability analysis of unbalanced distribution systems with synchronous machine and DFIG based distributed generators, IEEE 2014.
7. Resener M, Salim RH, Bretas AS. Impacts of excitation control modes of distributed generators on distribution systems transient stability: a case study. IEEE 2012.
8. Kundur P. *Power System Stability and Control*. New York: Editora McGraw-Hill; 1994.
9. Arrillaga J, Smith B. *AC-DC Power System Analysis*. Grã-Bretanha: IEE Press; 1998.
10. Anderson PM, Fouad AA. *Power System Control and Stability*. Piscataway, NJ: IEEE Press; 1994.
11. Nazari MH, Ilic M. Dynamic modelling and control of distribution energy systems: comparison with transmission power systems. IET Generation. Transmission & Distribution. 2013.
12. Salim RH, Ramos RA, Bretas NG. Analysis of the small signal dynamic performance of synchronous generators under unbalanced operating conditions. IEEE. 2010.
13. Abreu LVL, Marques Frederico AS, Morán J, Freitas W, da Silva Luiz CP. Impact of distributed synchronous generators on the dynamic performance of electrical power distribution systems. In: IEEE/PES T&D 2004 Latin America. 2004. São Paulo. 2004.
14. Grilo AP, Mota AA, Mota LTM, Freitas W. An analytical method for analysis of large-disturbance stability of induction generators. *IEEE Trans Power Syst*. 2007;22(4):1861-1869.
15. Kundur P, Paserba J, Ajjarapu V, et al. Definition and classification of power system stability. *Trans Power Syst*. 2004;19(2).
16. IEEE Working Group Report. IEEE screening guide for planned steady-state switching operations to minimize harmful effects on steam turbine-generators. *IEEE Trans Power Apparatus Syst* July/August. 1980;PAS-99(4):1519-1521.
17. IEEE PAS-92. no.6. Nov 1973. pp 1904-1915.
18. ANEEL - Brazilian Electricity Regulatory Agency. Procedures for Distribution of Electric Energy in the National Electric System (prodist). Module 8, Jan/2017.
19. Independent power system operator in Brazil (National System Operator - ONS) Network procedure, module 23. Guidelines and criteria for electrical studies. Dez/2016.
20. IEEE TPS. Hydro turbine (linear). 1992;7(1):167-179.
21. IEEE Std 421.5™-2005. Recommended practice for excitation system models for power system stability studies. Apr 2006;64:8.
22. Kamwa I, Grondin R, Trudel G. IEEE PSS2B versus PSS4B: the limits of performance of modern power system stabilizers. *IEEE Trans Power Syst*. 2005;20(2).
23. Alshamli Y, Hosseinzadeh N, Hasan Y, Al-Hinai A. A review of concepts in power system stability. 8th IEEE GCC Conference and Exhibition, Muscat, Oman, 1-4 February, 2015.

24. ABB http://new.abb.com/power-electronics/excitation-systems/add-on-functions/unitrol-power-system-stabilizer. Accessed on 09/24/2017.
25. Wang R. et al. Modeling and control of distributed generation under distorted and unbalanced conditions. Changshu: IEEE. 2013.
26. Ziegler JG, Nichols NB. Optimal settings for automatic controllers. *Transactions of the ASME*. 1942;64:759-768.
27. DIgSILENT POWERFACTORY – Technical references. Version 14.1. Germany. 2011.

How to cite this article: Madruga EP, Bernardon DP, Vieira RP, Pfitscher LL. A new methodology for transient stability in distribution systems with distributed generation. *Int Trans Electr Energ Syst*. 2018;e2567. https://doi.org/10.1002/etep.2567