Impact of Distributed Synchronous Generators on Distribution Feeder Stability

F. M. Gonzalez-Longatt, *Student Member*

Abstract—**The distributed generation is rapidly becoming a reality. Some technologies like micro turbine in split-shaft design use a power turbine rotating at 3600 rpm and conventional generator connecting via a gearbox to feed power into distribution feeder. In the future this technology of small to medium size dispersed generator will penetrate considerably the distribution networks, and impact the behavior of the system. This paper presents simulations on steady state of a typical distribution feeder with variable penetration and dispersion level of distributed synchronous generator. The impact of DG on distribution feeder stability is investigated by rotor speed variation in the transient resulting of the permanent three- phase fault in the distribution feeder that interrupt the power flow from the conventional generation system.**

Index Terms—**Distributed Generation (DG), distribution feeder, power system stability.**

I. Introduction

Today, with electricity utility restructuring, public environmental policy, and expanding power demand, small distributed generators are in great need in order to satisfy on-site consumer energy needs. Major improvement in the economic, operational, and environmental performance of small, modular units has been achieved thought decades of intense research. Some technologies, like micro turbines in split-shaft design and another, use conventional synchronous generator of modest size. In the future, the penetration levels of these technologies will be considerable, and these distributed resources will impact the steady state and dynamic behavior of the distribution system. The main objective of this paper is to know the impact (increase or decrease) that DG produces on the dynamics of a distribution system considering several aspects: penetration and dispersion level. The novelty of this paper is the use of equivalent model of the synchronous machines and simple gas turbine.

II. Modeling

A. Distributed Generators

In this paper only focused on distributed synchronous generators, for this reason, only synchronous machine with gas turbine system and gubernator speed, and a simple AVR modeled by IEEE type 1, are considered in this paper.

1) Synchronous Generator

The full detailed mathematical model of a synchronous machine takes into account several effects introduce by different rotor circuits, and consist of seven nonlinear differential equations for each machine. In stability study the complete mathematical description is really complicated, unless some simplifications were used [12-15]. Some simplification are possible, to satisfy a valence between data requirement and computer cost. A common simplification assumptions is neglected the stator transient, and damper winding. In this paper both suppositions are used, in other words, the two axis model [15-16], is employ in the simulations, neglecting the saturation effect. Table 1, shown the typical values of a synchronous generator used in this paper for simulations.

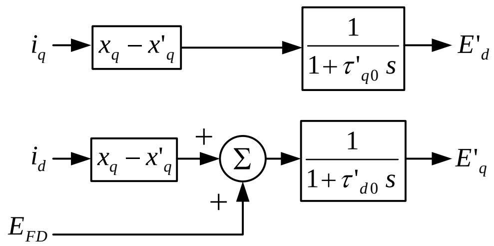


Fig. 1. Block diagram representation of the two-axis model, electrical behavior

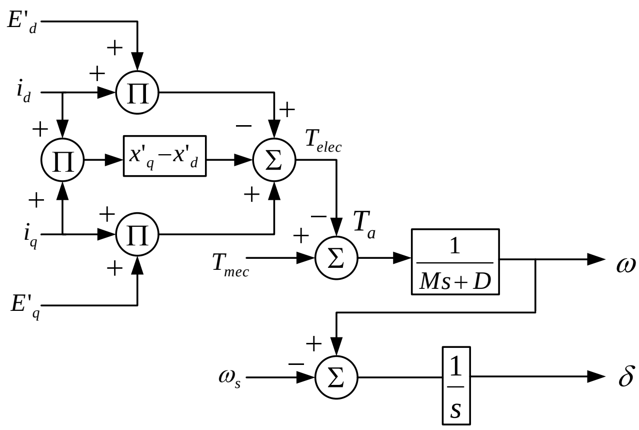


Fig. 2. Block diagram representation of the two-axis model, electro-mechanical behavior

TABLE 1
Parameter of Synchronous Generator

F. M. Gonzalez-Longatt is with Universidad Nacional Experimental Politécnica de la Fuerza Armada, Maracay, Estado Aragua, 2122 Venezuela (e-mail: fglongatt@ieee.org).

Parameter	Definition	Value
x_d	Direct-axis synchronous reactance	1.58 p.u
x'_d	Direct-axis transient synchronous reactance	0.274 p.u
x''_d	Direct-axis subtransient synchronous reactance	0.173 p.u
x_q	Quadrature-axis synchronous reactance	0.95 p.u
x'_q	Quadrature-axis transient synchronous reactance	0.217 p.u
x''_q	Quadrature-axis subtransient synchronous reactance	
x_l	Armature leakage reactance	0.052 p.u
r_s	Armature resistance	0.0036 p.u
τ'_d	Direct-axis transient open-circuit time constant	0.496 sec.
τ''_d	Direct-axis subtransient open-circuit time constant	0.022 sec.
τ'_{q0}	Quadrature -axis subtransient open-circuit time constant	0.05 sec.
H	Total inertia of the shaft	1.07 seg
D	Shaft damping factor	0

2) *Gas Turbine*

There exist several dynamic models of turbine-generator with varying degrees of complexity to represent different makes and models of gas turbine units. The GAST model [7], is one of the most commonly used dynamic model. This model is suitable to simulate the dynamic behavior of split-shaft design, where are two turbines, one is a gasifier turbine driving a compressor and another is a free power turbine driving a generator at rotating speed of 3600 rpm, there is only one combustor and one gasifier compressor [1], [8-9]. The model of the gas turbine used in this paper is shown in Figure 3 [10], and the typical parameters used for simulations purpose in this paper are shown in the Table 2.

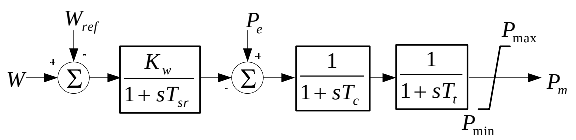


Fig. 3. Block model of a simple gas turbine and governing system

TABLE 2
PARAMETER OF SIMPLE GAS TURBINE AND SPEED GOVERNING SYSTEM

Parameter	Definition	Value
P_{max}	Maximum shaft power	1.2 p.u
P_{min}	Minimum shaft power	0 p.u
τ_c	Governor reset time constant	0.1 sec.
τ_{sr}	Speed relay time constant	0.15 sec.
τ_t	Turbine relay time constant	0.10 seg

3) *AVR*

An excitation system provide direct current to the synchronous machine field winding, to performs control and provide protective function essential to satisfactory performance of the power system by controlling the field voltage and thereby the field current [2], [14]. The IEEE type 1 is a type of exciter and AVR system represents a continuously acting regulator with rotating exciter system. Some vendors' units represented by this model include: Westinghouse brushless systems with TRA, Mag-A-Stat, Silverstat, or Rotoroal regulator, Allis Chalmers systems with Regulex regulator, General Electric systems with Amplidyne or GDA regulator [11].

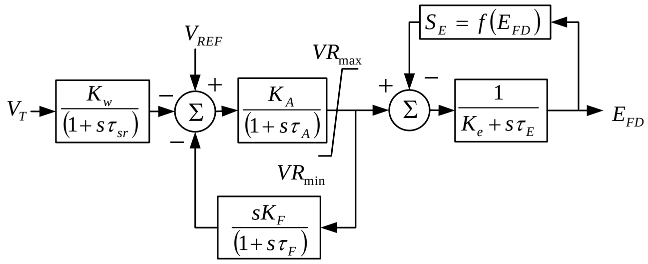


Fig. 4. Block diagram representation IEEE type 1 excitation system [2], [14]

In this paper the AVR is represented by IEEE type 1 excitation system, as shown on Figure 4, and the typical parameter used in the simulations are shown on Table 3.

TABLE 3
PARAMETER OF IEEE TYPE 1 EXCITATION SYSTEM

Parameter	Definition	Value
τ_R	Regulator input filter time constant, low pass	20 msec
K_a	Regulator gain	200
τ_a	Regulator amplifier time constant	0.02 sec
K_e	Exciter constant for self-excited field	1
τ_e	Exciter time constant	0 sec
τ_b	Transient gain reduction time constant 1	0 sec
τ_c	Transient gain reduction time constant 2	0 sec
K_f	Regulator stabilizing circuit	0.0001
τ_f	Regulator stabilizing circuit time constant	0.1 sec
K_p	Out put regulator gain	0
V_{Rmax}	Maximum value of the regulator output voltage	0 p.u
V_{rmin}	Minimum value of the regulator output voltage	6 p.u
E_{fdmax}	Maximum exciter output voltage	6 p.u

B. *Distribution Feeder*

A modified version of the distribution feeder in the Kumamoto area of Japan [1] is used in the studies. The network parameters can be found in Appendix A, where the base power is 10 MVA and the base line voltage is 6.6 kV. The loads are considered as constant power and the total load in this distribution system is P_{load} = 18.9 MW, Q_{load} = 1.3 MVAR. Fig. 1 shows the test system used throughout the simulations.

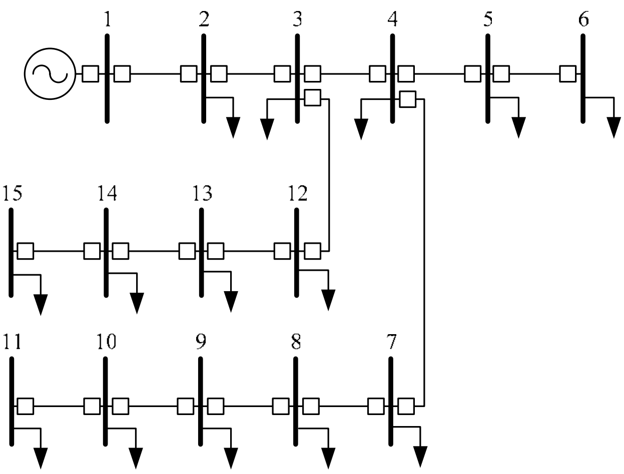


Fig. 5. Kumamoto 15-bus distribution system online diagram [1]

Only one centralized generator in this system is considered. The representation of engine control system of the synchronous machines, all distributed generator are considered driven by a simple gas turbine working in isochronous mode, with AVR tuned to satisfy 1.0 p.u voltage in terminals. The representative values for the parameters of the generators and the governor are taken form other sources [2], [3], [4], [5], [6].

C. Simulation Scenarios

The main objective of this paper is to know the impact (increase or decrease) that DG produces on the dynamics of a distribution system considering several aspects:

- *DG penetration level (%DG_{level})*: fraction of the total load in the test system that is served by GD. Thus, the DG penetration level in the system is defined by:

$$\%DG_{level} = \frac{P_{DG}}{P_{load}} \times 100\% \tag{5}$$

The main scenarios of penetration level that was simulated are the following:

I, II, III scenarios: In this scenarios DG was installed give penetration values of 10%, 20% and 30% respectively.

IV. Semi-Ideal scenario: DG capacity installed in this scenario is the half of the total load installed in the system.

V. Ideal scenario: In this scenario DG capacity installed is equal to all loads in the system.

The power installed in each bus is proportional to the load demanded in this bus.

- *DG dispersion level (%DG_{disp})*: ratio of number of nodes in which there is DG (*#$Buses_{DG}$*) and the number of nodes in which consumption exists (*#$Buses_{load}$*).

$$\%DG_{disp} = \frac{\#Buses_{DG}}{\#Buses_{load}} \times 100\% \tag{6}$$

The main scenarios of dispersion level that was simulated are the following:

I, II scenarios: In this scenarios DG was installed give penetration values of 21%, 28% respectively.

III. Semi-ideal scenario: In this scenario DG was installed only in half of the nodes in which demand exist.

The total load installed in each bus was used to give priority to install DG. These philosophy permits install larger units in those buses with large load. The synchronous generator was considered only to supply active power to the system, and the all reactive power is provided by the centralized generator.

The steady state of the test system was simulated and the voltage profile and the active power losses estimated in all scenarios.

The transient stability of the test system was investigated by applying a permanent solid three phase fault on the bus 2, near the centralized generation. It is assumed that the fault is cleared by tripping the fault after the 83.3 ms (i.e. 5 cycles at 60 hz).

III. Simulation Results

A. Steady State

The relevant results of the steady state simulations of 6.6 kV Kumamoto distribution feeder (Figure 1) are presented in this section. The steady state behavior of the test system was simulated by a program on MATLAB™ developed by the author. This program resolves the load flow problem, with a Newton-Raphson iterative method, and fully configurable to develop load flow studies. The load nodes are modeled as PQ node, with historical power factor provided by [1]. There are modeled as constant power load that is independent of voltage level. The DG nodes are modeled as PQ nodes, with active power constant, defined by the penetration level to be evaluated, and cos ϕ =1. In this case the, voltage support is do by the central generator (bus 1). This assumption is due some DG sauces can not supply reactive power.

Steady state without DG sources, show all bus voltages within limits (±0.05 p.u), and total losses are 0.045 p.u.

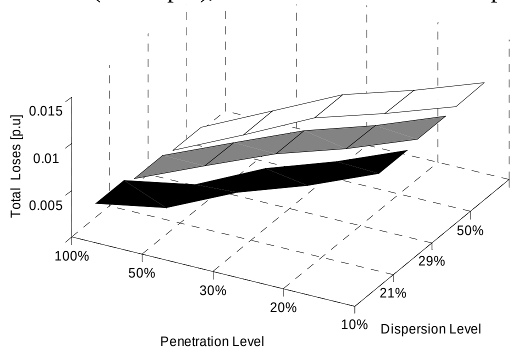
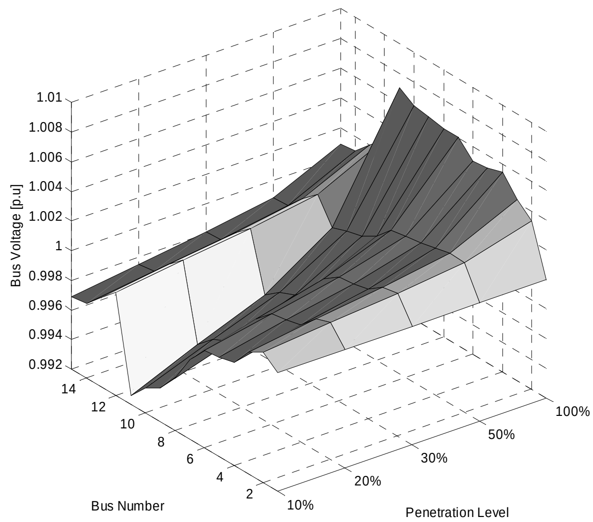


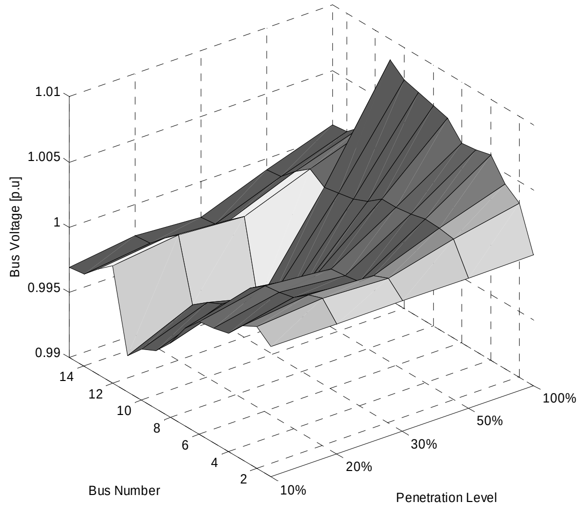
Fig. 6. Total loses for several scenarios of penetration and dispersion level

Fig. 6 shows the behavior of the total losses (in per unit) for several penetration and dispersion level of DG in the test system. The test system simulated show that losses become lower, at higher penetration and dispersion levels of DG.

The voltage profile is strongly modified by the penetration level. Higher voltages profile are found at high penetration levels.

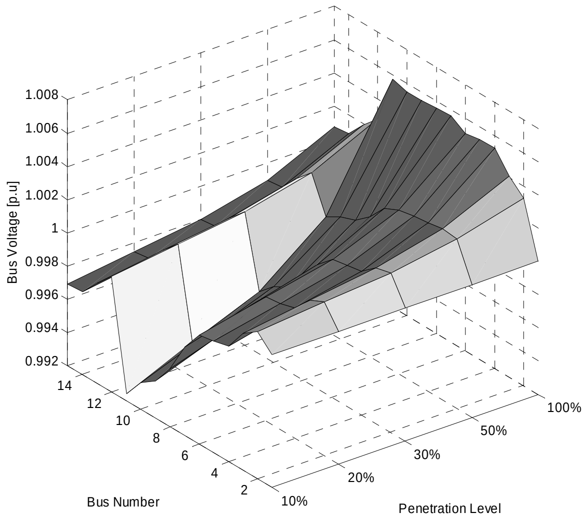


(a)



(b)

(b)



(c)

Fig. 4. Bus Voltage profile as function of penetration level for (a) 21%, (b) 29%, (50%) dispersion

Furthermore, the at high dispersion levels, better voltage profile are found. Figure 4, shows the bus voltage profile of the test system show, for several scenarios, better behavior at high level of penetration and high dispersion. Notice that best profile for low penetration result of low dispersion, this due the location and rating criteria used for DG in the test system.

B. Transient Stability

The test system dynamic simulation was done on rudimentary stability program on MATLAB™ developed by the author. This program employs the industry model for the dynamic equations of the elements, and permit use all kind of control system. Four-order Runge-Kutta method is used for resolve the differential equations. Though the program is capable of simulating the devices of protection and load rejection, these simulations are beyond of the paper purpose.

Initially, stand alone performance of the DG source is evaluated, for a three phase short-circuit in terminals. Figure 5 and 6 shows the power angle and rotor speed versus time curves for several clearing times (5, 8 12, 15, 18, 21 and 24 cycles at fundamental frequency).

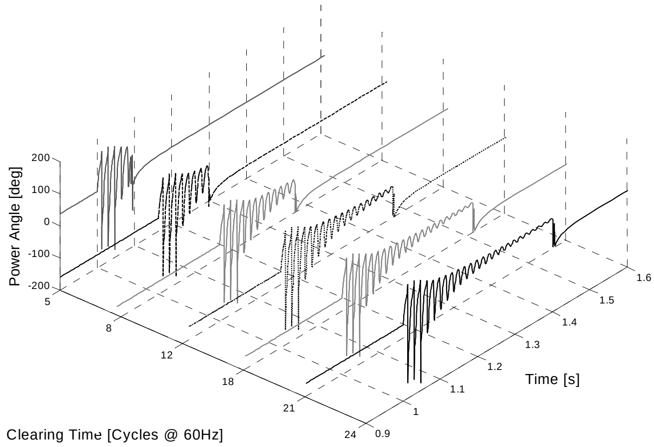


Fig. 5. Power angle versus time, for several clearing times

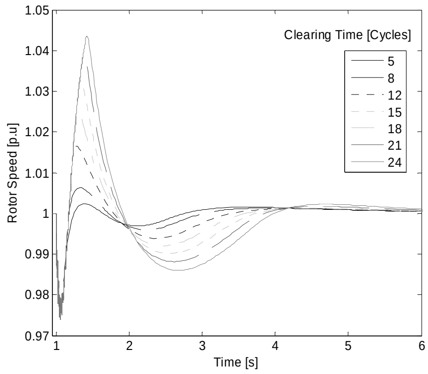


Fig. 6. Rotor speed versus time, for several clearing times

The maximum rotor speed increase with clearing time as shown in Figure 7.

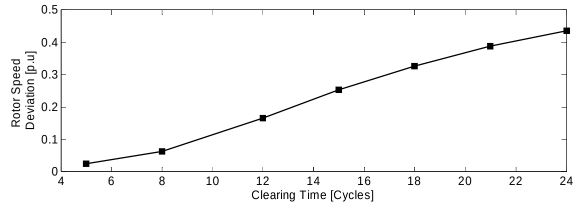


Fig. 7. Rotor speed deviation, for several clearing times

To evaluate the impact of the penetration level and dispersion level on the transient stability of test system the rotor speed was quantified. In Kumamoto distribution feeder a solid three phase short-circuit fault was simulated on bus 2, near the centralized generation unit. For simplicity, no protective devices are considered in these simulations, and clearing time of 5 cycles was used for eliminate the short circuit.

Fifteen scenarios was simulated, penetration levels of 10, 20, 30, 50 and 100%, and three different dispersion levels was simulated. Table 4 show a resume of the fifteen scenarios simulated.

Low penetration level of GD exhibit lower rotor speed deviation than high penetration level. For a same penetration level the minimum rotor speed deviation result high for high dispersion level (Fig. 5).

TABLE 4
MAXIMUM ROTOR SPEED [P.U.] FOR DIFFERENT PENETRATION AND DISPERSION LEVEL

		$\%DG_{level}$				
		10%	*20%*	*30%*	*50%*	*100%*
$\%DG_{disp}$	*21%*	1.00773	1.01778	Unstable	Unstable	1.03838
	29%	1.00987	Unstable	Unstable	Unstable	Unstable
	50%	1.00427	1.00903	Unstable	Unstable	Unstable

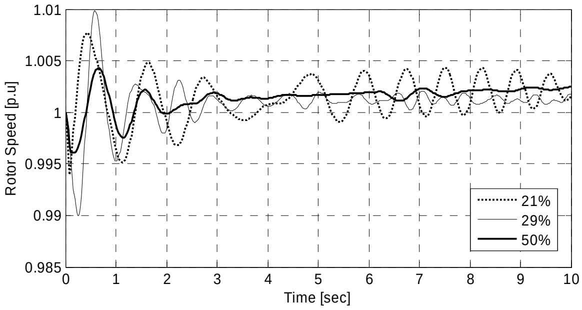


Fig. 5. Rotor speed of DG at bus 4, 10% penetration level for different dispersion level (21%, 29% and 50%)

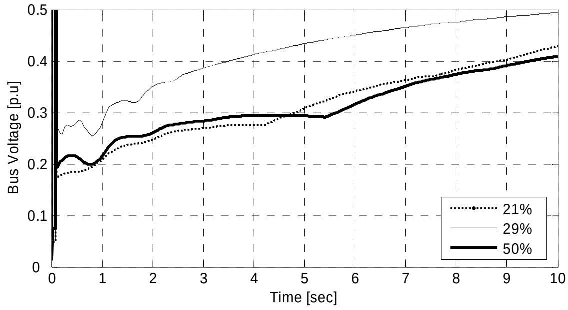


Fig. 6. Voltage in per unit at bus 4, 10% penetration level for different dispersion level (21%, 29% and 50%)

IV. CONCLUSIONS

This paper presents a first step to investigate the transient stability of distribution system with synchronous distributed generation, and show the simulation results of typical distribution feeder penetrated by small disperse synchronous generator, driven by gas turbine with AVR IEEE type 1.

A brief steady state analysis for several penetration and dispersion levels show that the bus voltage profile results acceptable at high level of penetration and high dispersion. In fact best profile for low penetration result of low dispersion, this due the location and rating criteria used for DG in the test system. Steady state simulation of the test system, show the ability of the DG for control the voltage profile and losses, specifically from local point view.

Presence of DG affects the transient stability, differently with respect to the penetration level, and fault duration. To evaluate the impact on transient stability several different levels of penetration (11, 29, 50%) and dispersion levels (10, 20, 30, 50 and 100%), was simulated. In particular, Low penetration level of GD exhibit lower rotor speed deviation than high penetration level. For a same penetration level the minimum rotor speed deviation result high for high dispersion level.

Dynamic behavior of the faulted test system, show the vulnerability of the transient stability. The reduced inertia and low damping of the distributed synchronous generator result critical when the fault limit the power flow from the conventional generator, low penetration level become more adequate to guarantee the stability.

V. APPENDIX

TABLE A.1
LINE AND LOAD DATA OF KUMAMOTO DISTRIBUTION SYSTEM [1]

Sending Node	Ending Node	*R* (p.u)	*X* (p.u)	*B* (p.u)	P_{load} (p.u)	Q_{load} (p.u)
1	2	0.00315	0.075207	0.00000	0.02080	0.0021
2	3	0.00033	0.001849	0.00150	0.04950	0.0051
3	4	0.00667	0.030808	0.03525	0.09580	0.0098
4	5	0.00579	0.014949	0.00250	0.04420	0.0045
5	6	0.01414	0.036547	0.00000	0.01130	0.0012
4	7	0.00800	0.036961	0.03120	0.06380	0.0066
7	8	0.00900	0.041575	0.00000	0.03230	0.0033
8	9	0.00700	0.032346	0.00150	0.02130	0.0022
9	10	0.00367	0.01694	0.00350	0.02800	0.0029
10	11	0.00900	0.041575	0.00200	0.21700	0.0022
3	12	0.02750	0.127043	0.00000	0.01320	0.0014
12	13	0.03150	0.081405	0.00000	0.00290	0.0003
13	14	0.03965	0.102984	0.00000	0.01610	0.0016
14	15	0.01061	0.004153	0.00000	0.01390	0.0014

Bus voltage = 6.6kV, Base MVA = 10 MVA

VI. REFERENCES

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VII. BIOGRAPHY

Francisco M. Gonzalez-Longatt (M'2001) he obtained the Electrical Engineer degree from Instituto Universitario Politécnico de la Fuerza Armada, Venezuela (1994). Master of Business Administration from Universidad Bicentenaria de Aragua, Venezuela (1999). He has been professor assistant with the Department of Electrical Engineering at Universidad Experimental Politécnica de la Fuerza Armada. He is currently pursuing Ph.D. in the Universidad Central de Venezuela, Venezuela.