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Distributed generation systems as a solution to reduce load shedding in central Africa

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Abstract

Distributed generation systems as a solution to reduce load shedding in central Africa

The electricity access rate is still very low in the majority of countries of central Africa. The development of this sector is slowed down by lack of funding. New and original solutions have to be found to solve this problem. Distribution Generation Systems have seen a great development last decade in many western countries and can be used for urban and rural electrification in central Africa. This paper investigates their impact on distribution grids in central Africa. The main characteristics of distribution grid in this region are briefly presented and grid connection issues are discussed. Load flow calculations with Power Factory DIgSILENT show that integration of Distributed Generations units in the distribution grid has a benefic impact on grid operation and can reduce load shedding.

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INTRODUCTION

The traditional way for increasing generation capability is to search for a suitable site where sufficient power can be produced to cover the present and future electricity demand. As the majority of suitable sites are far from important consumption points, transmission and distribution grids have been developed to transport power from power plants to consumers.

The need for a cleaner energy and the difficulty to find such large renewable power sites has led scientists and engineers to develop other solutions. One of them is the distributed generation system, which has seen great developments in the last decade.

The majority of people in central Africa live in rural areas where electricity access rates are very low. The region has seen a real desire to open the electricity industry but many electrification projects failed due to lack of money combined with low electricity tariff.

Proposed solutions for rural electrification are sometime unsuccessful just because they don't meet the special need of rural communities. Cigré [Zomers and Dagbjartsson, 2009] recognizes that rural electrification is really a challenge and specific technical and organizational solutions must be found.

We are convinced that distributed generation could be a solution for improving access to electricity in rural areas and reducing load shedding in bigger cities. Therefore, the need for further investigations on the impacts of distributed generation on distribution grid in Central Africa is real.

After presenting distributed generation technologies and the main characteristics of Central African grids, we have used Power Factory DIgSILENT to assess the impact of a distributed generation system on the distribution system of Kinshasa city.

DISTRIBUTED GENERATION SYSTEMS

Types of Distributed Generation

We find many classifications of Distributed Generation (DG) technologies in the literature [Knazkins, 2004; Short, 2004].

Considering their availability in Central Africa, the following technologies can be used :

- *Combined cycle gas turbine,*
- *Internal combustion engines*
- *Stirling engine*
- *Biomass gasification*
- *Small and micro hydro*
- *Photovoltaic array*
- *Solar thermal*
- *Geothermal*
- *Wind turbines*

Other technologies can also be found like fuel cells, ocean energy and battery storage.

The six last technologies are renewable types. According to the International Renewable Energy Agency [2003] solar and hydro systems are more likely to be developed in Central Africa than the other renewable types. Internal combustion and Stirling engines have the advantages of being easily and rapidly installed but the great disadvantages is their higher operating cost compare to other technologies.

Grid connection of DG

Combined cycle gas turbine, Internal combustion engines, Biomass gasification, Solar Thermal and Geothermal systems are thermal systems and use synchronous generators for electricity generation.

Small and micro hydro and Wind turbines systems use either synchronous or induction generator.

Photovoltaic and storage systems are connected via inverters.

Synchronous Generator Systems

The great majority of power plants use synchronous generators whose frequency can easily be kept constant by regulating the speed of the prime movers.

For systems like wind turbine where it's difficult to keep the rotor speed constant, the generator is connected through a power converter link as shown in Figure I.

The main disadvantage of this system is that the entire power flows through the power converter.

Induction Generator Systems

The development of wind systems and power electronics has enabled the development of induction generator systems with two versions: fixed-speed and variable speed.

Induction generators in general and squirrel cage in particular have the advantages of being cheaper and more robust than synchronous generators. But a reactive power source may be needed to enhance the global power factor.

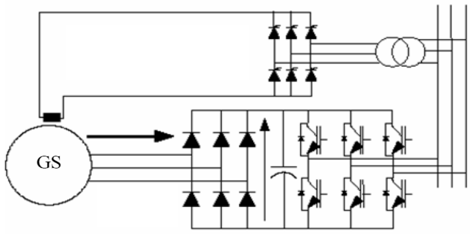

Figure I | Synchronous Generator with a Power Converter link

Fixed-Speed Systems

As shown in Figure II the generator is directly connected to the grid which is supposed strong enough to impose its frequency but the slip must be kept less than to 2% to limit the stator current [Poitiers, 2003].

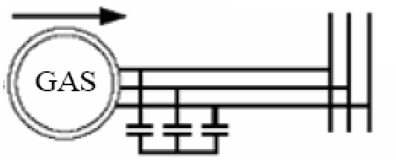

Figure II | Squirrel cage Induction Generator directly connected (fixe speed)

Variable Speed Systems

Self-excited Induction Generator with Frequency Converter

This system is similar to the one previously seen for the synchronous generator with the advantage of a lower acquisition and maintenance cost for the generator.

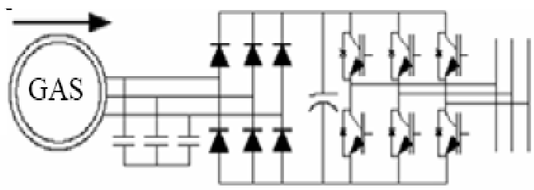

Figure III | Squirrel cage Induction Generator with a Power Converter link (variable speed)

Doubly-Fed Induction Generator

The doubly-fed induction generator has seen its rise in wind industry. As seen in Figure IV, the stator is directly connected to the grid while the rotor is fed via an electronic power converter which adjusts the rotor current to produce stator current at the right frequency.

Losses in the power converter are reduced due to the fact that only a portion of the power goes through it. The advantages of DFIG are widely investigated in Petersson's PhD thesis [2005].

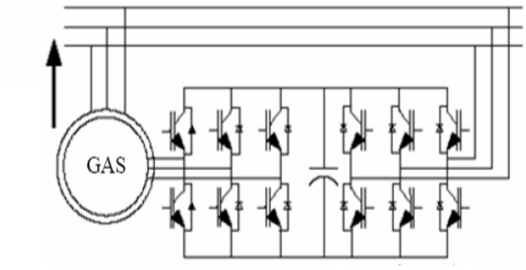

Figure IV| Doubly-Fed Induction Generator

DC Systems

DC systems like Photovoltaic array are connected to the grid via inverters (line commutated or Self commutated) .

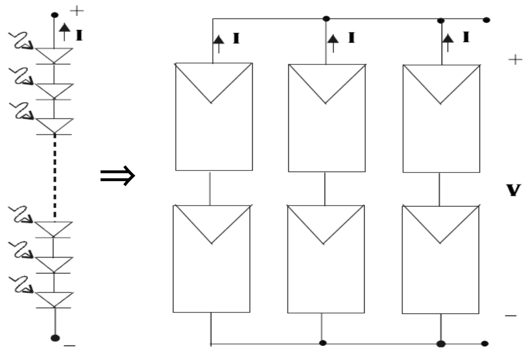

Figure V| Photovoltaic array

Self-commutated inverters are more advantageous especially the fast switching pulse-with modulation (PWM) inverter which can control the power factor in a grid- connected configuration or operate alone and control voltage in stand- alone operation [Short, 2004].

Distributed generation units modeling

The impact of DG on the power grid can be assessed using power flow calculations provided that the penetration ratio of this DG is still small [Knazkins, 2004]. Models used for Distributed Generation units are chosen for that specific application.

Except Photovoltaic cells which convert solar power directly in electricity the other DG systems produce mechanical power and need a generator to produce electricity. Thus only the generator will be modeled for these systems.

Photovoltaic cell Model

Development of solar photovoltaic plants all around the world has led to a lot of researches on photovoltaic cell modeling [Salmi et al, 2012; Hayoun et al, 2011 ; Messenger et al, 2005]. The simplest model is the four parameters model as shown in Figure VI.

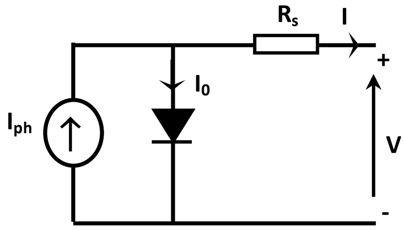

Figure VI|Photovoltaic cell model

This model corresponds to the following relation.

$$I = I_{ph} - I_0\left[\exp\left(\frac{q(V + IR_s)}{nkT}\right) - 1\right] \quad (1)$$

With Iph the photocurrent, I0 the reverse saturation current of the diode, q the electron charge (1.602×10-19 C), V: the voltage across the diode, K: the Boltzmann's constant (5.6704×10-8Wm-2K-4), T the junction temperature in Kelvin, N is the ideality factor of the diode, and Rs the series resistor of the cell.

However, our choice for a PV Cell model has been led by two considerations.

Equation (1) is not that easy to implement in a normal load flow program. Furthermore, the reverse saturation current is very small for all kind of diodes. Its value is around 10-5-10-6 amps according to Aoun [2010]. In normal operation, the current produce by a photovoltaic cell doesn't vary that much at constant solar irradiation as can be seen in Figure VII from Messenger et al,[2005].

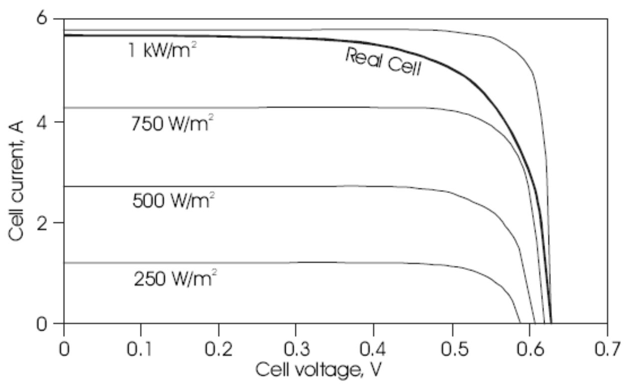

Figure VII| I-V characteristics of real and ideal PV cells [Messenger et al, 2005]

The simplest way to model distributed generators for load-flow analysis is as negative loads [Short, 2004]. Three load models are found in the literature: a constant power, a constant impedance and a constant current I.

From the foregoing (and in particular Figure VII) it is clear that a constant current model is a good model for photovoltaic cell representation.

Synchronous and induction Generators Models

Taking into account, the facility offers by load flow computer programs, we suggest using more accurate models for synchronous and induction generators.

For these generators, we will use their steady-state models, which many authors have work on [Van Cutsen, 2010; Kamabu, 2008 ; Maun, 2001; Nasar, 1990; Chatelain, 1982].

The steady-state model of a synchronous generator is given in Figure VIII and the corresponding electrical equation is:

$$\underline{E}_q = \underline{V}_a + R_a \underline{I}_a + jX\underline{I}_a \qquad (2)$$

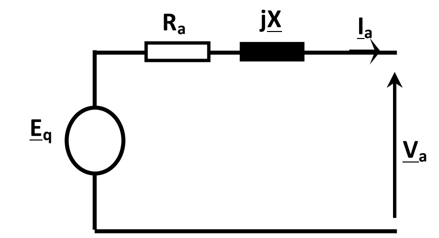

Figure XIII| Synchronous generator steady-state model

Active and reactive powers are given by relations (3) and (4).

$$P = \frac{3E_q \cdot V}{Z} \sin\varphi \qquad (3)$$

$$Q = \frac{3E_q \cdot V}{Z} \cos\varphi - \frac{3V^2}{Z} \qquad (4)$$

The steady-state model of an Induction generator is shown in Figure IX and the corresponding electrical equations are.

$$\underline{U}_s = R_s \underline{I}_s + jX_s \underline{I}_s + jX_m \underline{I}_m \qquad (5)$$

$$\frac{\underline{U}_r}{g} = 0 = \frac{R_r}{g} \underline{I}_r + jX_r \underline{I}_r + jX_m \underline{I}_m \qquad (6)$$

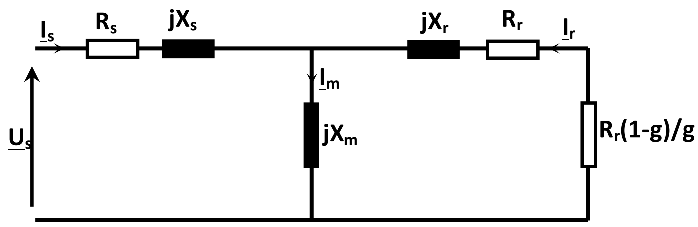

Figure IX| Induction generator steady-state model

INTEGRATION OF DG ON DISTRIBUTION GRID

General Impacts of DG on Power System Operation

A lot of authors [PHAM, 2006; Knazkins, 2004; Short, 2004] have studied the impact of DG on power system operation for different grid configurations.

The main known impacts of DG on distribution grid are as follows:

- Impact on losses: except when the DG production is larger than approximately twice the total load in the distribution grid, the DG will reduce losses in the distribution grid [Knazkins, 2004].
- Impacts on power flow: integration of DG in the distribution grid may change the power flow direction.
- Impacts on the voltage profile: in most of the cases, DG enhances the voltage profile in the grid.
- Impacts on the short-circuit level: the presence of DG in the distribution grid will increase the fault current levels. Nevertheless, this increase is not always significant enough to change the protective equipments. In addition, Knazkins [2004] argues that DG technologies which do not possess energy storage devices are unable to essentially contribute to short circuit power. (e.g a photovoltaic element without a battery)
- Impacts on power quality :
  - Harmonics: some DG technologies used power electronic devices that cause harmonics.
  - Unbalance system operation: single phase generators can cause unbalanced operation of the system.
  - Flicker
- Impacts on System Stability.

Main characteristics of distribution grids in central africa

All the countries in central Africa have a low electricity access rate. Many areas are totally unsupplied while others in and around big cities, have a total installed capacity far below the electricity demand. Therefore, the utility generally establishes a load shedding program to protect cables and transformers (which are in many case already operated near or above their rated power).

Three parameters are critical for utilities and lead load shedding programs:

- loading of cables and transformers
- voltage level.
- Availability of power

A typical daily load curve is shown in Figure III. For load shedding purpose there is no power transmitted Tuesday. 15:00 to 18:00) and Saturday (14:00 to 16:00).

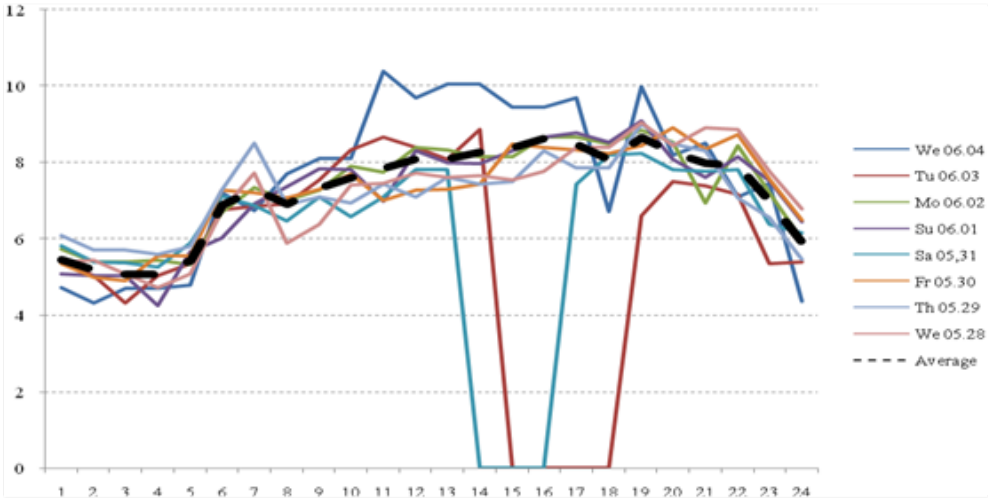

Figure X Daily load curve of Novatex feeder from Funa substation

Impact assessment on central African distribution grid

To assess the impact of distributed generation on a typical Central African distribution grid, we have made some load flow calculations in the distribution grid of Kinshasa . We have chosen to integrate three types of DG sources in a MV feeder from Funa substation: Photovoltaic (PV),Plants Micro hydro Power Plants and Thermal Power Plants (Solar or Diesel)

PV plants have been modeled as DC current sources connected to the grid via a PWM Inverter. As said previously, Thermal and hydro plants will be modeled by their generators

Five cases have been simulated:

i. Initial operation
ii. Integration of induction generators (Micro hydro plant)
iii. Integration of synchronous generators (Micro hydro or Thermal plant)
iv. Integration of photovoltaic arrays

The grid has been modeled with DIgSILENT Power Factory 13.2 using the parameters proposed by Maun [2001], AREVA [2002] and Short [2004] for small generators and data from the Electricity Utility of DR Congo (SNEL) and DigSilent Power Factory database [2007] for busbars, cables, lines and transformers.

Table I. Line and cables parameters [DIgSILENT, 2007]

Name	Type	Length[a]	R1[*]	X1[*]	Irated[b]
Line_Liminga-Funa	220kV_2x210mm2	4.86	0,4787	1,5008	0,76
Cable_Funa-CroixRouge	NA2XSEY 3x240rm 12/20kV	2.419	0,3024	0,2432	0,405
Cable_CroixRouge-BT Nianza	NA2XSEY 3x240rm 12/20kV	0.35	0,0438	0,0352	0,405
Cable_BT Nianza-ITAGA	NA2XSEY 3x240rm 12/20kV	0,29	0,0363	0,0292	0,405
Cable_ITAGA-LuvuaII	NA2XSEY 3x240rm 12/20kV	0,46	0,0575	0,0462	0,405

A: km; *: Ohm; °: b: kA

Table II. Transformers parameters [DIgSILENT,2007:SNEL]

Name	rtd.Pow. [a]	HV-rtd.Volt.*	LV-Rtd.Volt.[*]	Shc Volt.[b]	Cop.Los. [c]	Vector group
MT/BT transformer	0,63	20	0,4	6	6,9	Dyn11
HT/MT transformer	100	220	22	18,05	0,1	YNd11

A: MVA; *: kV; °: b: %; c: kW

Table III. Synchronous generator parameters [Short,2004;Maun,2001]

Designation	Value
App.Pow. (kVA)	350
Nom.Volt. (kV)	0,4
Pow.Fact.	0,8
x (pu)	2
Min.React.Power Limit (pu)	-0,5
Max.React.Power Limit (pu)	0,5

Initial operation situation

We have used the data collected on June the 6th 2014.

As it can be seen on Figure XI load flow calculations show that the main cable has a loading of 105%. Itaga and Luvua II MV/LV transformers have a loading of respectively 107.0% and 107.28 % and their LV bus bares are 0.94 pu.

Table IV. Induction generator parameters [DIgSILENT,2007]

Designation	Value
Nominal Apparent Power (kVA)	355855
Nominal Voltage (kV)	0,4
Power Factor	0,88
Rated Mechanical Power(kW)	300
Mag. Reactance (pu)	3 7963
Stator Res. (pu)	0,015
Rotor Res. (pu)	0,1
Stator Reac. (pu)	0,2
Rotor Reac.	0,2

To keep the loading below 100% for each element and voltage above 0.95 660 kW must be removed from the grid which means to disconnect one 630 kW transformer and some customers fed by another MV/LV transformer.

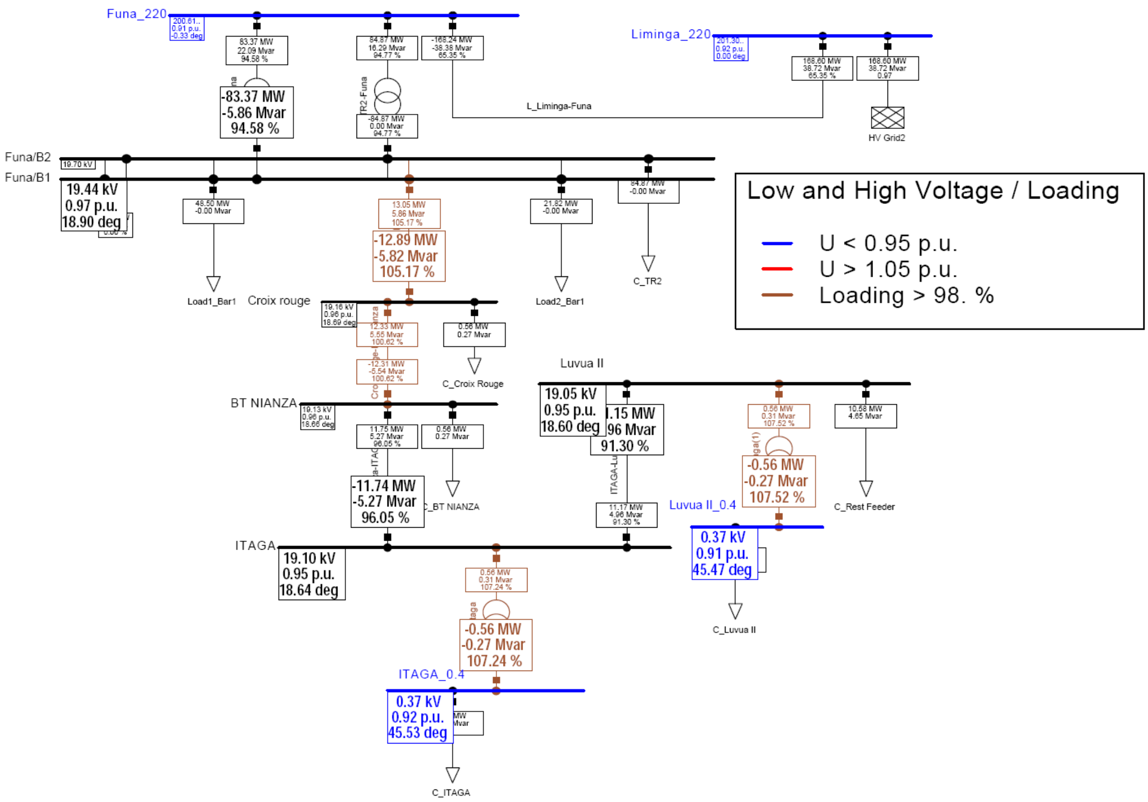

Figure XI| **Simulation #1 – Load flow results on the single line diagram of the grid during initial situation**

Integration of induction generators

Two 300 kW induction generators are feeding the distribution grid from 0.4 kV bus bars.

We have considered two cases: with and without compensation.

Induction generator without compensation

The integration of these generators reduces the active power flow from the grid but the main cable loading stay above 100% and voltages at the connection bus bars drop below 0.94 pu due to the flow of reactive power needed by generators.

A load shedding of 660 kW is still required to keep voltage at 0.95 pu at Itaga and Luvua II substations. In that case the main cable loading drop to 96.82%.

Induction Generator with compensation

To clearly show out the influence of the compensation, we have used two different values for each capacitor bank:

QITAGG=200 kVar

QLuvua II= 270 kVar.

As it can be seen on Table V to VII the main cable has now a loading of 100.27% (a reduction of 4.9%), voltages rose to 0.95 pu at the two connection bus bars.

MV/LV transformers loading drops at 60.88% for Itaga and at 57.46% for Luvua II which has a higher compensation. To lower the main cable loading drop below 100% a load shedding of 40 kW is required or an increase of the capacitor bank of Itaga from 200 kVAr to 280 kVar.

Integration of synchronous generators

Two 350 kVA synchronous generators are feeding the distribution grid from 0.4 kV bus bars.

They are operated as PV nodes with active power and voltage set at:

PSG=280 kW

VSG= 1 pu

The reactive power delivered by the generator is limited to 50 % of the generator rated power:

QSG,max = 175 kVar

Load flow calculations results show that the main cable has now a loading of 99.75% (a reduction of 5.4%), voltages rise above 0.96 pu at the two connection bus bars.

Transformers loading drop at 49% for both MV/LV substations and no load shedding is required.

Integration of Photovoltaic arrays

Two Photovoltaic arrays are feeding the distribution grid from 48 V bus bars. They are modeled as DC current source set at:

IPV=6.25 A.

PWM inverters convert DC to AC. They are operated on P-Q control mode with active and reactive power set at:

PPV=300 kW

QPV= 100 kvar.

Load flow calculations results (Table V) show that the main cable has now a loading of 99.98% (a reduction of 5.2%), voltages rise to 0.96 pu at the two connection bus bars.

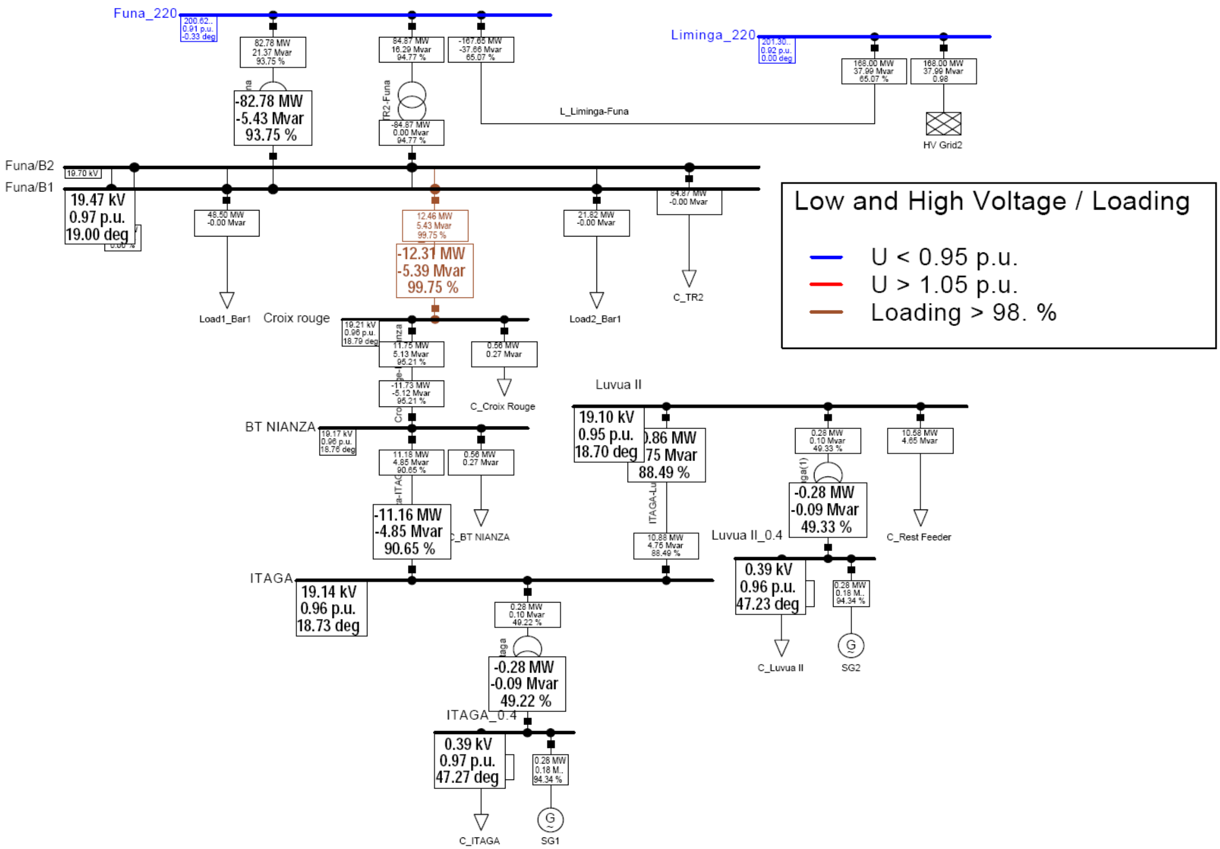

Figure XIII | **Simulation #4 – Load flow results on the single line diagram of the grid after integration of synchronous generators.**

Transformers loading drop at 5.2 % for both MV/LV substations and no load shedding is required.

RESULTS AND DISCUSSION

Load flow calculation results are presented in Table V for the main cable loading and in Table VI and Table VII for ITAGA and Luvua II substations respectively. The results in Table V show that the integration of generators in the distribution grid reduces the power income from the grid and normally reduces MV cables loading.

Table V. Results for Main cable

Study cases	Main cable loading
	%
Initial situation	105.15
Induction generator without compensation	102,15
Induction generator with compensation	100,27
Synchronous generator	99,75
Photovoltaic array	99,98

Table VII. Results for Luvua II substation

Study cases		Infeed		Bare Voltage	Transformator loading		
		P	Q	U	P	Q	%
		kW	kvar	pu	kW	kvar	
Initial situation		0	0	0,94	560	270	107,28
Induction generator without compensation		300	-180	0,93	260	450	90.64
Induction generator with compensation	Generator	300	-180	0,96	260	170	52.46
	Capacitor		270				
Synchronous generator		280	175	0,96	280	90	49,33
Photovoltaic system		300	100	0,96	260	170	52,29

We notice a smaller reduction for systems with induction generators without compensation. Indeed, these types of generators need reactive power and take it from the grid.

For over-loaded grids, induction generator can be used provided that a compensation system (capacitor bank) is added to cover generator and grid needs.

Table VI. Results for Itiga substation

Study cases		Infeed		Bare Voltag	Transformator loading		
		P	Q	U	P	Q	%
		k W	kvar	pu	kW	kvar	
Initial situation		0	0	0,94	560	270	107,00
Induction generator without compensation		300	-180	0,93	260	450	90.37
Induction generator with compensation	Generator	300	-180	0,95	260	750	60.88
	Capacitor		200				
Synchronous generator		280	175	0,97	280	90	49.22
Photovoltaic system		300	100	0,96	260	170	52,16

Results show that synchronous and solar systems have greater benefits on the grid operation. Thus no more load shedding is required for the distribution grid.

Nevertheless Figure X shows that the peak of the average load curve occurs around 19:00 when there is no more sun light. Without a storage system solar systems won't be able to supply the grid.

CONCLUSION

The impact of distributed generation in a distribution grid in Central Africa has been analyzed on a part of Kinshasa's grid . Load flow calculations have shown that integration of generators in the distribution grid enhance its parameters, reduces the power supply from the grid and thus MV cables and transformers loading.

Analysis shows that systems using synchronous generators (thermal or hydro plants) have greater benefit on grid operation. Solar plants integration also improves grid parameters but the availability of power during night is still an issue. Through systems with induction generator are more and more used in Western countries. They seem to be not suitable for grid facing load shedding problems.

The results of grid simulations show also that it is possible to reduce the load shedding by installing small, modular generation systems in the distribution grid. As most of the countries in central Africa are opening their electricity market, it is an opportunity for small scale producers (1 - 300 kW) to actively participate as Independent Power Producers.

Therefore, it will be important to continue investigating on short-circuit, power quality, stability, monitoring and management issues.

RESUME

Le taux d'accès à l'électricité est encore très faible dans la majorité des pays d'Afrique central. Le développement du secteur est freiné par le manque de financement. Aussi, des solutions nouvelles et originales doivent être trouvées pour solutionner ce problème. Les systèmes d'énergie distribuée ont connu un grand développement dans de nombreux pays occidentaux et pourraient être utilisé pour l'électrification urbaine et rurale en Afrique centrale. L'article analyse leurs impacts sur les réseaux de distribution en Afrique centrale. Les caractéristiques principales des réseaux de distribution de la région sont brièvement présentées et les problèmes de connexion au réseau sont discutés. Des calculs d'écoulement de charges avec Power Factory DIgSILENT montrent que l'intégration d'unités à énergie distribué sur le réseau de distribution a un effet bénéfique sur le fonctionnement du réseau et permet de réduire le délestage.

Mots-clés : *Energies distribuées, énergies renouvelables, génératrice asynchrone, génératrice synchrone, cellule photovoltaïque, distribution de l'énergie*

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