Power System Modeling in the View of Large Scale Photovoltaic Plant Integration: Case Study of Burkina Faso Power System

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Abstract- With increasing demand for energy, the goal to reduce fossil-fuel dependence can be addressed in multiple ways: renewable-energy generation system, storage technologies, demand response, etc. For the developed countries, it is high time to introduce renewable energy such as solar in the power system dominated nowadays by thermal power plants using mainly fossil fuel. This paper expands the modeling and simulation of a power system in the view of large-scale photovoltaic integration into an unstable grid. Burkina Faso National Network Interconnection power system has been taken as a case study. Besides, the study aims to provide a predictive tool which consists to model the entire grid using flexible software and perform simulations to understand better the behavior of the grid under different operation conditions. Afterwards, the model and simulation have been performed using Simpower System Tool box and Matlab/Simulink scripts, and the model has been validated by comparison simulation results with real grid data provided by SONABEL, the electrical utility company of Burkina Faso.

Keywords- Power system; Modeling; Simulation; Power plants; National network interconnected; Simpower.

1. Introduction

Nowadays, electricity is an essential and vital resource for sustainable human development. Access to electricity and reliable supply are key elements that support the economic development within a country or a region. The correlation between access to modern energy, per-capita energy consumption and human development index (HDI) has been demonstrated [1]. The population growth and urbanization associated with poor rainfall conditions have led many developing countries to increase the part of thermal power generation of medium and large capacity to meet their electricity needs.

It is obvious that fossil fuels will not disappear overnight but a scarcity or an inability of the supply to follow the demand will cause by simple effect, a drastic growth of the fuel price and the increasing cost of electricity. Furthermore, with the growing cost of fossil fuels and the look for energy independence coupled with environmental concern, energy policies must be put in place to support the growth of energy demand, especially in developing countries. Some feasibility solutions are listed below:

- Rational use of energy
- Replacement of obsolete equipment of high consumption whenever possible
- Progressive renewal of current lighting equipment by new equipment with reflectors and electronic ballasts
- Adaptation of the computer equipment: selection of moderate consumption feeders and LCD-type screens.
- Publicity campaign oriented to the population promoting consumption moderation and environmental consciousness in public and in private

- Intensification of regional power grid's interconnection with Côte d'Ivoire, Ghana and Nigeria via Niger. Besides, the West African Power Pool (WAPP) aims to interconnect all the ECOWAS (Economic Community of West African States) countries' grid among them.
- Development of alternative energy sources by using renewable-energy power plants tied to the national grid to form a mix-energy power system.

If some of the tracks can contribute a bit to reduce the growth rate of electricity consumption and satisfy the energy demand, the two last tracks seem to be the best for a sustainable and environment-friendly electricity production. Renewable energy is therefore, an alternative to fossil fuels with the following advantages:

- Importance of energy independence vis-à-vis to fossil fuel producer nations,
- Renewable energies are generally less disruptive to the environment (less or no rejection of greenhouse-gas emissions) and inexhaustible across the life of humanity,
- Possibility of autonomous or decentralized production adapted to both local needs and resources.

The main renewable energy sources available within the ECOWAS area for electricity production are water, solar and wind. Directly competitive for remote sites but can also be connected into the grid under certain conditions. For the ECOWAS region, the energy coming from the sun seems to be one of the best as the area has a large solar belt which varies between 4.2 to 6.5 kWh / m² / day depending on the latitude (Fig.1).

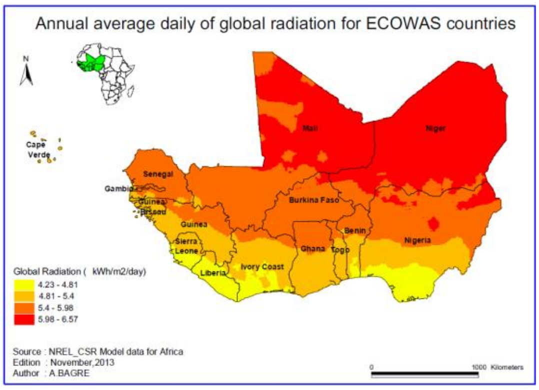

Fig. 1. Annual average daily of global radiation in ECOWAS countries [3]

The conversion of solar power to electricity is based on two main technologies:

- Concentrated Solar Power plant (CSP) which converts heat to power for electricity production. An example is Seville in Spain power plant inaugurated on March 30th 2007 with a capacity installed of 11 MW and predicted to provide yearly 23 GWh [2].
- Photovoltaic plant which converts directly the solar radiation to electricity by using photovoltaic modules.

Nowadays, photovoltaic system connected to the grid has one of the highest growth rates in the world among the other renewable-energy technologies. In fact, from 2011 to 2012 the growth rate rise to 30% as it can be notice on Fig.2.

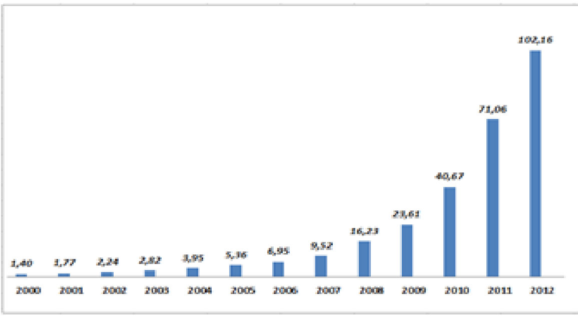

Fig. 2. Development of photovoltaic power installed capacity in the world (2000-2012). [4]

2. Overview of Burkina Faso power system

2.1. General Presentation

In Burkina Faso electricity production and its distribution are mainly operated by SONABEL, the utility company. In 2001, electricity production has been liberalized and within the « B.O.T » scheme adopted by the government, private producers can Build, Operate and Transfer the power plants to SONABEL with some incentives, and the whole production must be sold to SONABEL. Two companies namely APR Kossodo and GPS Ouaga 2000 have been settled base on this scheme. SONABEL has an interconnection network called National Network Interconnected (NNI) and also operates isolated power systems working in islanding mode. The overall power installed capacity of the NNI is around 260 MW at the end of the year 2012 and comprises mainly of thermal and hydro power plants. The transportation framework is made with voltage of 225 kV, 132 kV and 90 kV and the distribution lines' voltage are 33 kV, 20 kV and 15 kV. The NNI is connected to Cote d'Ivoire [5].

2.2. Power Generation

The energy produced and imported by SONABEL during the year 2012 through the NNI was 1140 GWh. The share of local thermal power plants (Sonabel + Independent Private Producers (IPP)) in this production was 52% as shown in Fig.3. In the same time the growth rate of energy demand ranks between 2.5% and 12%.

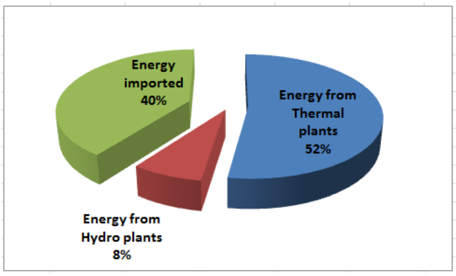

Fig. 3. Share of energy produced in the NNI at the end of year 2012

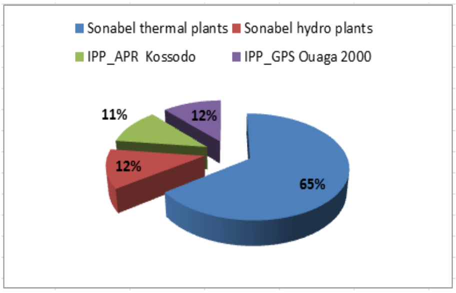

Fig. 4. Share of power plants production capacity in the NNI at the end of year 2012

Table 1. Yearly energy production versus yearly growth rate of energy

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Total Energy produced (GWh)	513.71	569.44	641.56	687.72	736.63	755.12	844.40	949.87	1107.45	1139.99
Growth rate %		10.85	12.67	7.19	7.11	2.51	11.82	12.49	16.59	2.94

As one can see on Fig.5, the energy produced by hydro power plants has remained almost stable from 2003 to 2012, and the energy imported has nearly the same level from 2003 to 2009 before a drastic growth rate from 2009 due to the energy demand. More than 50% of the energy produced in Burkina Faso is from thermal power plants; they are the main power supply within the country and are used as the basic means to stabilize the grid. Therefore, the cost of energy suffers from higher production costs related to increasing in oil prices.

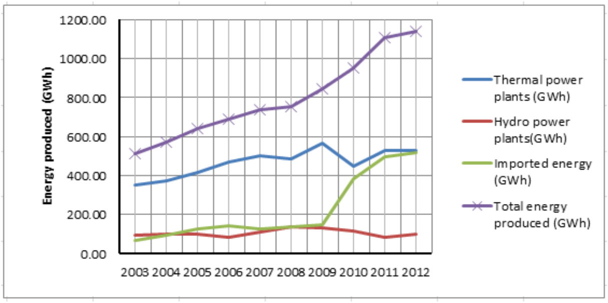

Fig. 5. Evolution of energy generation by source from 2003 to 2012

2.3. Projection Projects

The energy sold by Sonabel is strongly depending on the cost of imported fuel, and the energy purchased from neighboring countries. In addition to this energy dependence, Sonabel meets difficulties to satisfy the energy demand growth with a yearly average growth rate of 8% over the past decade, leading to load shedding used as load management. In this context, some feasible solutions have been proposed below [6]:

- Full liberalization of the energy sector by privatizing the electricity production and its distribution;
- Speeding up of interconnections project within the sub region grid as well as the isolated grid managed by Sonabel
- Build new thermal plants and reinforce the existent;
- Construct solar power plants of large scale; many projects are already at the state of implementation or are in the pipeline:
- solar power plant project of 20 MW led by a mining company and the government of Burkina Faso
- solar Power Project of 33 MW funded by European Union and the government of Burkina
- solar Power Project of 20 MW in Ouagadougou by an international private group.
- As one can observe, the magnitude of large-scale photovoltaic grid-tied projects in short term in Burkina Faso is high and requires, then, the modeling of the NNI in the view to predict their impacts on the grid.

3. Model and Simulation

3.1. Grid Topology

The high-voltage transmission line between Ferkessédougou in Côte d'Ivoire and Kodeni in Burkina has an approximate length of 560 km (68 km on Ivorian territory), and the voltages are 225 kV. 172 km of 132 kV transmission line made the connexion between the hydro power plants in the Eastern region and Ouagadougou. The distribution lines have scattered voltages of 33 kV, 20 kV and 15 kV.

The topology of the grid shown on Fig.6 is made from the original grid line diagram and the grid's data collected from SONABEL. The NNI can be subdivided into three sub-grids as respectively in "Center-grid" with Ouagadougou as a focal point, "Western-grid" with Bobo Dioulasso as a base and finally, the "Eastern-grid" with the two biggest hydro power plants. The "Pa" power substation is used as a hub by connecting the Central -grid to the Western-grid.

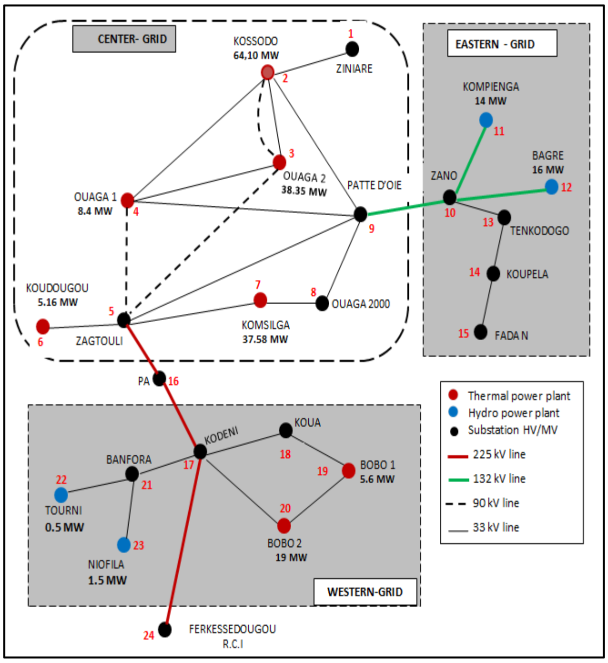

Fig. 6. Topology of the National electrical Network Interconnected of Burkina Faso

One can notice that a simple incident (line loss) on the transmission radial line linking Ferkessedougou to Ouagadougou can disturb or make the collapse of all the power system on the NNI. The Eastern-center link could face the same situation. On the other hand, within the « center-grid » which has a meshed grid, the power system could continue to operate thanks to the alternative lines, except for radial lines such as Ziniare and Koudougou.

Finally, the NNI grid is presented on IEEE 24 nodes on Fig.7. The grid has 24 nodes and 11 generators at the nodes 2, 3, 4, 6, 7, 11, 12, 19, 20, 21 and 23.

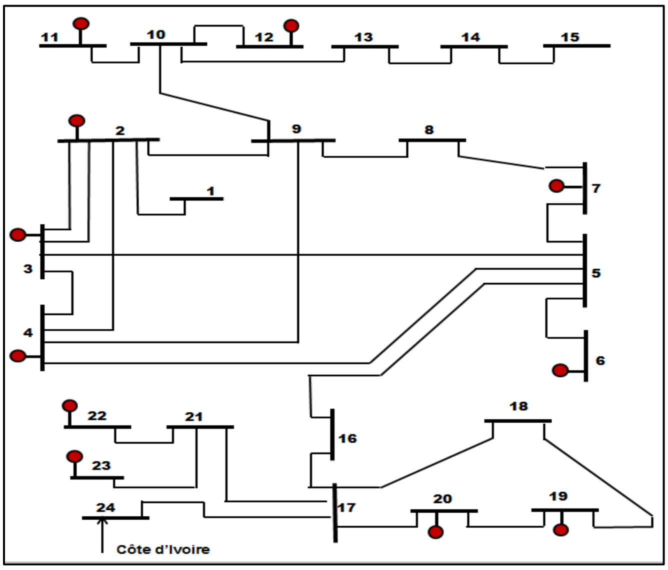

Fig. 7. National electrical Network Interconnected of Burkina Faso on IEEE 24 standard diagram

3.2. NNI Modeling

Modeling of power systems has always been a challenge. Indeed, they are characterized by a high complexity which can be summarized by strong interactions between a large number of distributed components and the emergence of properties across the grid from local behaviors do not meet the same properties[7]. Whatever the type of grid, particular attention must therefore be paid for the quality of supply voltage, but also the safety and reliability of the grid. This consideration must be applied at the overall system level, but also at subsystems and components level [8].

For a grid, the power flow calculation is necessary to determine the different electrical parameters at a given time (current across the distribution lines, nodal voltages, phase shifts and power flows, etc.) for a particular status of the power system. The power flow calculation is one of the key elements for understanding and predicting the behaviour of electrical systems [9]. To do a power flow calculation, it is necessary to model first the power system to be studied. Four fundamental elements are necessary:

- Generation system, transmission lines, transformers
- Loads.

The modeling tool used for this study is Simpower of Matlab/Simulink. The flexibility of the software eases the modeling process of the NNI which is made step by step on the way already presented in [10] which main principles are:

- Modeling all components (generators, transformers, capacitor, loads, cable, circuit breakers etc...) related to a specific power plant or a substation. On Fig.8, a thermal power plant is illustrated as a simple component with the system control panel and its synchronous machine
- Link each component to others for the whole power plant or the substation to form a single entity. This step is illustrated by Fig.9.

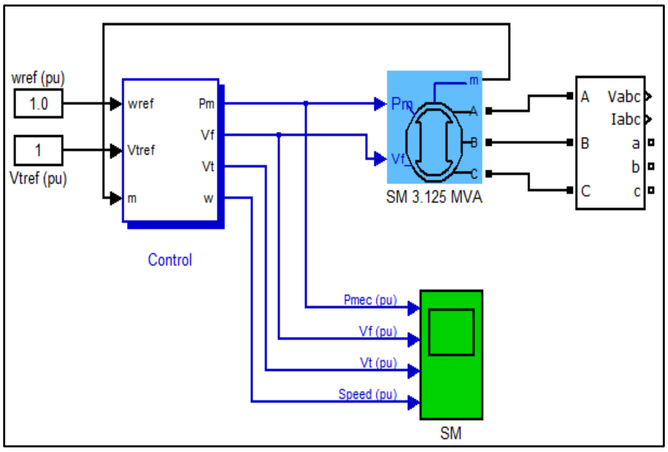

Fig. 8. Simpower's model of Diesel generator with the control system panel and the synchronous machine.

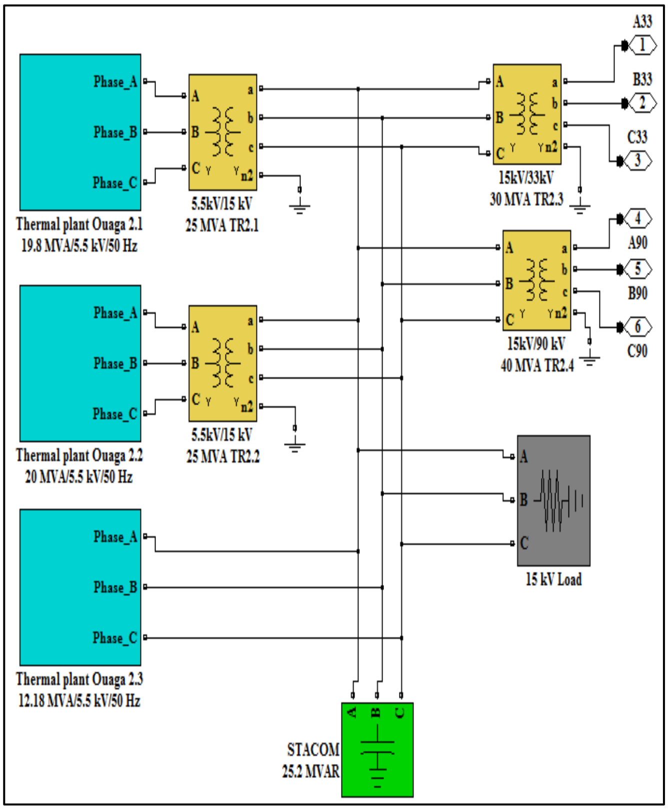

Fig. 9. Simpower model of Ouaga 2 themal power plant

- Then link all the power plants and substation together according to the region layout in order to form the Regional Network. The Central Region Network shown on Figure 11 is given as an example.
- Finally connect all the regional power system and imported power from the neighbourhood to form the national interconnected network (NNI) as it is highlighted on Fig.10.
- Based on this method, the NNI has been modeled using Simpower System tool box and Matlab/Simulink scripts. Some parts of the power system are shown on the following figures.

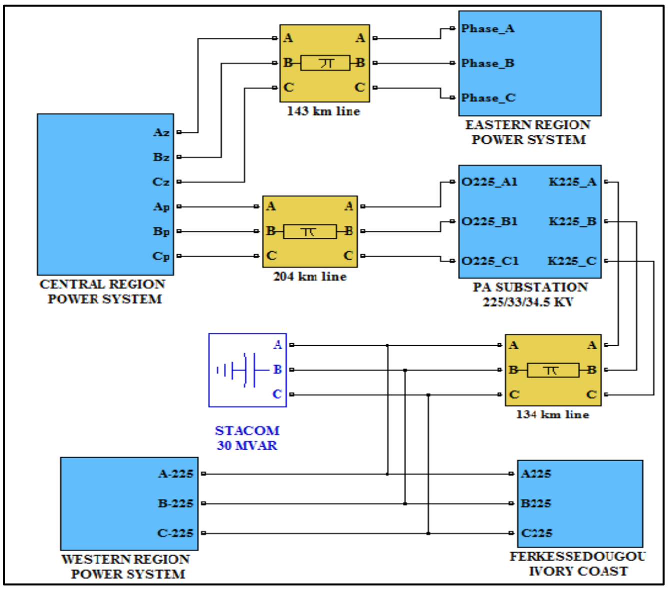

Fig. 10. Simpower model of the overall NNI power system

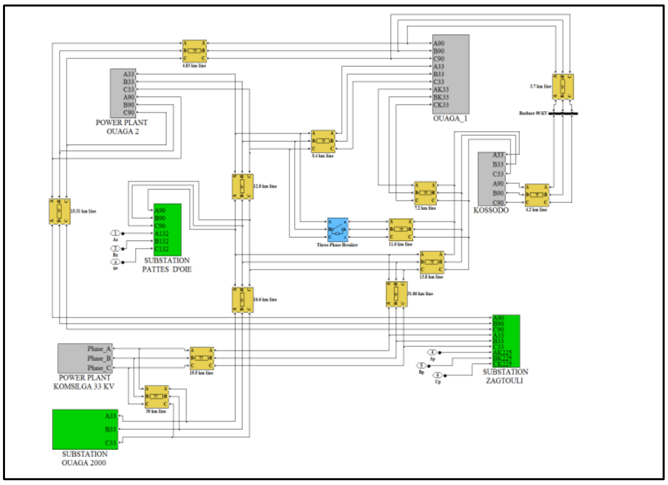

Fig. 11. Simpower model of Central region power system

4. Model Simulated in Steady State

4.1. Assumptions of the Simulation

The modeling of the NNI grid (grid topology, lines, power plant's data, distribution of loads, etc.) is based on data given by Sonabel to which we have added some assumptions required for information not available at the time of the study. For the simulation, many simplifying assumptions have been made to solve both the complexity and the range of validity of the model [11] [12]. The main assumptions are:

- Only the behaviour in a steady state at 50 Hz is studied.
- The network is assumed to be linear.
- The network operates on a balanced power system.

4.2. Simulation

To simulate the NNI mode in steady state, the operation baseline data from the grid are needed. Two states of operation data have been obtained from the utility company for August 13th 2012 respectively at 7:10 p.m. and 4:08 p.m. These data are the snapshot of the NNI at the given time and clearly identify the plants in operation, the power produced by each plant, the active and reactive power of the loads, voltage, frequency and capacitor's power on each busbar. The utility company Sonabel uses SCADA system to monitor and collect data from the grid. Unfortunately, the data monitoring system does not cover all the NNI or at the measurement time, some sensors failed. Therefore, the present data concern only nodes 7, 8, 9, 11, 12, 18, 19, 20, 21, 22, 23. Table II and III summarize the available data provided by the utility company and used throughout the simulations.

At 4:08 p.m., the total power produced by the local power plants throughout the NNR was 19.22 MW and were mainly from hydro power plants such as Bagre, Kompienga in the Eastern-grid, and Tourni and Niofila from the Western-grid. At the Kodeni power substation, it is noticed an incoming power transit of 106.44 MW representing the contribution of Côte d'Ivoire to establish the balance between production and consumption. In addition, the outgoing power transit from Kodeni substation to Zagtouli's one was 85.63 MW. No inductance was in service at the time of the measurement.

Table 2. Sonabel operating data on 13th August 2012 at 4.pm

Node number	Plants Substations	Load power		Busbar voltage	STACOM	Plants in activity
		MW	MVAR	U (kV)	MVAR	MVA
20	BOBO 1	18.2	12.12	33.2		
19	BOBO 2	1.39	0.31	34.32		0
22	TOURNI	2.84	1.52	33.74		0.625
23	NIOFILA	21.01	9.99	15.37	14.4	1.875
18	KOUA	29.2	5.81	15.63	5.5	0
21	BANFORA	5	1.14	33.76	7.1	0
9	PATTE D'OIE	15.84	3.24	33.99	4.8	0
8	OUAGA 2000	4.85	4.95	33.7	4.8	0
7	KOMSILGA	4.85	4.95	33.79	4.5	0
12	BAGRE					18
11	KOMPIENGA				3.5	15.4
13	Tenkodogo	6.34	2.52	34.22		
		109.52	**46.55**		**44.6**	**35.9**

At 7:10 p.m., the total power produced by the local power plants throughout the NNR was 48.62 MW and came from thermal power plants (Ouaga 2, Kossodo and Komsilga) as well as (hydro power plants (Kompienga, Tourni and Niofila). The power imported from Côte d'Ivoire was 88.96 MW, which brought the overall power at 137.58

MW. No inductance was in service at the time of the measurement.

Table 3. Sonabel operating data on 13th August 2012 at 7.pm

Node number	Plants Substations	Load power		Busbar voltage	STACOM	Plants in activity
		MW	MVAR	U (kV)	MVAR	MVA
17	KODENI	23.72	20.68	33.09		
16	PA	1.59	0.53	33.92	0	0
5	ZAGTOULI	4.04	3.46	32.77	0	0
3	OUAGA 2	24.89	12.68	15.86	18.9	1.89
4	OUAGA 1	20.72	5.67	15.77	11.8	0
2	KOSSODO	6.42	1.77	33.17	7.1	5.13
9	PATTE D'OIE	19.26	8.08	16.29	4.8	0
8	OUAGA 2000	5.7	4.72	33.69	4.8	0
7	KOMSILGA			34.36		23
12	BAGRE					13
11	KOMPIENGA				3.5	4.79
13	TENKODGO	6.83	2.32	34.09		
	TOTAL	**113.17**	**59.91**		**50.9**	**47.81**

4.3. Results and Discussion

The results of the two steady states' simulation made on the NNI model are summarized in Table IV where the voltage is given in « per unit» (p.u).

Table 4. Voltage deviation at different busbar

					Deviation at 7 pm		Deviation at 4 pm	
	Sonabel data (pu) 7 pm	Simulation data (pu) 7 pm	Sonabel data (pu) 4 pm	Simulation data at 4 pm (pu)	Sonabel baseline 7 pm	Simulation 7 pm	Sonabel baseline 4 pm	Deviation 4 pm
Ouaga 1	1.01	1.03	1.01	1.04	-1.42	-2.80	-1.42	-4.00
Ouaga 2	1.00	1.06	1.00	1.03	-0.42	-5.60	-0.42	-3.00
Patte d'oie	1.03	1.00	1.03	1.02	3.00	0.00	3.00	2.00
Ouaga 2000	1.04	1.00	1.04	1.02	-3.79	0.00	-3.79	-2.00
Kossodo	1.01	1.04	1.01	1.03	-0.52	-4.20	-0.52	-3.00
Komsilga	1.02	1.04	1.02	1.05	-2.39	-4.00	-2.39	-5.00
Zagtouli	0.99	1.02	0.99	1.01	0.70	-2.00	0.70	-1.00
Kodeni	0.97	0.99	1.00	1.02	2.76	1.00	0.00	-2.00
Pa	1.00	1.03	1.00	1.04	0.27	-3.00	0.27	-4.00
Tenko	0.99	0.96	0.99	0.99	1.42	4.00	1.42	1.00

The difference between the baseline and simulation values is between 0.4% and 2.48% for at 4 pm steady state, while it is around 1.34% to 4.9% at 7 pm as shown in Table IV. Fig.12 and Fig.13 show that even for the baseline case, the voltage at some busbar on the distribution grid are difference to 1 p.u but remain on the values admitted by the regulation standard (Umin =0.9 p.u, Umax = 1.1p.u) [13].

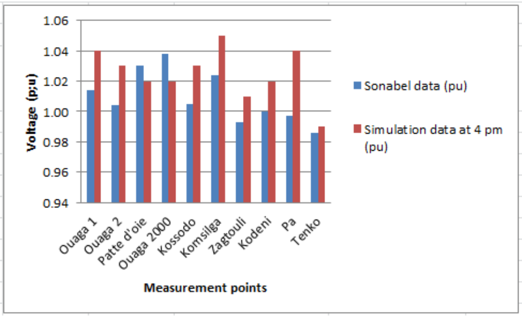

Fig. 12. Voltage per unit (pu) on different busbar on SONABEL power system network on 3rd August 2012 at 4 pm

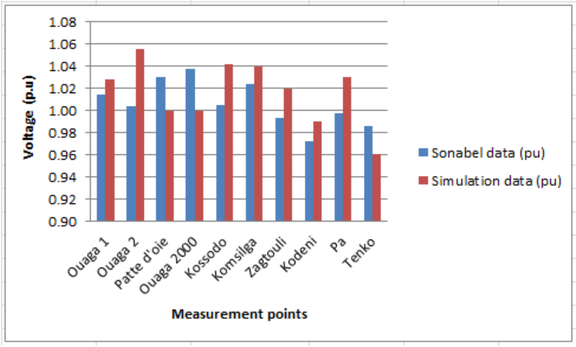

Fig. 13. Voltage per unit (pu) on different busbar on SONABEL power system network on 3rd August 2012 at 7 pm

The voltage variations may occur because of many different reasons. Line impedances cause a significant drop in voltage. Moreover, when the available reactive generation cannot meet the growing demand for reactive power at customer's sides, a voltage drop may occur in the system. Also, for long radial feeders, the transmission of reactive power may not be possible and therefore voltage drop will also be increased at the end user's connection points of loads. Therefore, the voltages of load buses at the remote ends are usually lower than the voltages of load buses close to the utility substation. The voltage variation is commonly called voltage deviation and can be defined as the difference between the nominal voltage and the actual voltage as is written in [14]. The voltage condition of the system is better when the deviation of bus voltage from the nominal voltage, is small.

In our study, the voltage deviation as one can read on Fig.14 and Fig.15 with the baseline data is less than 5% for 4 pm case and less than 6% for 7 pm in absolute value. The standard deviation for 4 pm and 7 pm is respectively 2.08% and 2.89% for the baseline state, whereas it is 1.69% and 1.72% for the simulation results.

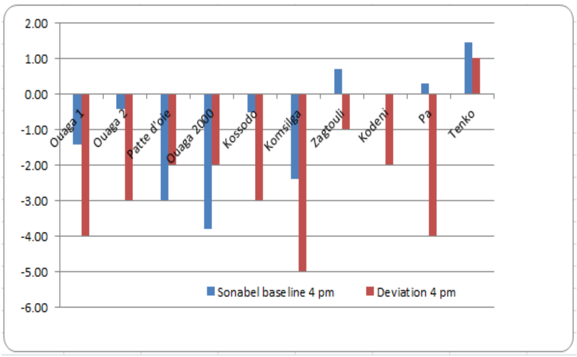

Fig. 14. Voltage deviation (%) on different busbar on the NNI power system on 3rd August 2012 at 4 pm

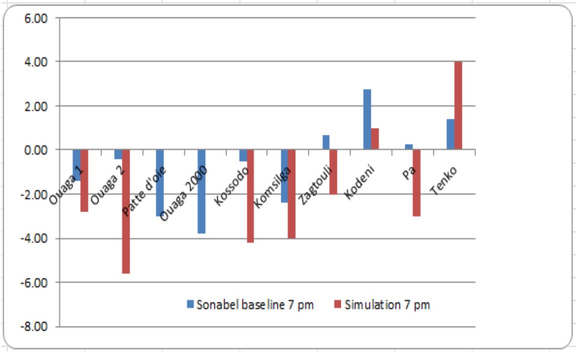

Fig. 15. Voltage deviation (%) on different busbar on the NNI power system on 3rd August 2012 at 7 pm

5. Conclusion

The National electric Network Interconnected of Burkina Faso has been modeled, and simulation made in steady states with baseline data provided by the utility company. The difference between the measured values and results obtained after simulation is quite acceptable. However, it can be seen on Figures 12 and 13 that most of the data obtained by simulation tends to be slightly higher than those obtained by measurement. We must keep in mind that the model is a predictive tool and does not take into account many factors such as the aging of cables, transformers, generators, etc., and the actual operating conditions of production units.

For future works, the tool will be used to investigate the impact of the large-scale photovoltaic power system integrated to weak grids commonly found in developing countries. Furthermore, a work must be done to remove some barriers for large-scale PV plant integration. Indeed, PV power plants have to act as much as possible as conventional utility power plants by meeting critical utility needs, such as control of generation status, ride-through of disturbances, reactive power (V_{ar}) generation and voltage support.

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