J. Automation & Systems Engineering 11-4 (2017): 265-279

Regular paper

Stability of the Tunisian electricity distribution network (ASHTART) following massive integration of offshore wind turbines

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Following the important request of electricity, the appeal to the integration of wind power in electricity grids remains highly remarkable. This kind of power present a source which is renewable and clean without degrading the quality of the air. The integration of wind turbines is not totally perfect view that the rate of integration into the network is quite low because of their random production, as well as the continuity of service and the preservation of the stability will not always guaranteed. Offshore Wind turbines are often located in far-off regions where grid access is relatively weak. This paper focuses on the study of the electric networks stability in the presence of disruptions and following the integration of offshore wind turbines. The application of simulations shows that after the addition of a FACTS (Flexible Alternating Current Transmission Systems) device such as STATCOM, the level of penetration of wind energy without losing the stability of the network has been significantly improved, as well as maintaining stability increases even when a fault occurs. Simulations were achieved on the Tunisian electricity distribution network (ASHTART) of the SEREPT (Society for Research and Exploitation of Petroleum) using the Matlab-based toolbox (PSAT).

Keywords: stability, offshore wind energy integration, STATCOM, ASHTART.

1. Introduction

Man has a big profit of the strength of the wind which has appeared since the antiquity with the use of windmills. It is only today that the wind energy has become the greatest form of renewable energy thanks to the Herculean strength which produces wind. It is also the least expensive clean energy to produce, which explains the strong enthusiasm for this technology. Such penetration of wind energy in electricity consumption, raises many questions as to its perfect fit with the technical constraints of the electrical system in particular regarding the quality of electricity and the security of electrical energy systems which are relatively delicate because of being subject to disturbances and may lead in the majority of cases to damage to the conditions of normal functioning, they also cause the loss of stability of the entire system, the imbalance between production and consumption and the discontinuity of service.

In this paper, we are going to deal with the analysis of the static and transient stability of the networks of electrical energy further to disturbances:

- Variation of overload affecting the system,
- Application of defect (three phase symmetrical fault),
- Integrating a source of wind by using a DFIG wind turbine (Doubly-fed induction generator).

The structure of this paper is as follows. First, wind turbine concepts are mentioned, second, the stability is defined, also, the effect of inserting wind power to the network is sited, then, the Flexible Alternating Current Transmission System is briefly described and finally, the test system and the result of all simulations are presented.

2. Turbine models

There are many different types of wind turbines in use around the world, each having its own list of benefits and drawbacks [1].

In recent years, the majority of wind farms that are connected to the grid are equipped with DFIG. This kind of wind turbines is the most popular technology among several wind turbines technologies because of their numerous advantages over other types of generators when used in wind turbines as that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor, so DFIG can be directly connected to the ac power network and can remain synchronized at all times with the ac power network. It is also able to control the power factor while keeping the power electronics devices in the wind turbine at a moderate size [2]-[3].

In this paper we will focus on a variable-speed wind turbine with a doubly-fed-induction generator (DFIG) and Fig. 1, shows the basic structure of this turbine.

The DFIG consists of a wound rotor induction generator and back to back converter connecting the rotor slip rings to the grid. The wind turbine is connected to the induction generator through a mechanical shaft system. A gearbox is linking high and low speed shafts in the shaft system. The induction generator stator is directly connected to the grid whereas the rotor is fed through a back to back voltage source converter [4].

Also, the active and reactive power output of the DFIG can be fully controlled by rotor side converter. The rating of rotor side converter and grid side converter of DFIG are about (25-30%) of the total wind power [5].

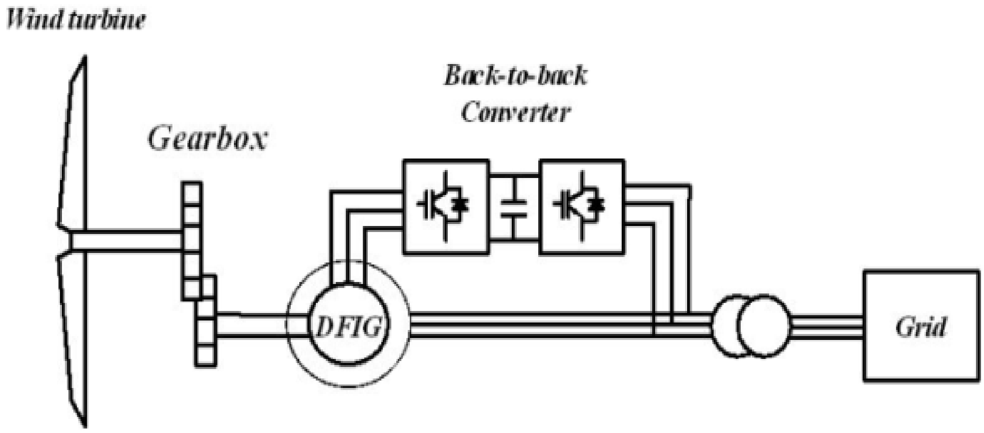

Fig. 1. Doubly-fed induction generator.

3. Stability

Electrical systems present delicate systems in that they are often subject to various disturbances such as balanced three-phase short circuit or sudden changes in loads.

These disturbances can in most cases lead to damage generators and transmission lines, as well as normal operating conditions, they also cause loss of stability, production-consumption imbalance and discontinuity of service.

In this work we will study the stability of the conventional network so stability is the capacity of an electrical energy system, for the same operating conditions, to find the same initial state after undergoing a physical disturbance, keeping most of the variables within their allowable limits [6].

For an electrical network, there are three types of stability [7]:

- Static stability for steady state,
- Dynamic stability concerning a variation in the structure of the network following the appearance of small disturbance.
- Transient stability concerns the few seconds following the appearance of a large network disturbance.

4. Wind power

Nowadays, it is highly remarkable that wind energy could satisfy the world's demand for electricity, for that an integration with the conventional network under various levels of voltage is desirable or even imperative. But it should not be forgotten that this energy as a source of distributed generation causes disturbances in the network and increases the loss of its stability.

In this step, the challenge is therefore to maintain the reliability and the quality of power supply despite the integration of wind turbine imposing difficulties that compromise:

- The production-consumption balance,
- The amount of energy,
- Safety and stability of electrical networks [8], [9].

5. FACTS systems

With instantaneous power demands, Flexibles AC Transmission Systems have been introduced in the networks to control the flow of power and to improve the stability of electrical systems [10].

In view of the excessive integration of renewable energies into the grid and the new load constraints, there is an increase in the importance of FACTS in the operation and control of electricity networks [11]. Hence the existence of several types of FACTS:

- Series FACTS systems such as TCSC, TSSC, SSSC and TCSR.
- Parallel FACTS systems such as STATCOM and SVC.
- Hybrid FACTS systems such as UPFC.

In our study, we are interested in parallel FACTS systems and more precisely to the effect of the application of STATCOM (static synchronous compensator) which is a shunt power compensation device (generating or absorbing reactive power) when powered by a source of wind energy as it is mentioned in the Fig. 2, [12].

The STATCOM has several advantages:

- Good response to low voltage, the STATCOM is able to provide its nominal current, even when the voltage is very low (almost zero),
- Good dynamic response, the system responds immediately [13].

In this paper we will be interested in the effect of the application of STATCOM on the conventional network, which will take an important part in our simulation work.

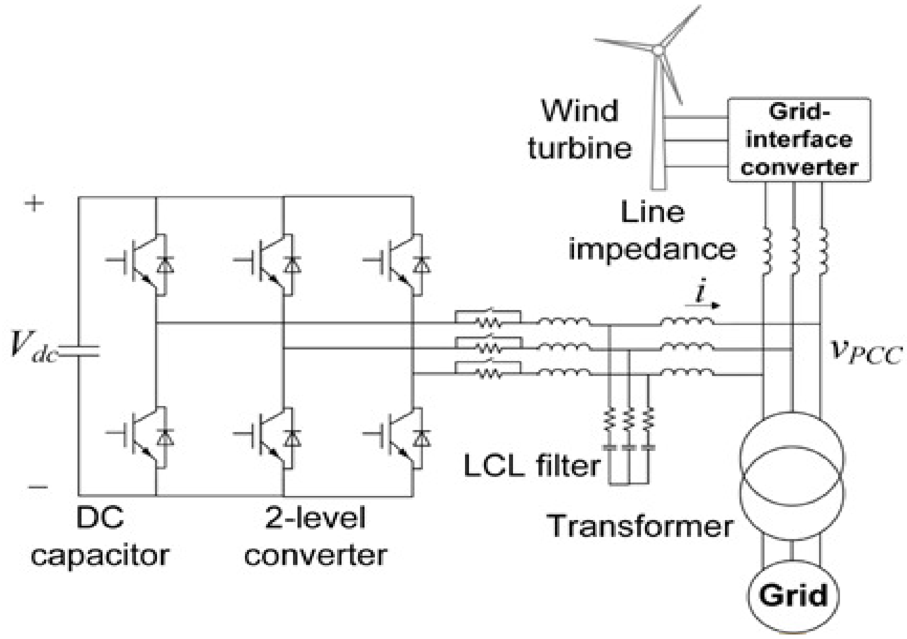

Fig. 2. Static synchronous compensator.

6. Test system

The test system for this study is presented in Fig. 3, (Model implanted under PSAT), it represents the offshore distribution network of the SEREPT named as "ASHTART" network, composed essentially of 5 platforms and each contains specific buses:

- ASPF1, it contains the buses NNF106 / NNF104 / NNF103 / NNF101B / NNF101A,
- ASPF2, it contains the buses NNF250 / MCCGIII/ NNF203B /NNF203A / NNF202B / NNF202A / NNF207A / NNF207B /NNF201A / NNF201B,
- ASPP1, it contains the buses NNP101A /NNP101/ NNP102A / NNP102B / NNP103 / NNP100A / NNP100B,
- ASPP2, it contains the buses NNP201 / NNP202 / NNP 203 / NNP204,
- ASPF3, it contains the buses NNF350 / NNF301.

ASHTART is a network compound of 6 generators, 33 buses, 25 lines, 14 transformers and 8 loads.

It must be noted that all simulations are developed by PSAT (version 2.1.2) [14].

7. Working procedure

First, the static stability will be analyzed. The study is to identify the most sensitive buses to the power variation by change of percentage of overload until a limit value beyond which the system loses its stability and this in order to determine the optimal location of STATCOM for improving the maximum load that can be supported by the network without losing its static stability.

Second, the transient stability is studied. The study is to determine:

- The impact of the fault application (balanced three-phase short circuit) on network stability, the calculation of Critical Clearing Time "CCT", then the effect of adding STATCOM on improving the "CCT",

- The impact of the integration of a source of wind power on the stability of the test network by using DFIG wind generator, then the maximum rate of wind energy integrated into the network without losing its stability by gradually increasing the quantity of energy added to the network up to the limit of instability. At this stage, we are going to add a STATCOM and see its influence on improving the network's ability to accept more of wind energy.

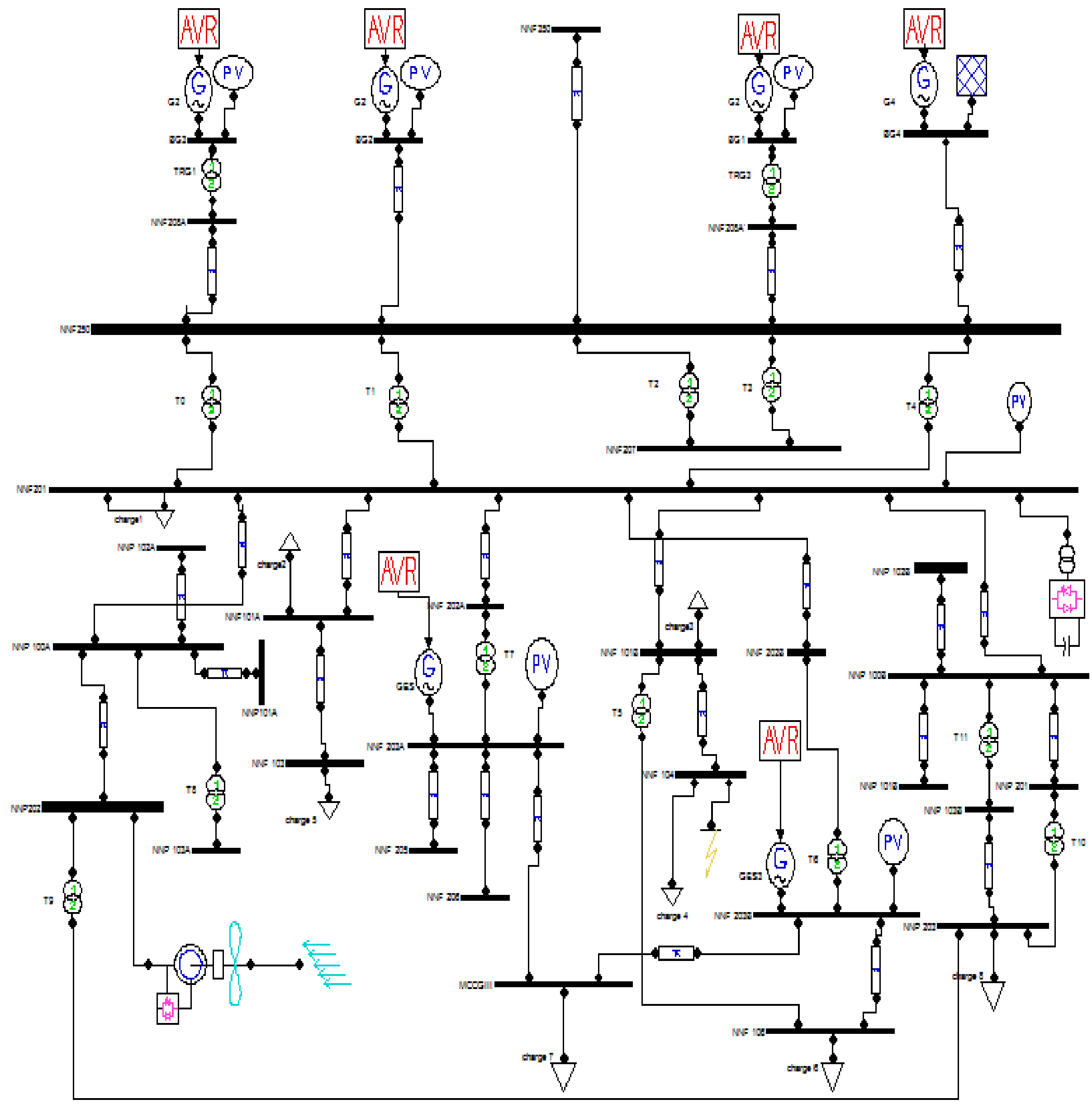

Fig. 3. Model of ASHTART network implanted under PSAT.

8. Results and discussions

8.1. Analysis of STATIC STABILITY

8.1.1. Limit of the Overload

Fig. 4, and Fig. 5, Recapitulate the initial state of the ASHTART network (Analysis of voltage profile of all buses) which is characterized by the active losses in the transmission lines « ΔP=4.695MW»and reactive losses « ΔQ=3.614MVAR ».

Fig. 4. Voltage modules in the initial state.

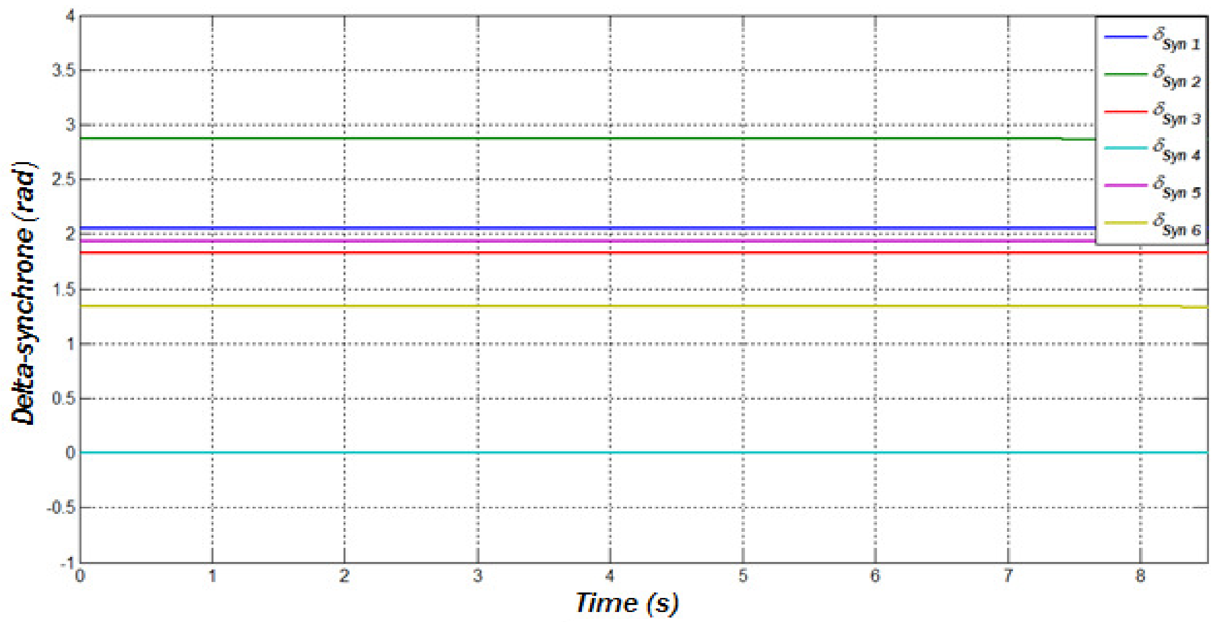

Fig. 5. Angle of synchronism in the initial state.

8.1.2. Evolution of Voltage for Various Load Values

Now, we are going to increase the load gradually by a coefficient λ of overload and see the Evolution of the voltage for every overload value (10%, 20%, 25% and 29%) as shown in Table 1 and Fig. 6.

Table 1: Different cases of overloading

Buses	Initial state	10% of load	20% of load	25% of load	29% of load
BG2	1	1	1	1	1
BG4	1	1	1	1	1
NNF350	0.99021	0.98839	0.98646	0.98545	0.98504
NNF107A	1	1	1	1	1
NNF208A	1.0408	1.0435	1.046	1.0472	1.0459
NNF107A'	1	1	1	1	1
NNF208A'	1.0404	1.0431	1.0456	1.0468	1.0479
NNF250	0.99021	0.98839	0.98646	0.98545	0.98504
NNF207	0.99047	0.98864	0.98671	0.9857	0.98529
NNF201	0.98883	0.9869	0.98486	0.9838	0.9833
NNF101B	0.99847	0.99819	0.9979	0.99774	0.99765
NNF202B	0.99331	0.99188	0.99035	0.98955	0.98919
NNF202A	0.99246	0.991	0.98945	0.98864	0.98828
NNP102A	0.98663	0.98449	0.98223	0.98107	0.98049
NNF103	0.98152	0.97888	0.97614	0.97473	0.97395
NNF203A	1	1	1	1	1
NNF203B	1	1	1	1	1
NNF104	0.99829	0.99799	0.99768	0.99751	0.99741
NNP101A	0.98663	0.98449	0.98223	0.98107	0.98049
NNP100A	0.98663	0.98449	0.98223	0.98107	0.98049
NNF106	0.99737	0.99708	0.99677	0.99662	0.99651
NNF205	1	1	1	1	1
NNF102B	0.98665	0.9845	0.98225	0.98109	0.98051
NNP100B	0.98665	0.9845	0.98225	0.98109	0.98051
NNP103A	0.98663	0.98449	0.98223	0.98107	0.98049
NNF101A	0.98153	0.97889	0.97615	0.97474	0.97396
NNP101B	0.98665	0.9845	0.98225	0.98109	0.98051
MGCCIII	1.0016	1.0017	1.0018	1.0019	1.0019
NNP202	0.98663	0.98448	0.98223	0.98106	0.98048
NNP201	0.98664	0.9845	0.98225	0.98108	0.9805
NNP103B	0.98664	0.9845	0.98225	0.98108	0.9805
NNP203	0.98662	0.98447	0.98222	0.98105	0.98047
NNF206	1	1	1	1	1
Active losses [MW]	4.695	5.528	6.41	6.896	7.085
Reactive losses [MVar]	3.617	4.262	4.945	5.3	5.48

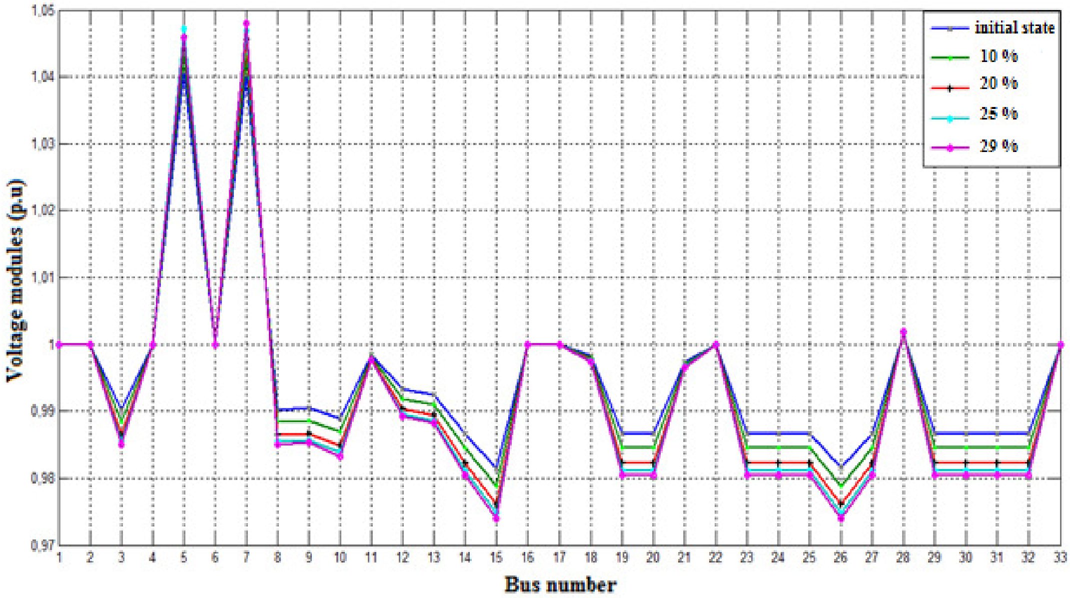

Fig. 6. Evolution of the voltage according to load evolution.

According to results, it is very clearly that the voltage of all buses decreases during the increase of the load up to a limit where the network doesn't support more additional overload (loss of static stability as shown in Fig. 7, so the overload limit is equal to 29% (λ_{max} =1.331) as shown in curve (V, λ) of Fig. 8.

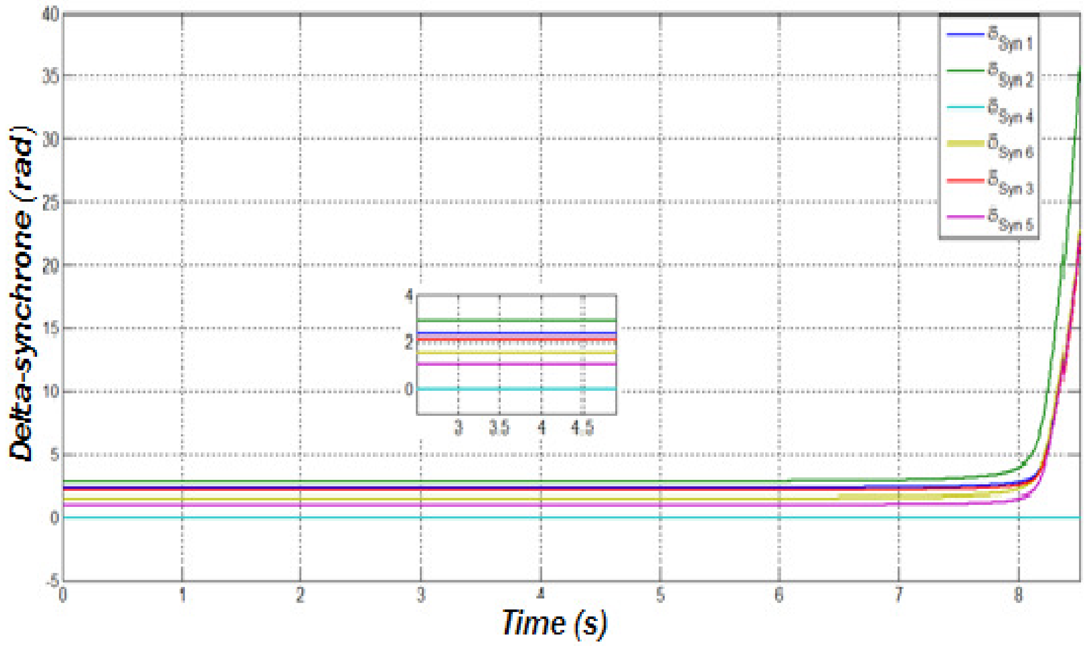

Fig. 7. Angle of synchronism for an overload value ≥ (29%).

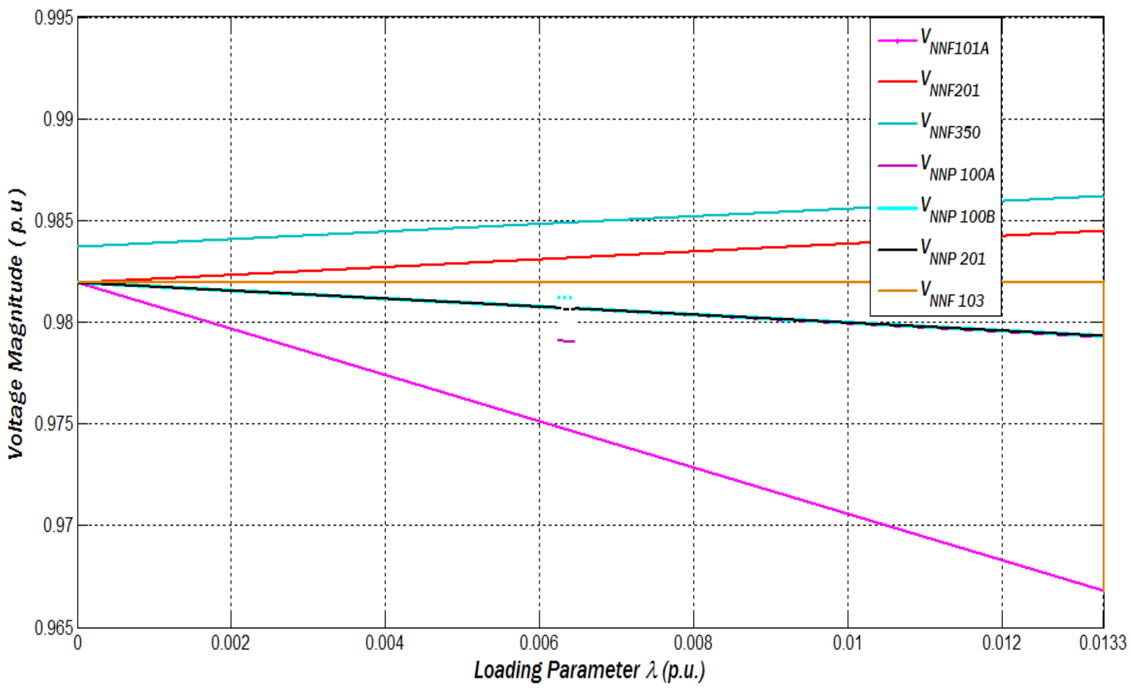

Fig. 8. Evolution of the voltage magnitude with the variation of load parameter.

Fig. 9, compares the critical state with the initial state of the network.

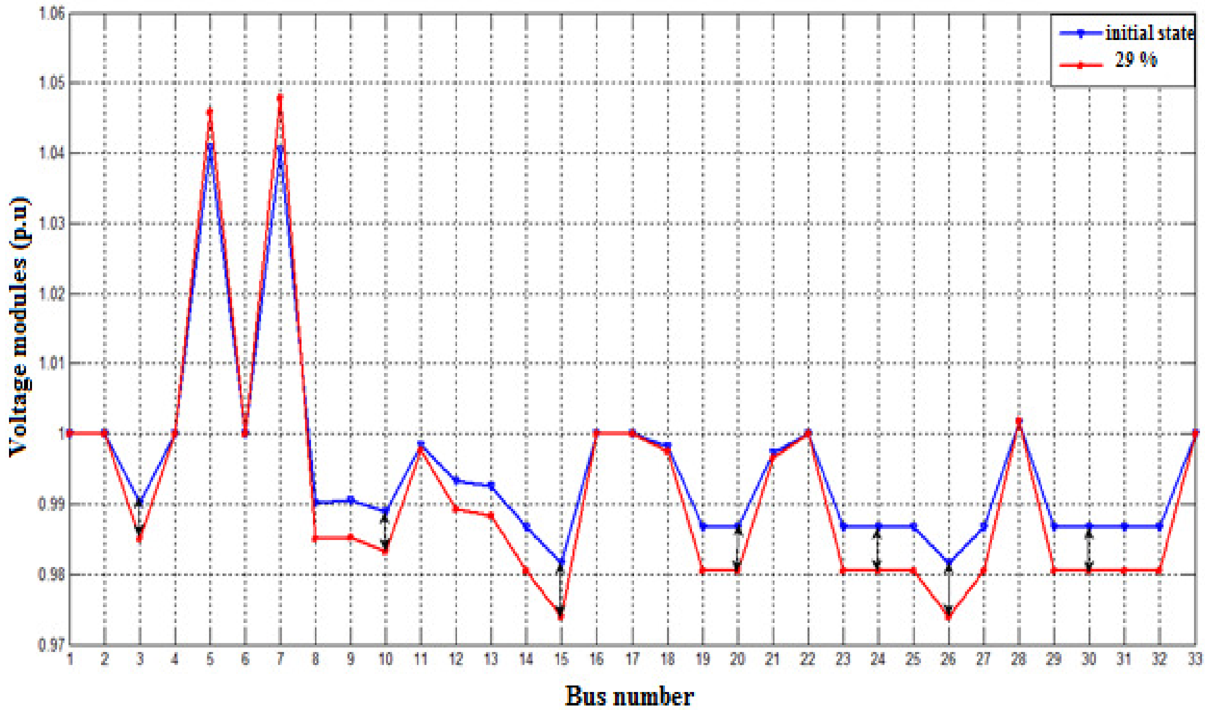

Fig. 9. Critical deflection of voltage.

It is clear that the critical deflection voltage mainly concerns the bus 3, 10, 15, 20, 24, 26 and 30 which will be the candidate places for STATCOM insertion.

8.1.3. Optimal Location of STATCOM

Fig.10, Fig.11, Fig.12 and Table 2 show successively the effect of different location of STATCOM on the network, the variation of the active and reactive losses for every case.

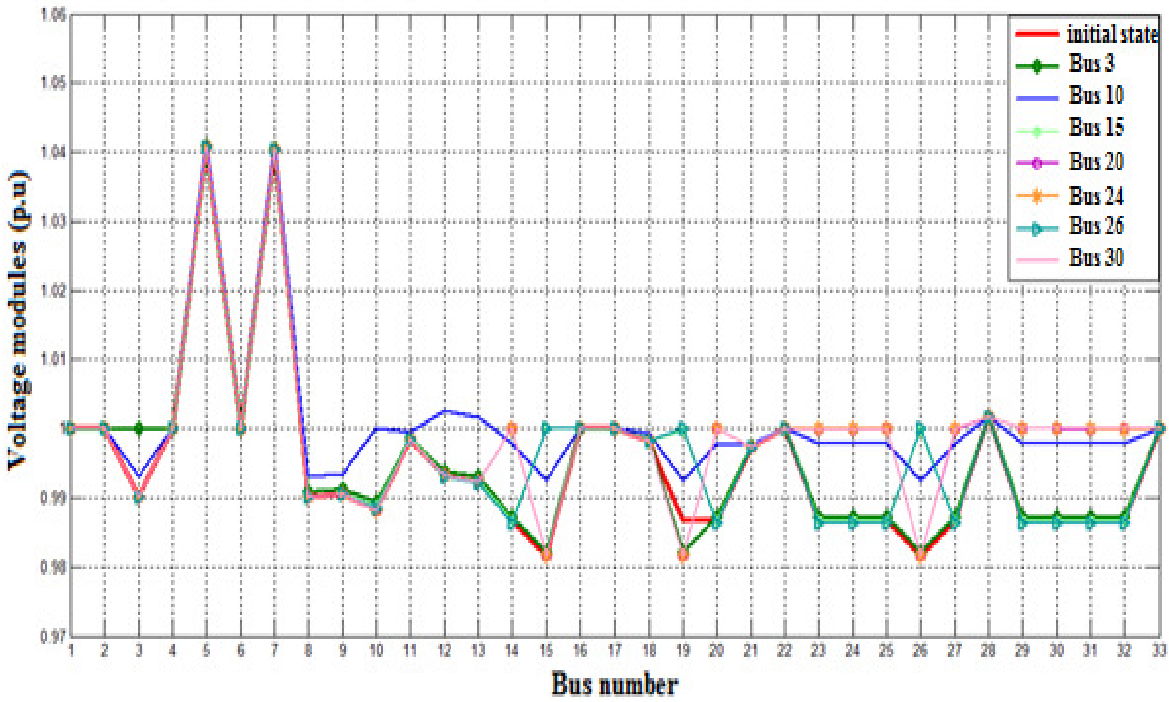

Fig. 10. Voltage profile for the different location of STATCOM.

Table 2: Case after STATCOM location

Buses	Initial state	Case 1: Bus 2	Case 2: Bus 10	Case 3: Bus 15	Case 4: Bus 20	Case 5: Bus 24	Case 6: Bus 26	Case 7: Bus 30
BG2	1	1	1	1	1	1	1	1
BG4	1	1	1	1	1	1	1	1
NNF350	0.99021	1	0.99315	0.99024	0.99023	0.99023	0.99026	0.99023
NNF107A	1	1	1	1	1	1	1	1
NNF208A	1.0408	1.041	1.0416	1.0408	1.0408	1.0408	1.0408	1.0408
NNF107A'	1	1	1	1	1	1	1	1
NNF208A'	1.0404	1.0406	1.0412	1.0404	1.0404	1.0404	1.0404	1.0404
NNF250	0.99021	0.99098	0.99315	0.99024	0.99023	0.99023	0.99026	0.99023
NNF207	0.99047	0.99124	0.9934	0.99049	0.99048	0.99048	0.99051	0.99048
NNF201	0.98883	0.98951	1	0.98889	0.98882	0.98882	0.98851	0.98882
NNF101B	0.99847	0.99853	0.99951	0.99848	0.99847	0.99847	0.99844	0.99847
NNF202B	0.99331	0.99387	1.0025	0.99336	0.9933	0.9933	0.99305	0.9933
NNF202A	0.99246	0.99302	1.0017	0.99251	0.99245	0.99245	0.9922	0.99245
NNP102A	0.98663	0.98731	0.99778	0.98669	1	0.99994	0.98632	0.99997
NNF103	0.98152	0.9822	0.99261	1	0.98151	0.98151	0.99999	0.98151
NNF203A	1	1	1	1	1	1	1	1
NNF203B	1	1	1	1	1	1	1	1
NNF104	0.99829	0.99835	0.99933	0.99829	0.99828	0.99828	0.99826	0.99828
NNP101A	0.98153	0.98221	0.99262	0.99967	0.98152	0.98152	1	0.98152
NNP100A	0.98663	0.98731	0.99778	0.98669	1	0.99994	0.98632	0.99997
NNF106	0.99737	0.99739	0.99767	0.99738	0.99737	0.99737	0.99737	0.99737
NNF205	1	1	1	1	1	1	1	1
NNF102B	0.98665	0.98733	0.9978	0.98671	0.99991	1	0.98634	0.99999
NNP100B	0.98665	0.98733	0.9978	0.98671	0.99991	1	0.98734	0.9999
NNP103A	0.98663	0.98731	0.99778	0.98669	1	0.99994	0.98632	0.99997
NNF101A	0.98153	0.98221	0.99262	0.99967	0.98152	0.98152	1	0.98152
NNP101B	0.98665	0.98733	0.9978	0.98671	0.99991	1	0.98634	0.99999
MCCGIII	1.0016	1.0016	1.0016	1.0016	1.0016	1.0016	1.0016	1.0016
NNP202	0.98663	0.98731	0.99778	0.98669	0.99998	0.99995	0.99632	0.99997
NNP201	0.98664	0.98733	0.99779	0.9867	0.99994	0.99999	0.98633	1
NNP103B	0.98664	0.98732	0.99779	0.9867	0.99994	0.99999	0.9863	1
NNP203	0.98662	0.9873	0.99777	0.98668	0.99998	0.99993	0.98631	0.99996
NNF206	1	1	1	1	1	1	1	1
Active losses [MW]	46.95	43.86	36.84	44.96	45.99	39.99	41.36	38.99
Reactive losses [MVar]	36.17	33.1	26.15	36.08	35.21	31.21	31.62	28.21

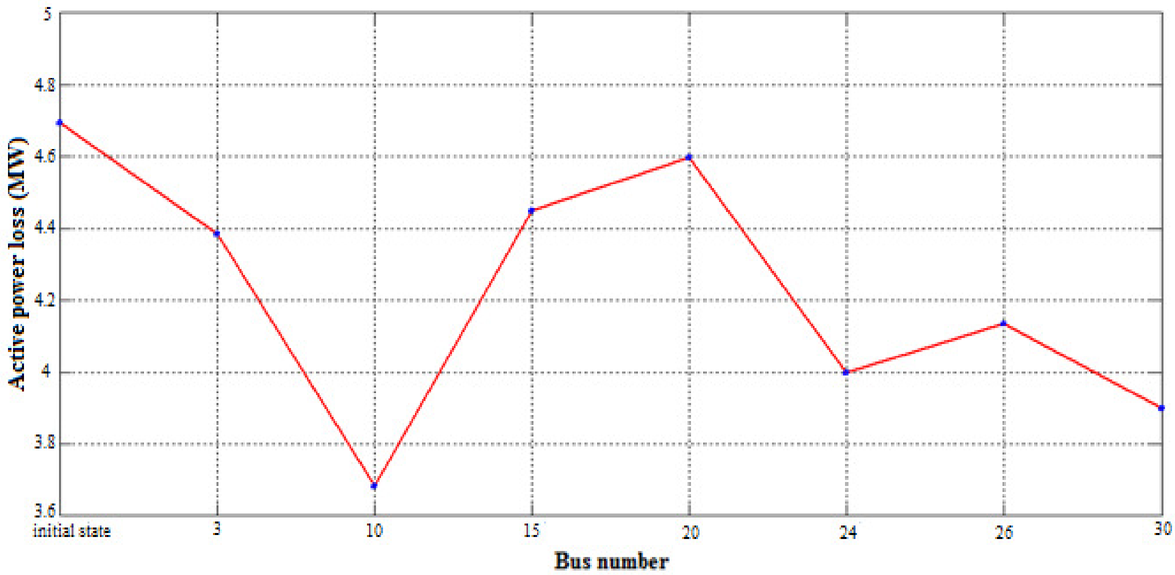

Fig. 11. Reactive losses for the different locations.

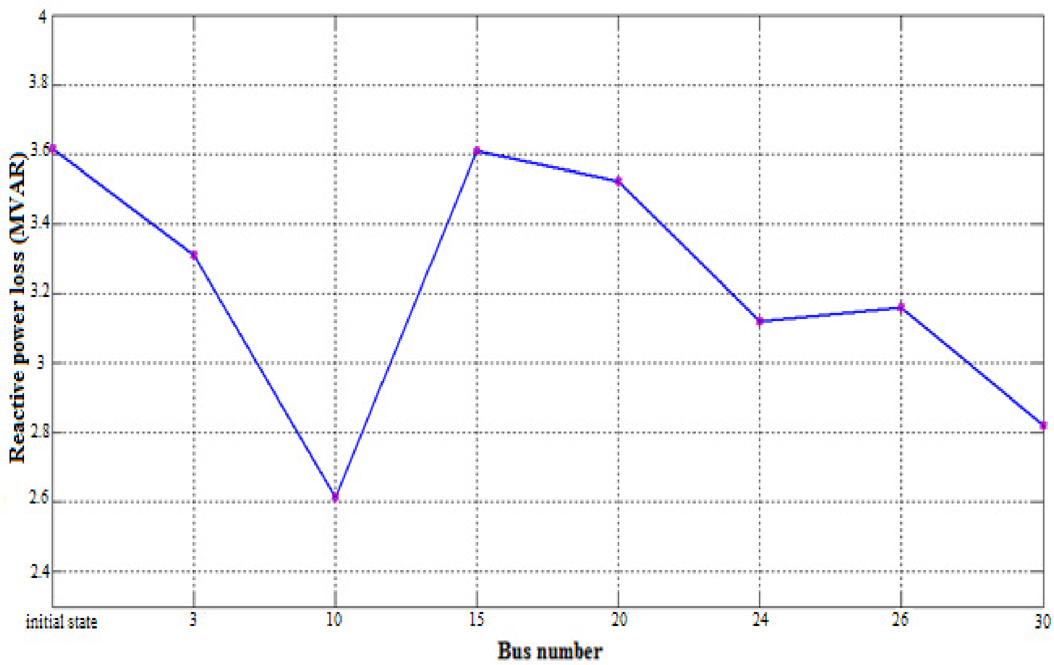

Fig. 12. Active losses for the different locations.

The optimum location of the STATCOM is at the bus 10 because the voltage profile is well improved and there is a remarkable decrease in the power losses comparing to the initial case.

8.2. Analysis of Transient STABILITY

This analysis was realized in two parts, it requires the application of three-phase symmetrical fault and see the transient behavior of the network in order to identify the exact value of the critical clearing time "CCT" (which represents the Index of stability adopted in our transient study):
-Calculating the maximum rate of wind power penetration estimated from simulations in the temporal domain,
-Improving wind penetration rate in the conventional network by introducing a STATCOM.
It must be noted that the location of the STATCOM in bus 10 will be adopted for all that follows.

8.2.1. Influence of Fault Locations

The study involves applying a default to all load bus and seeing the behavior of ASHTART following this disturbance given in Table1 which shows that the most unfavorable place is in bus 18 where CCT is the lowest.

Table 3: CCT for Different Fault Locations

Buses	Bus 10	Bus 11	Bus 15	Bus 18	Bus 21	Bus 26	Bus 28	Bus 32
CCT (ms)	661.3	700.08	655.5	650.63	701.85	655.78	709.06	673.14

The variation speed of the rotors of the various generators is shown in Fig. 13 and Fig. 14.

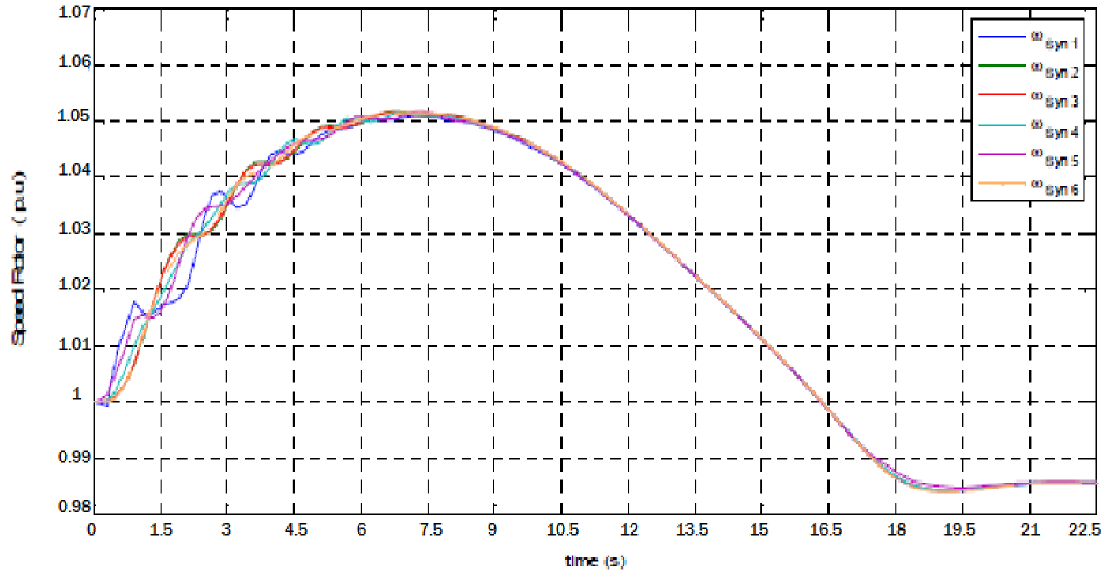

Fig. 13. Speed evolution for CCT =650.63ms.

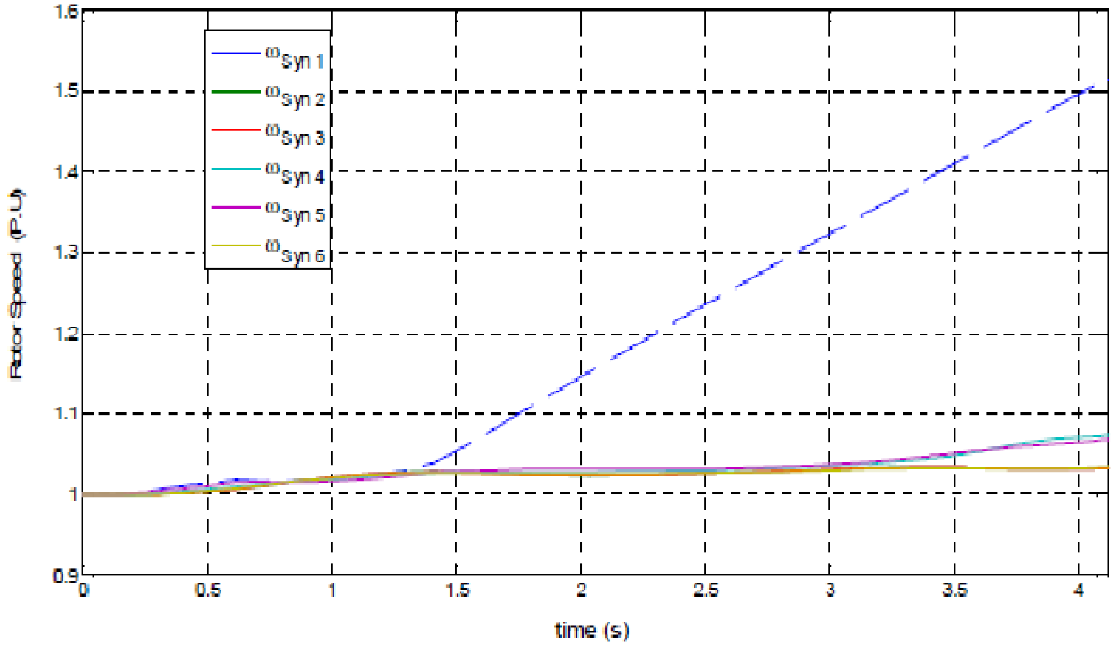

Fig. 14. Speed evolution for CCT =651ms.

We can conclude that the CCT without integration of a STATCOM is of 650ms and beyond this value, the network loses its transient stability.

8.2.2. Behavior of Network after STATCOM Integration

Now, we insert a STATCOM into all buses except in generation buses and Bus 18.

We can say that inserting a STATCOM in any bus has improved the CCT compared to CCT found without adding a STATCOM.

Table 4: Transient Stability for the Different Location of STATCOM

Classification of buses	Link buses	CCT (ms)
1	Bus 3	652.05
17	Bus 5	701.95
25	Bus 7	810.96
26	Bus 8	914.17
16	Bus 9	697.18
4	Bus 10	662.04
7	Bus 11	669.02
3	Bus 12	655.62
23	Bus 13	732.82
22	Bus 14	725.58
14	Bus 15	684.56
5	Bus 19	668.21
2	Bus 20	653.35
19	Bus 21	718.19
13	Bus 22	684.02
18	Bus 23	703.27
8	Bus 24	676.65
11	Bus 25	678.92
21	Bus 26	725.01
9	Bus 27	677.19
6	Bus 28	668.91
10	Bus 29	677.62
24	Bus 30	734.63
15	Bus 31	692.26
20	Bus 32	719.61
12	Bus 33	681.03

8.2.3. Impact of Wind Integration on Transient Stability

Now the study consists of adding a source of wind energy to the ASHTART network exactly on bus 29 and increases the penetration rate of wind power (10 to 80MW) in order to observe transient behavior of the network during the same defect by calculating the rate of wind integration in the network given by the ratio between the power generated by wind turbines and the total power consumed.

Table 5: CCT for Different Penetration Wind Power Rates (without STATCOM)

Installed capacity of Wind sources (MW)	**10**	**20**	**40**	**60**	**80**	**>80**
Rate of wind sources penetration (%)	**2.69**	**5.39**	**10.78**	**16.17**	**21.56**	**>22**
CCT (ms)	**463**	**375**	**242**	**113**	**67**	**0**

This table shows that more than 80MW of wind power integrated causes the loss of network stability.

8.2.4. Impact of STATCOM on the Integrated Wind Power Rates

Now, the study consists of inserting a STATCOM on bus 29, the same place of wind source integration.

Table 6: CCT for Different Penetration Wind Power Rates (with STATCOM)

Installed capacity of Wind sources (MW)	**80**	**100**	**120**	**140**	**≥140**
Rate of wind sources penetration (%)	**21.56**	**26.95**	**32.34**	**37.73**	**≥38**
CCT (ms)	**132**	**107**	**96**	**0**	**0**

This table shows that integrating a STATCOM allows the system to support more power than the case without STATCOM.

Besides its performance of stability, we notice that adding STATCOM leads to improve the integration of wind power rates in the network, and to increase its ability to support a disturbance without losing stability.

8. Conclusion

As a conclusion, we can say that this paper has focused mainly on the assessment of two types of stability: "static stability" and "transient stability".

According to the previous simulations, the following conclusions are obtained:

- the optimal location of a STATCOM is determined to improve the maximum load that the network can support without losing its static stability,
- It is proved that either a high level of wind power penetration or the excess of the critical clearing time "CCT" due to three- phase symmetrical fault destabilize the power system,
- The addition of STATCOM gives better performance to enhance the amplitude of the voltage profile during disturbances, also its important effect to increase wind energy rate integrated in the network without losing its transient stability.

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