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Analysis of Transient and Voltage Stability of an 11-Busbar Testing System

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***Abstract* – A comprehensive treatment from the physical and mathematical perspective supply modelling, analysis, control and covers a range of topics including modelling, computation of load flow in the transmission grid, stability analysis of the transient state. It is widely accepted that transient stability is an important aspect in designing and upgrading electric power system. In utility planning, transient stability is studied by numerical simulation. It involves the study of the power system following a major disturbance. In order to study Electric Power System transient stability, the models to describe their components should be defined. The components are defined using the classical model, which is valid to time periods up to 2 seconds. This project contains 11 busbars, 1 synchronous generator, 3 loads and 8 transformers. This research is done in DIgSILENT PowerFactory software for network modeling and simulation by using Stability Analysis Functions (RMS) advanced feature. In this paper we are analyses the maximum rated power of distributed generation (DG) considering only the terms of voltage limit constraints, the N-1 operational criterion analysis and three-phase symmetrical fault analysis for N-1 criterion is examined.**

***Keywords* - high load, n-1 criterion, synchronous generator, transient stability analysis**

1. Introduction

Stability in Power Systems is one of the importances of a system that had increased. It is the most widely used from power blackouts. Today, usage of power systems interconnection had increased using of new technologies and controls, and the increased its usage in highly demanding situations. In order to maximize the system stability research on power system stability should be carried out. In order to design the perfect system to solve this problem a detailed study of the design should be performed. In the last years [1], due to the spread of electric generation facilities and economic factors, Electric Power Systems operate more closely to their limits. Thus, more than before, it is of crucial importance the existence of methods to assess the system stability. In [2] there are two kinds of stability problems: voltage stability and transient stability. This paper addresses the transient stability.

Transient stability analysis of a power system is concerned with the system's ability to remain in synchronism following a disturbance. Following a large disturbance, the synchronous alternator the machine power (load) angle changes due to sudden acceleration of the rotor shaft. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance. The loss of synchronism develops in a very few seconds after the disturbance inception, among the phenomena transient stability is the fastest to develop. These challenging aspects motivate our choice to mainly concentrate on transient stability. The conventional transient stability measure of the system robustness to withstand a large disturbance is its corresponding critical clearing time (CCT). This is the maximum time duration that the disturbance may act without the system losing its capability to recover a steady-state operation. Another transient stability measure of great practical importance is the power (generation or transfer) limit. It is defined as the largest power sustainable without loss of synchronism, given the occurrence of a large disturbance and it's clearing scenario. In [4], note that the measures imply consideration of three distinct phases: the pre-fault, the during-fault, and the post-fault one. In [5] faults need to be cleared within critical clearing time and after that system need to be able to regain stability. Some of the most important parameters influencing stability are fault clearance time, fault location, and type of the fault.

2. Literature Review

Mania Pavella [3] identified three classes of approaches – Decision Tree, KNN and neural network - to transient stability and analyzed which can meet most stringent requirements of transient stability. It is found that stability could be achieved with the appropriate combinations of numerical, direct, and automatic learning techniques.

Mirza Saric and Irfan Penava [5] in their research discussed theoretical background of induction generator, its simulation model, as well as dynamic response analysis procedure for a wind farm connected to real network. Thought their research they showed the importance of transient stability in case of integration of large renewable sources to the network. In terms of rotor angle, frequency and voltage stability issues the observed case of wind farm integration was not appropriate to connect to the network with induction generator as the rotor speed was too large, with sharp reduction of reactive power as voltage and active power equal to zero for period that are too long for system to operate in stable state.

Innocent Davidson and Immanuel Mbangula [6] examined and analyzed the fault that appeared on the 330kV transmission line between Omburu sub-station and Ruacana power station where the blackout happened for 6 hours. The goal of this research was to investigate what fault occurred, what is the cause and solutions to prevent such fault occur again. The results from DIgSILENT PowerFactory are compared with data obtained from NamPower records and it is found that it was the single phase to ground fault.

Ioanna Xyngi, Anton Ishchenko, Marjan Popov, and Lou van der Sluis [7] in their research described the transient stability analysis of a 10-kV distribution network with wind generators, microturbines, and CHP plants modeled in Matlab/Simulink and investigated faults that are simulated on various locations. They showed that in the network with distributed generators (DGs) the protection settings must be adjusted accordingly in order to have stable system as the undervoltage protection should be different for different DGs.

Diaz-Alzate, Candelo-Becerra and Villa Sierra [8] investigated and found a new way of managing and controlling transient stability based on relative angles. They showed how predefined thresholds of relative angles which they attained by offline simulations and the relative angles attained during the online operation with PMUs are useful in the process of monitoring as well as predicting transient stability under real-time operation. They performed analysis on New England with 39 busbars and IEEE with 118 busbars networks with different contingencies and control actions that are applied at predicted time. The relative angle and the predefined thresholds of the relative angle helped in monitoring and predicting of the systems instability with enough time to respond to oscillations that appeared in the system.

3. Methodology

In this part we will show 3 different steps of methodology. In first step we will search and show what is the maximum power that satisfies standards of synchronous generator while checking the voltage profile. In the second step we will do N-1 operational criterion analysis for 6 different cases in this grid and found the new maximum power that satisfies the network. In the last step we will do three phase symmetrical fault analysis for N-1 criterion, with 4 different cases in it.

(a) In the first part of the project the maximum rated power of a generator at BB13 (DG), considering only the voltage limit constraints is found, and then the three-phase symmetrical fault analysis is performed for the value of maximum power. We investigate fault duration period of 0.02 seconds. After the RMS simulation is done, voltage development, rotor angle, active and reactive powers are plotted for the further analysis.

b) In the second step the n-1 criterion in terms of voltage profile development, as well as line and transformer loading, for 6 different cases for high load scenario, with maximum DG power was investigated. An operational criterion N-1 can be applied to the existing network, if there may be planned or unplanned congestion that may exist at a certain moment. If the criterion is satisfied, that means the system will be able to support a predefined contingency, operating after that, with a minimum performance. The N-1 criterion requires that the system can be able to tolerate the outage of any one component without disruption and does not concern itself with the probability of an outage. If an outage is highly unlikely, the criterion is still generally applied because system failure due to a lost component is unacceptable. The criterion is generally considered as the need to balance generation and load. For modeling network for 6 different scenarios, 6 lines from which the network is consisted are modeled with the following event that placed lines one by one out of service. The voltage on the critical busbar – point of coupling - was monitored along the way, as well as the voltage in the entire system, with the line and transformer loading, making sure that the voltage or line and transformer loading does not exceed the permitted limit specified by the standard EN 50160 for delivered power quality. Minimum upper limit for the voltage, as denoted in the EN 50160 standard, is 0.9 p.u., while maximum upper limit for the voltage is 1.1 p.u. Regarding the line and transformer loading the constraint limits determined by the standard EN 50160 is that it does not exceeds loading of 100 %. In such way the n-1 criterion is investigated and the maximum power for which the system is in the stable mode operation is found for each of the different scenarios when one by one line were out of service. For different events that placed different line out of service, the system will be stable for different maximum power produced from generator.

c) In the next part of the research the three-phase symmetrical fault is simulated and the rotor angle, active power, reactive power and voltage development for the following cases, for high load conditions and maximum DG power is to be reported in the results and discussion part of this research project. Three-phase symmetrical fault is simulated in the DIgSILENT PowerFactory software for network modeling and simulation, one second before, during and 5 seconds following the fault on 6 different lines for each of the case scenario. This research is done in DIgSILENT PowerFactory software for network modeling and simulation by using Stability Analysis Functions (RMS) advanced feature. First, the maximum power generation from synchronous generator is found by using the power flow option in the program where all voltage on all busbars, as well as line and transformer loading in the network, is checked so to satisfy EN 50160 standard limits. Next, in order to satisfy limits, set by EN 50160 standards in terms of voltage profile, line and transformer loading when 6 lines of which the system is consisted are modeled with an event that placed line one by one out of service. In such way, by using the power flow analysis function when lines are out of service the n-1 criterion is investigated. For the third part of the research, where three-phase symmetrical faults are simulated on each of the 6 lines that were investigated. The duration of the fault is for the analysis of the 4 case scenarios set on lines to be 0.02, 0.05, 0.5 and 5 seconds and then rotor angle, active power, reactive power and voltage development for the following cases, for high load conditions and maximum DG power are plotted in the graphs, and in such way the behavior of the system could be tracked.

d) In the last part of this project the power factor is changed when line 2 is followed with an event that placed it out of service, thus when investigating the N-1 criterion. Values of power factor that are taken into consideration are 0.8, 0.9 and 1, both capacitive and inductive while the voltage development is analyzed and new maximum power of generator is determined in order to satisfy EN 50160 standard for voltage variation in the network for new values of power factor.

4. Results and Discussion

A. Maximum Power from Generator in Terms of Voltage Profile

In the first part the maximum voltage in the network is found by changing the power generated by the synchronous generator while checking the voltage profile of the network in order that voltage does not increase beyond allowed limits. In the Table III. main results of power flow in terms of voltage magnitude and angle at the busbar BB11 which is the point of coupling, are shown when network operates with no any faults occurring in the system. Maximum power generated from synchronous generator that satisfy the voltage limits set by EN 50160 standard is found to be 286 MW, while the maximum power that satisfy all criterions from the standard – voltage, line and transformer loading – is found to be 104 MW.

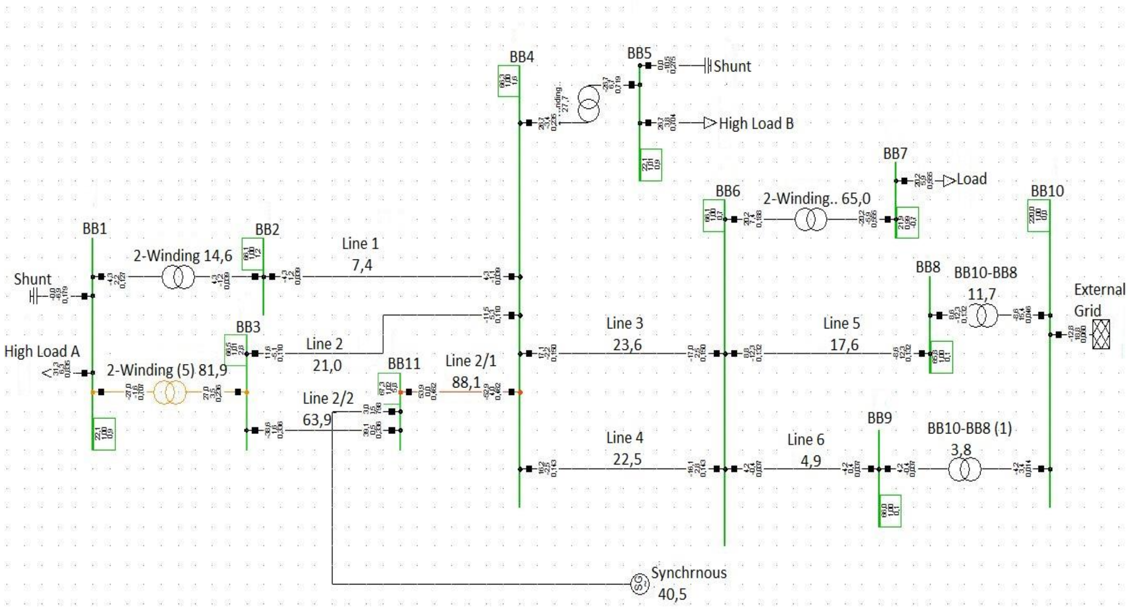

Fig. 1. Network Model from DIgSILENT PowerFactory software

The power stability analysis of the given network is done in terms of three-phase symmetrical fault analysis for the maximum power which satisfies the allowed voltage limits and equals to 286 MW. The three cases are investigated where the duration of the fault is set to be 0.02 seconds in fist case, 0.05 seconds in second case and 0.2 seconds in third case. The results obtained when duration of fault is taken to be 0.02, which is expected to show the best results due to lowest fault duration, are shown in Fig.1. In the Fig 1. where the graphs of voltage of the busbar which is the point of coupling, angle of rotor of the synchronous generator, as well as active and reactive power of the synchronous generator are plotted. It can be seen from the graphs that for the maximum power that satisfy the EN 50160 standard only in terms of voltage profile, the system is unstable even for the very small periods of fault duration and it shows that for this high power of generator the network quite inadequate to operate.

B. N-1 Operational Criterion Analysis

Summary of results obtained when different lines in the network placed out of service are presented in the Table I. and dynamic response of voltage profile in Fig.2., as well as rotor angle in Fig.3. It can be observed which line is the most critical and which is maximum power for such line. The maximum power that satisfies the n-1 criterion for the entire network is found to be 93 MW, since it satisfys the n-1 criterion for the most critical line, which is little bit lower than the maximum power that satisfys the EN 50160 standard for delivered power quality when all lines are in service that is found to be 104 MW. The maximum power for line 1 and line 2 is 93 MW, thus, this value of generated power is compared with maximum power of all other lines in the system, while the voltage magnitude, as well as angle, does not change significantly. In the Table II. the line and transformer loading is compared for same lines for their maximum power and value of 93 MW, and as it can be seen, there is approximately more that 10% of difference in line loading and around 4% in transformer loading. From the results obtained it can be concluded that the most realiable solution is to consider value 93 MW as maximum power that satisfy N-1 criterion for entire network.

Table 1. Voltage developments for maximum power for each line in the network determined by N-1 criterion

Out of service (BB11)	**UI, Magnitude MV**	**u, Magnitude p.u.**	**U, Angle deg**
Line 1 93 MW	67,81801	1,027546	6,905885
Line 2 93 MW	67,1283	1,017095	6,473696
Line 3 93 MW	67,4659	1,022211	6,748108
Line 3 105 MW	68,03866	1,030889	8,197442
Line 4 93 MW	67,39707	1,021168	6,682203
Line 4 105 MW	67,94841	1,029521	8,111645
Line 5 93 MW	65,03935	0,985445	8,237019
Line 5 100 MW	65,13477	0,98689	9,947232
Line 6 93 MW	67,48871	1,022556	5,909104
Line 6 105 MW	68,16291	1,032771	7,01058

Table 2. Line and transformer loading for N-1 criterion in %

N-1 criteria (BB11)	**Power**	**Loading [%] line 2/1**	**Loading [%] Two-winding transformer (5)**
Line 1	93 MW	97,9854	93,85382
Line 2	93 MW	99,39992	96,90187
Line 3	93 MW	87,84784	81,66314
	105 MW	99,58101	84,96854
Line 4	93 MW	87,93902	81,74933
	105 MW	99,71524	85,08491
Line 5	93 MW	91,17996	84,81535
	100 MW	98,65325	87,13317
Line 6	93 MW	87,81764	81,63461
	105 MW	99,39667	84,80878

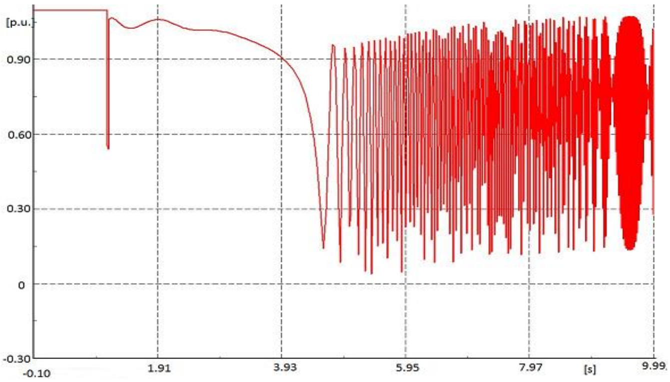

Fig. 2. Dynamic response for 0.02 s fault duration on lines – Voltage

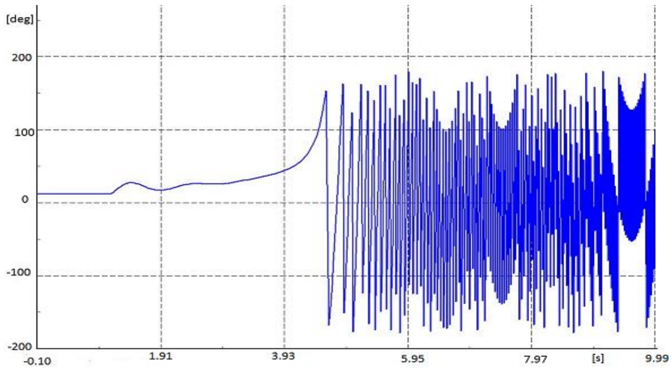

Fig. 3. Dynamic response for 0.02 s fault duration on lines – Rotor Angle

C. Three Phase Symmetrical Fault Analysis for N-1 Criterion

Since it has been shown that the system is unstable for the maximum power that satisfy EN 50160 standard in term of voltage variation, the three-phase symmetrical fault analysis is done after the N-1 criterion is satisfied for the observed network. The maximum power on the most critical line is previously found to be 93 MW by using the N-1 criterion, and in this part, this is the power for which the system is analyzed. The four cases are examined where the duration of the fault is set to be 0.02 seconds in the first, 0.05 seconds in the second, 0.5 seconds in the third and 5 seconds in the fourth case. Since the line 2 is shown to be most critical in the network after the N-1 criterion analysis done for this case, the result for this line are shown in the graph plotted after the RMS simulation done. In the Fig. 4. the dynamic response for 0.02 seconds fault duration on line 2 in terms of voltage profile is shown. As it can be seen from the graph, when the fault occurs in the system on the line 2, there is voltage drop at the time of fault occurrence and as the duration of the fault is 0.02 seconds, the system returns to be in the balance eventually. In the Fig. 5. there is rotor angle of synchronous generator, active and reactive power presented. As it can be observed from the figures, the system is for the 0.02 seconds fault duration stable and the network for power of 93 MW generated from synchronous generator is adequate and secure for operation as the system after some period reaches equilibrium state.

The dynamic response in terms of voltage profile is same as for 0.02 s which is shown is Fig.3., while in Fig. 6. dynamic response of rotor angle of synchronous generator, active as well as reactive power is shown when duration of fault is taken to be 0.05 s for the three-phase symmetrical fault simulation. As it can be seen from Fig. 5. when the fault occurs in the system on the any line, there is voltage drop as the fault occurs on the line, after which, for all lines except line 1, system is stable and able to reach new equilibrium. Voltage dynamic response is same as in Fig.3 when the fault occurs in the system on line 1. There is the voltage drop where voltage drops to approximately zero for longer period than it was case on all other lines, and it will oscillate in the range from value slightly higher than 0 p.u. to approximately 0.35 p.u., with no signs that it will eventually come to the state of balance. However, observing the dynamic response of rotor angle, active and reactive power for the line 1 from Fig.7. for 0.05 s fault duration, the system is unstable to adequately operate since it is unable to attain equilibrium state again.

In the Fig. 8. and Fig. 9. after the RMS simulation is done, the results obtained show that in terms of voltage development seen from the Fig. 8., at the time of fault occurrence there appears the voltage drop where the system goes back to the balanced state eventually. In the Fig. 9. the system response of rotor angle of synchronous generator, active and reactive power show that the system for the 0.5 seconds fault duration is stable and the network for power of 93 MW generated from synchronous generator is adequate and secure for operation in case for all analyzed lines except for line 2. Considering case when fault simulated on line 2 for 0.5 s, the dynamic response of voltage development, rotor angle, active and reactive power is similar as response in Fig. 8. while voltage dynamic response is shown in Fig. 10. There is a major voltage drop in the system which is the consequence of the fault that occurred on the line 2. The voltage, after it drops to value slightly higher than zero, is oscillating from that value to approximately 0.35 p.u. Since, also, all other parameters continued to oscillate equally for all 10 seconds and t will not came back to the balanced state, thus, the system is denoted as unstable in terms of all parameters examined.

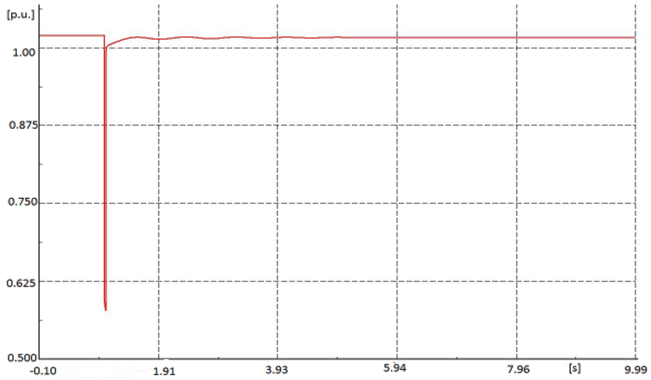

Fig. 4. Dynamic response for 0.02 s fault duration on line 2 – Voltage

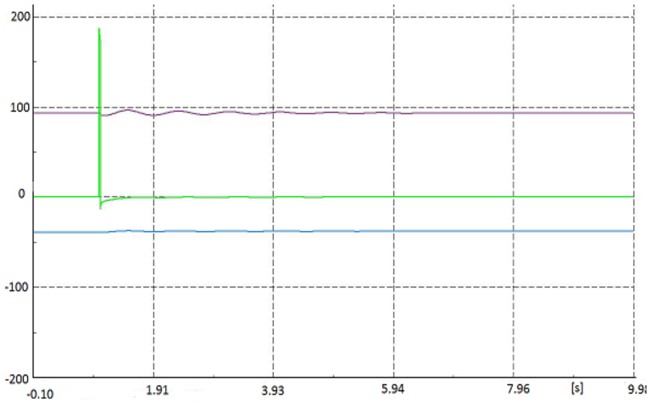

Fig. 5. Dynamic response for 0.02 s fault duration on line 2 – Rotor Angle (blue), Active (purple) and Reactive Power (green)

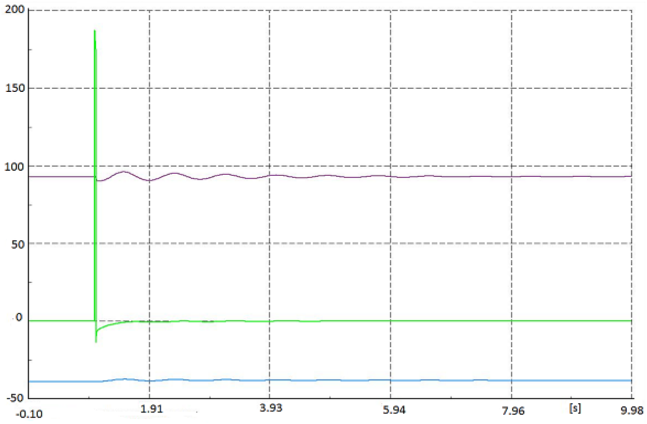

Fig. 6. Dynamic response for 0.05 s fault duration on lines – Rotor Angle (blue), Active (purple) and Reactive Power (green)

In the Fig. 11. the results obtained from the three-phase symmetrical fault analysis when duration of fault is taken to be 5 seconds occurring on the line 2 is shown in terms of voltage profile and in Fig. 12. rotor angle response is shown. Since the duration of the fault on lines is taken to be 5 seconds, which represents too long period for a fault, it can be observed that there is the breakdown of the system in terms of rotor angle where the dynamic response is infinitely oscillating where the speed of the rotation is increasing causing system to be out of balance. There is with the voltage drop at the time the fault occurs there is rise in the angle of rotor which starts to excessively rotate, and drop in active power to the respect of reactive power rise. At the time there is fault on the line 2 it can be observed that all analyzed parameters are oscillating in the smaller range, while at approximately 6th second, when the duration of the fault is over, there are greater oscillations where the system is unable to reach the equilibrium state and, instead, and reaches the state of complete breakdown.

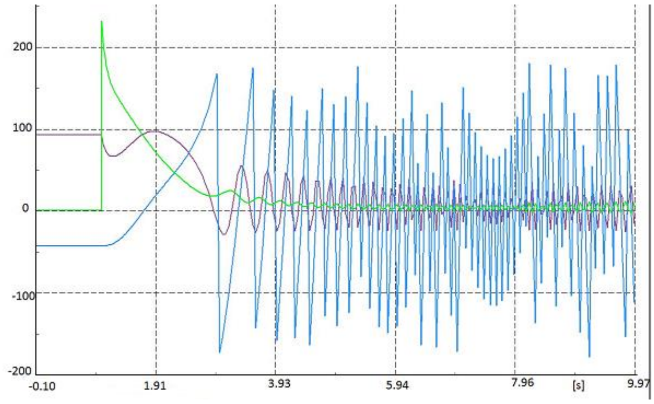

Fig. 7. Dynamic response for 0.05 s fault duration on line 1 – Rotor Angle (blue), Active (purple) and Reactive Power (green)

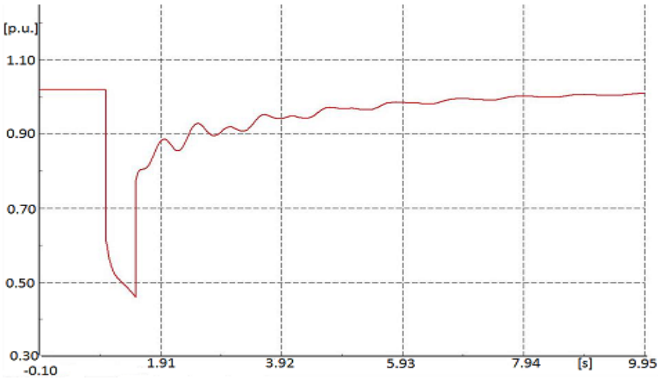

Fig. 8. Dynamic response for 0.5 s fault duration on lines – Voltage

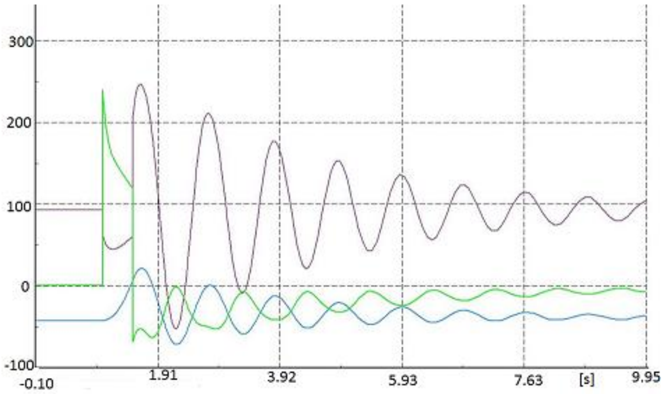

Fig. 9. Dynamic response for 0.5 s fault duration on lines – Rotor Angle (blue), Active (purple) and Reactive Power (green)

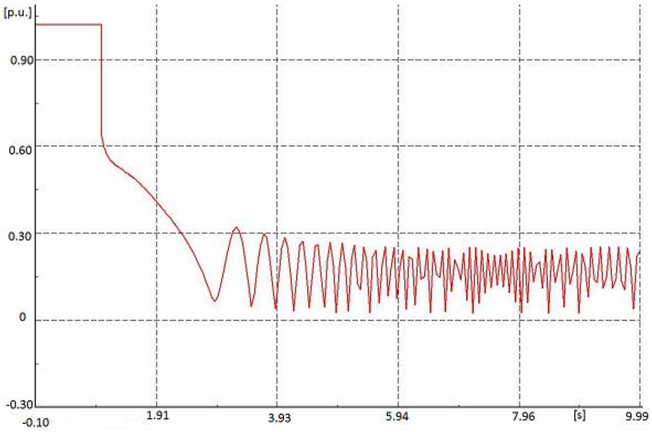

Fig. 10. Dynamic response for 0.5 s fault duration on line 2 –Voltage

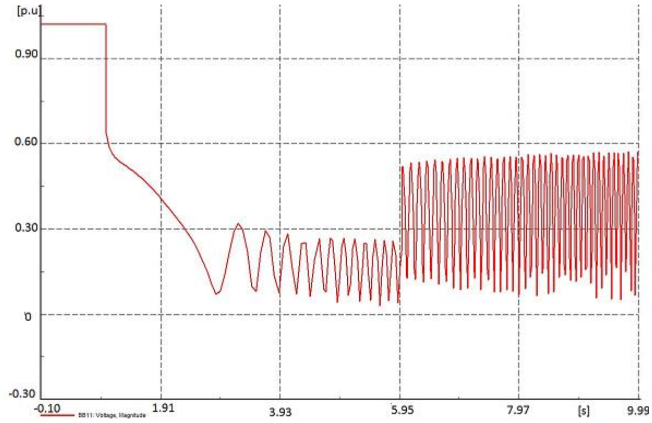

Fig. 11. Dynamic response for 5 s fault duration on lines – Voltage

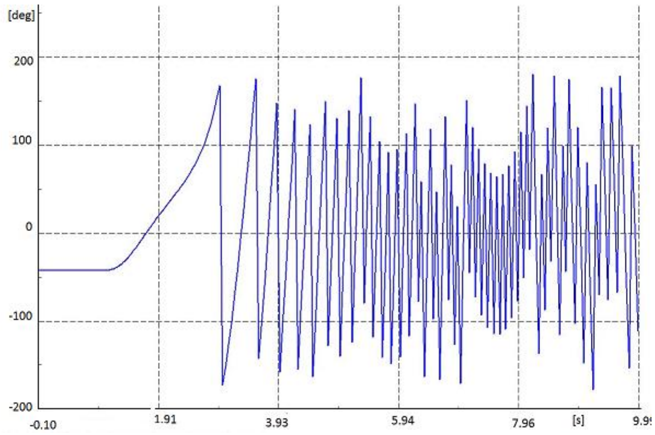

Fig. 12. Dynamic response for 5 s fault duration on lines – Rotor Angle

D. Voltage Control by Power Factor Correction for N-1 Criterion

In the Table III. The results of voltage development on the BB11 busbar are presented when the power factor of the synchronous generator is varied. As the generator is operated under different power factor, there is a change in the active and reactive power production in order to maintain voltage within limits set by EN

50160 standards. The results obtained show how the voltage is regulated by power factor correction as the in the case of 0.8 capacitive power factor voltage magnitude for 93 MW falls below allowed limits, and new maximum power is determined to be 45 MW. As in the case of 0.8 inductive power factor the voltage goes beyond upper allowed limit in case when power production of 93 MW, and the new maximum power for stable operation is found to be 74 MW. In cases when power factor is 0.9 in both capacitive and inductive mode, the voltage on the critical busbar, as well in the entire network, stays within allowed limits and does not change significantly for both power of 93 MW and new found power. It can be then concluded that if the generator operates under power factor of 0.8 in both modes, there is less active power produced, while if it operates under power factor of 0.9 in both modes, as well as under power factor of 1, the maximum power of 93 MW previously determined satisfy N-1 criterion and offers stable and secure network operation. Considering results obtained and presented in Table IV., in terms of line and transformer loading, for power of 93 MW any power factor in either capacitive or inductive mode less than unity, the power of 93 MW will distort the network operation and stability. Thus, it can be concluded that considering only voltage constraints the system will be stable for power factor of 0.9 capacitive and inductive, while when line and transformer loading taken into consideration, there is all cases when power factor less than 1 new maximum power for unstable and unsecure network operation.

Table 3. Voltage developments for different power factor

Power factor BB11		**UI, Magnitude MV**	**u, Magnitude p.u.**	**U, Angle deg**
CAP	Line 2 0.8 (45 MW)	59,59856	0,903006	3,5407772
CAP	Line 2 0.8 (83 MW)	55,44239	0,840036	13,12576
IND	Line 2 0.8 (74 MW)	72,79612	1,102971	1,038122
IND	Line 2 0.8 (93MW)	75,16263	1,138828	2,164138
CAP	Line 2 0.9 (73MW)	60,93922	0,923322	7,032856
CAP	Line 2 0.9 (93MW)	60,2638	0,913088	10,3019
IND	Line 2 0.9 (89MW)	72,12859	1,092857	3,275636
IND	Line 2 0.9 (93MW)	72,52091	1,098802	3,567566
IND	Line 2 1 (93MW)	67,06188	1,016089	6,509941

Table 4. Line and transformer loading for different power factor

Power Factor		**Power**	**Loading [%] line 2/1**	**Loading [%] Two-winding transformer**
CAP	Line 2 0.8	45MW	40,80236	74,93822
CAP	Line 2 0.8	93MW	167,4764	123,1931
IND	Line 2 0.8	74MW	92,47962	87,84803
IND	Line 2 0.8	93MW	116,5894	98,82892
CAP	Line 2 0.9	73MW	98,69827	93,07358
CAP	Line 2 0.9	93MW	131,5861	109,3657
IND	Line 2 0.9	89MW	99,38897	93,99311
IND	Line 2 0.9	93MW	104,098	96,17869
IND	Line 2 1	93MW	99,53208	96,96105

4. Conclusion

Voltage stability is the main problem concerning utilities due to the continuous growth and deregulation. In this paper, the network with 11 busbars is examined for a transient stability. Transient stability studies deal with the effects of large and sudden disturbances that occurs within the network such as it is a fault, the sudden outage of a line or the sudden removal or application of load. It is very important to do the transient stability analysis of a system in order to ensure that the system can handle the transient condition which is followed by a major disturbance. Transient stability and voltage instability analysis done in this research for the network with high load conditions shows that for a smaller period of fault duration, the system can be denoted as stable, while in case when the fault duration is somewhat higher than 0.02 seconds, the system is unstable and not secure in operation being unable to attain the equilibrium state and synchronism considering all parameters analyzed – voltage development, rotor angle speed, active and reactive power. In cases when fault duration greater than 0.02 seconds, there is breakdown state appearing in the network after the fault where the rotor speed is increasing, thus, causing system to go unstable and out of synchronism. Also, during the fault, there is voltage drop, active power drop and reactive power rise, after which there is an oscillation which cannot reach equilibrium. When fault duration increased to 0.05 or 0.5 seconds, the system is unstable only when fault simulated on one line, while when fault duration is increased to 5 seconds, then for every line examined and analyzed for three-phase symmetrical fault, the system is unstable.

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