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Influences of a "Hybrid Grid" on the Network's Voltage Quality and Supply Reliability

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Summary: **The electricity is a basic need for functioning of modern society. In the deregulated electricity market, delivering quality power to the clients is a challenge for the utilities. In this paper, a "hybrid grid" is discussed that consists of centralized generations and localized distributed generations which may be comprised of small-scale conventional and sustainable sources. Energy storage option is also integrated in the hybrid-grid. Simulations are done on a test network, using "Power-Factory" software. It was found from the analysis that voltage quality and power supply availability of a hybrid-grid can be improved by proper selection of energy storage system along with protective and control devices.**

Keywords:
hybrid grid,
DG,
power system reliability,
voltage quality,
interruption,
NaS storage system

1. INTRODUCTION

The research paper presents one of the possible scenarios of the future electricity network of the Netherlands. A "Hybrid Grid" scenario is proposed in which the electricity network integrates large centralized power plants along with small scale distributed generations (DG), which may be comprised of small scale conventional energy source based generations (e.g. gas, diesel) as well as various sustainable energy resource based generations (e.g. wind, solar). Also, the option for energy storage system is integrated in the hybrid grid. It is expected that a "hybrid grid" concept will improve the network's technical performances.

A test network is selected on which a number of case studies are conducted to find out the consequences of the proposed concept. Various electrical simulations on the test network are done by using "Power Factory" analysis tool, developed by DIgSILENT Gmbh, Germany.

In the first part of this paper, electric power system reliability concepts are briefly discussed. Some simulation results are analyzed to indicate the variation of customer's reliability indices at different points of the test network.

In the second part of this paper, various voltage quality issues in terms of voltage dips and power supply interruptions are discussed. Case studies are conducted on the test network for various types of short duration network faults to analyze the influence of DG and storage system on the network's voltage distribution. Also, the possible effects on the customer's equipments during temporary power supply interruptions are briefly discussed.

In the last part of this paper, the probable influences of a storage system in the network are discussed. A suitable storage system is selected for the test network and a case study is done to analyze the influence of a storage system on the network performances.

2. OBJECTIVES OF RESEARCH

Foreseeing the increasing importance of a high quality hybrid network, the objective of this project is chosen to analyze various technical aspects of a future hybrid grid, relating to operational reliability and voltage quality issues.

In this paper, the wind energy based sustainable DG is considered. As the power outputs from the wind based DG are dependent on the meteorological conditions, it can influence the grid's voltage quality and reliability to a large extent. One of the most important criteria for the successful and large scale implementation of sustainable energy sources in the existing grid is that the proposed network should perform technically the same or better than the present network. Looking to the future, the success of "sustainable resource based DG" may depend on integrating energy storage system to provide optimum energy delivery solutions. The following research questions are formed to formulate the research goal.

- Does a "wind power based DG" have major influence on the network's reliability?
- How does a DG influence the voltage quality of the network during a failure event of a network's component?
- How does a storage system influence the network's voltage quality and the reliability?

3. TEST NETWORK

A test network called "Testnet" developed by Continuon, a Dutch network operator, is chosen to do the simulations for this research. This network comprises of 150kV high voltage, 10kV medium voltage and 690V low voltage busbars. The high voltage substation of this network is connected to a strong external grid which has high short circuit capacity. The network also contains DG which is considered to be fed from wind energy. Realistic load demand data is fed to model various load points. After the network is selected, it is reduced to a single string with various network components, loads and DG. Only a small part of the original network is chosen for the present research so that it can be modified (and extended) easily depending on the research's need, avoiding complicacy. The simulation study of this paper is mainly focused on the medium voltage part of the test network shown in Figure 1.

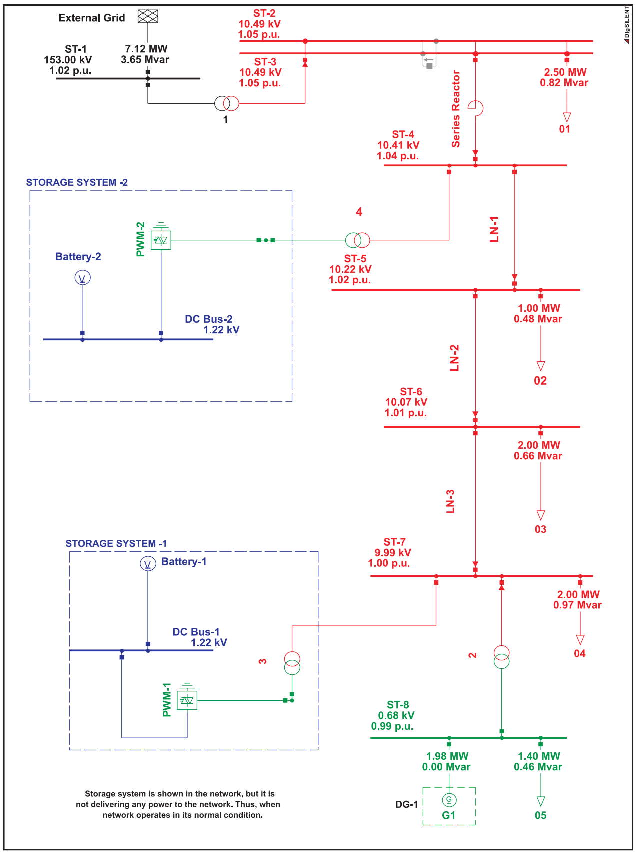

Fig. 1. Load flow results of the test network

From Figure 1, it can be noticed that the test network is of radial configuration and it has power imports at the top and the bottom end of the network. The average load demand of the network is estimated to be approximately 10 MW. Proposed energy storage option is also included in the test network and is indicated in Figure 1.

4. RELIABILITY ANALYSIS

4.1. Basics of reliability analysis

In the recent years, the increased deployment of distributed generations (DG) and their interconnections with the electricity grid have been identified as a means to enhance the electric transmission and distribution system performance and the customer service availability. Power system reliability is defined as to provide electricity to the customers efficiently and with a reasonable assurance of continuity and quality [1]. So, the utility is obliged to provide the power supply which should be continuous and have the voltage and frequency within allowable ranges around the nominal standard values.

4.2. Reliability analysis methods

Reliability analysis methods are broadly categorized in two types: a) deterministic and b) probabilistic method as shown in Figure 2 [3].

Deterministic techniques imply engineering experience and judgment while probabilistic method use statistical approaches to support engineering judgments. This technique

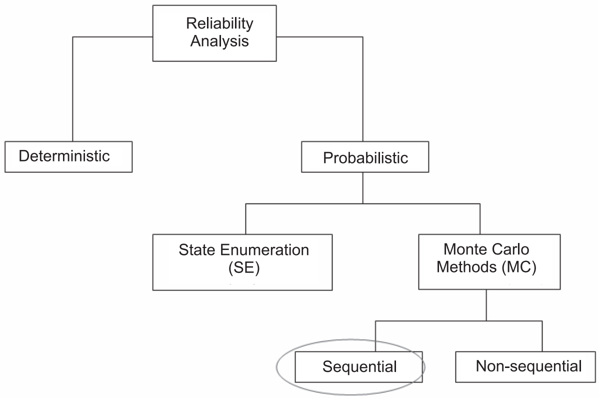

Fig. 2. Reliability analysis methods

is based on historical performance to predict the effects of changing conditions on system performance.

The probabilistic method can be subdivided in two categories: a) State Enumeration (SE) – an analytical technique, b) Monte Carlo (MC) method – a simulation approach. In this paper MC method is considered because of its capability of modeling the full range of network operating conditions. It estimates different reliability indices by simulating the actual processes and the random behavior of the system. One disadvantage of this model is that it requires a large number of simulation events to obtain a realistic result and thus processing time is relatively longer [1].

For complex operating conditions, MC methods are preferable. MC simulation technique can be sub-divided in two categories: sequential and non-sequential technique. In the non-sequential method, states of all components are sampled and a non-chronological system state is obtained. In the sequential approach, up and down cycles of all the components are simulated and a system operating cycle is obtained by combining all the component cycles. Also, the real time chronological load and generation data can be considered in sequential MC method [1], [4]. In this paper, the sequential MC method is chosen for the network simulation.

4.3. Reliability indices

The reliability of power supply to various customer loads is described by three main indicators [3]. The relations among these indices can be interpreted in Figure 3.

— *Average customer interruption frequency in a year (ACIF)* – It is the failure rate of the available supply in a year. It is represented as number of failures/year.

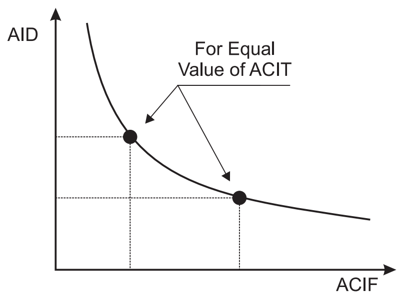

Fig. 3. Relations among the reliability indices

Table 1. Failure rate of network components [9].

Network Component	Failure rate (number of failure per year)	Repair time of component for each failure (hours)	Average duration of supply restoration (hours)
150 kV high voltage busbar	0.1	4.0	1
10 kV double busbar	0.02	4.0	1
10 kV single busbar	0.0126	4.0	1
Substation transformer (150/10kV)	0.025	10.0	2
Step down transformer (MV/LV)	0.011	10.0	2
Cable (all types) per 100 km	1.19	4.0	2

— *Average customer interruption duration per year (ACIT)* – It is defined as the total duration of failures in a year and is expressed in hours/year.

— *Average interruption duration for each failure (AID)* – It is the average duration of a failure of the power supply in a year. AID is expressed in number of hours / failure.

4.4. Simulation results

The sequential MC method is used to simulate chronological data of the test network components. This approach moves chronologically through the system states for the whole cycle of system operation. In this paper, it is considered that the simulation period is hundred years, considering 8760 hours for each year. Depending on the availability of network components, the network status is evaluated. It is assumed that during an outage of a network component, DG is switched off for safety and practical reasons. In the simulation, "hourly data" is chosen as the reference time frame for "Power Factory" software. Various failure rates of network components considered in the simulation are shown in Table 1.

It can be noticed from Table 1 that 150kV busbar which is connected to external grid, has higher value of failure rate than other type of busbars. It is because to count the failure events of other networks that might be connected to 150kV grid. The supply restoration times for various components, in Table 1, is assumed to be integer number for simplification of the simulation. In the analysis, it is assumed that an alternative supply or a feeder is present in each part of the test network that provides power supply (within one/two hours of restoration time, depending on fault location), when its parallel branch is out of service due to a failure event.

In this analysis, the storage system is not considered. Various load points reliability indices of the radial test network are calculated in the simulation and the results are shown in Figures 4 and 5. Different load points of the test network are plotted along the horizontal axis. In Figure 4, various ACIT values for different loads are shown along the vertical axis while ACIF values are indicated in Figure 5 along the vertical axis.

It can be noticed from Figures 4 and 5 that the upstream customer load points that are near to the external grid suffer less frequent and lesser duration of power supply interruption than the downstream loads. In this study, the DG is switched off due

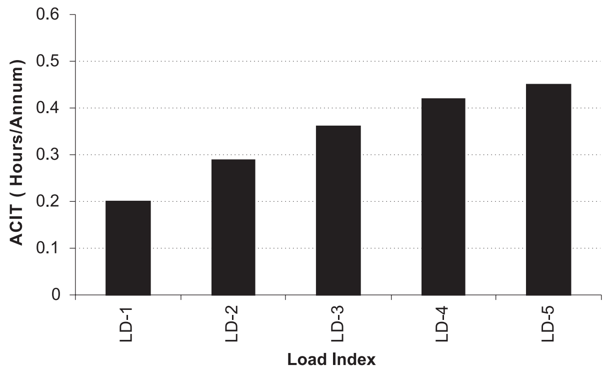

Fig. 4. ACIT for various loads

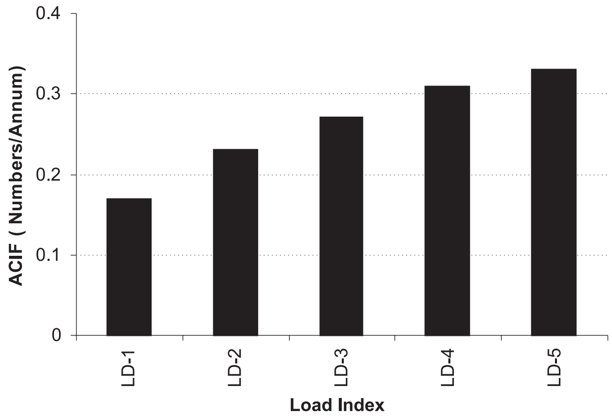

Fig. 5. ACIF for various loads

to the safety requirement of wind turbine during a failure event of a network component. Thus, the presence of DG does not have any additional impact on the network reliability.

5. VOLTAGE QUALITY

5.1. Definition and characterization

Voltage quality can be described in terms of magnitude and waveform distortion of the three phase supply voltages. The electricity utility is responsible to provide good quality voltage to the customers.

Due to the increasing use of sensitive customer devices, the operation of modern equipment is highly vulnerable to supply voltage quality. Also, the increased growth of DG and their integration in the network, the grid voltage quality can be affected significantly. In Figure 6, various voltage quality issues defined in the European standard EN 50160 are presented.

Voltage quality is a very broad area for research. To limit the present scope, only various types of supply voltage interruptions are focused in this paper.

5.2. Interruptions

In EN 50160 standard, an interruption occurs whenever the supply voltage drops below 1% of the rated voltage. Various types of interruptions are classified in Fiure 7.

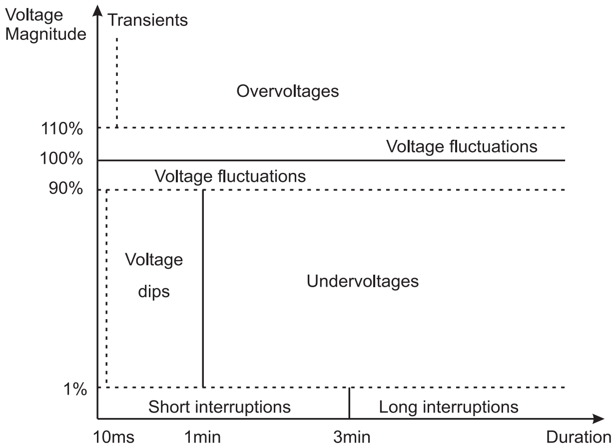

Fig. 6. Definition of voltage quality as per EN50160

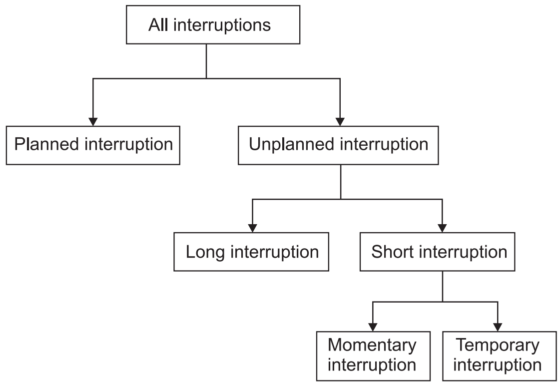

Fig. 7. Classification of interruptions

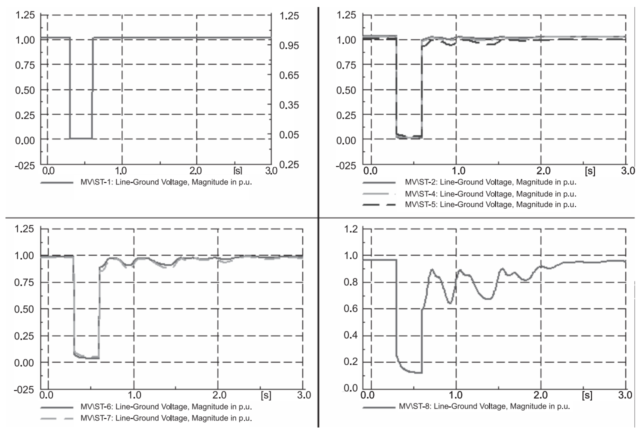

Fig. 8. Voltage profile of busbars for first case study

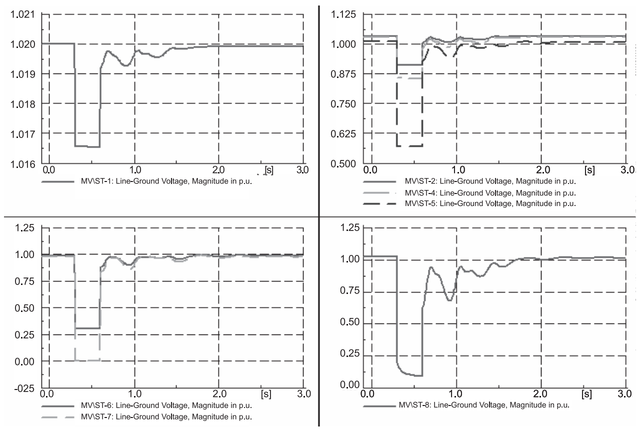

Fig. 9. Voltage profile of busbars for second case study

From Figure 7, it can be shown that interruptions can be broadly categorized in two types: planned and unexpected interruptions. Planned interruptions are generally defined as those where customers have been given in advance notice with a corresponding minimum notice period. An unexpected interruption is that which could not be avoided (an accidental case) and where advance notice could not be provided within the required notice period. It can also be divided in two types: long and short interruptions [3].

An interruption up to three minutes is called a "short interruption" and when the interruption duration is more than 3 minutes, it is called "long interruption". A short interruption can be of two types: momentary and temporary interruptions. A "momentary interruption" is a very short loss of utility power that lasts up to two seconds, usually caused by the utility switching operations to isolate a nearby electrical problem. A "temporary interruption" is a loss of utility power lasting from two seconds to less than three minutes, caused by a nearby short circuit due to something like animals or accidents.

The concerns created by interruptions are evident and include inconvenience, loss of production time, and loss of service to critical facilities. In this paper, three phase short circuit faults in the test network components are studied and the influence of DG on the network voltage is analysed.

5.3. Simulation results

It is found from the statistics that the medium voltage (MV) network has relatively large contribution to the average customer interruption duration in a year with respect to the high and low voltage networks. This is due to a huge number of nodes and branches with feeders and load points connected to the medium voltage network. Also, it can be found that the majority of MV faults occur in the cable and its accessories [5].

To study the voltage profile of the network during a short circuit event in test network, two case studies are done: a) a three phase short circuit at 150kV busbar (ST-1) for 300 millisecond (msec) and b) fault at 10kV line LN-3 (close to busbar ST-7), for a duration of 300 msec. For both cases, it is assumed that after the fault is cleared, the system restores back its power supply and network configuration remains unchanged. This analysis is done without storage system in test network. Each simulation is done for 3 second.

The simulation results of the first case study are shown in Figure 8. Various busbar voltages are represented in per unit (p.u) and are plotted along the vertical axis while the simulation interval is shown along the horizontal axis.

It can be noticed from Figure 8 that the busbar voltage of ST-1, at which the fault is simulated, falls to zero during the failure interval. The voltages of other busbars are in the range of 2–18% of their nominal value. The voltage of busbar ST-8 is the maximum during the fault interval as it is located furthest from the fault point.

In Figure 9, the simulation results of the second case study are shown. Various busbar voltages (in p.u) are plotted along the vertical axis while the simulation interval (in sec) is shown along the horizontal axis.

For this case, the fault is occurring close to busbar ST-7 and so it can be noticed from Figure 9 that ST-7 busbar voltage falls to zero during failure interval. The ST-8 busbar, which is also close to fault point, has a voltage of 15% of its nominal value during the fault interval. The other busbar voltages vary in the range of 30–90% of their nominal values depending on their relative distances from the fault point. The 150kV busbar ST-1 has hardly any effect during this failure event as it is connected to a strong external grid.

5.4. Consequences on customer's loads

From the simulation results of the previous section, it can be noticed that the voltages of various busbars suffer a deep voltage dip during a failure event in the network which in turn can effect the operation of customer loads.

When a busbar voltage falls below a certain level, the customer suffers a superficial voltage interruption at his load terminal. It is because of the fact that the customer has different kinds of loads at his connection point, which may have different voltage sensitivity for their operation. Some of the loads, especially motor loads, can sustain voltage dip up to 50% whereas electronic loads are much more sensitive to the voltage dip and most of the time can sustain a voltage dip of only 20% of their nominal value. Voltage sensitivity of some of the customer loads is presented in Table 2. The abbreviations used in Table 2 for "Vmin" means the threshold voltage that a device should have continuously at its terminal to operate correctly. "Tmax" means the maximum time interval during which a device can operate with its terminal voltage below "Vmin."

From Table 2, it can be seen that when a 3.7 kW ac drive is connected to a busbar in an electrical network, it has a voltage tolerance limit of Vmin 75% with Tmax of 50 msec. It means that the ac drive can withstand any voltage lesser than 75% of the nominal voltage for a maximum period of 50 msec and more than 75% of nominal voltage for indefinite period. So, any voltage dip longer than 50 msec and deeper than 25% of the nominal value will lead to tripping or malfunction of the ac drive. Thus, if an ac drive is connected to a busbar of the test network that has a fault voltage lesser than 25% of nominal value, the drive operation will be interrupted during the fault event. Also, the fault should be cleared by the fast acting protective devices to limit the voltage dip of various busbars and the load power supply interruption [3].

Table 2. Voltage tolerance of customer devices [2].

Equipment	Equipment's tolerance limit (Average)		Allowable voltage dips (continuous)
	V_{min}	T_{max}	Average
PLC (programmable logic controller)	60%	260 msec	40%
3.7 kW ac drive	75%	50 msec	25%
Ac control relay	65%	20 msec	35%
Motor starter	50%	50 msec	50%
Personal computer	80%	30 msec	40%

6. STORAGE SYSTEM

6.1. Overview of electricity storage system

Looking to the future, the success of sustainable energy based DG, in terms of market penetration, may depend on integrating energy storage to provide energy delivery for meeting specific load requirements. Electricity storage can be viewed as a multi purpose tool to improve network operation.

A storage system can be used in the transmission and distribution networks, ancillary services and the end use applications for short duration power demand of relatively low rating. On the contrary, the storage systems used for generation and load demand management are mainly for longer duration and are rated for several hours with high power delivery capacity. In Figure 10 various applications of an electricity storage system are described.

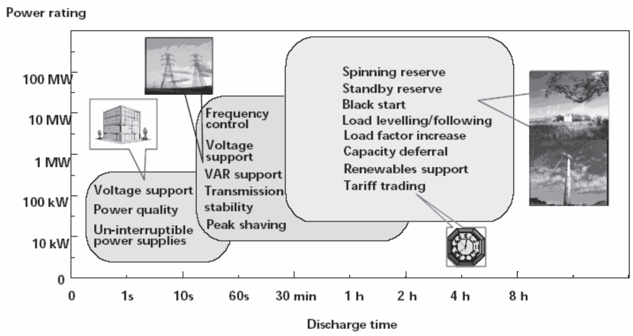

Fig. 10. Applications of electricity storage system [6]

Storage systems can be classified by construction technology, power rating and application purposes.

For this research, it is noticed from the Table 1 that the failure interval of a network component is on an average two hours. The average load demand of the test network is found 10 MW. It was found from the literature that sodium sulphide (NaS) energy storage technology is the most appropriate for this test network [7, 8]. NaS storage system serves efficiently for the power as well as the energy demand applications.

6.2. Modeling of NaS storage system

NaS storage system has some advantages over the conventional battery storage system. It has following main features which are important for modeling aspects [8]:

- Peak shaving (PS) and power quality (PQ) support.
- Superior energy density and small footprint.
- Environment friendly, insensitive to ambient temperature.
- Long life (minimum 15 years).
- High efficiency and less maintenance.
- No self discharge and no memory effect.
- Very fast response – full power charge to discharge in 1msec. Typical discharge characteristic of a 50 kW NaS storage system is shown in Figure 11.

In this research, two storage systems are chosen for the test network: one 4 MW storage system near to the end of network (at busbar ST-7) and another storage system of 2 MW

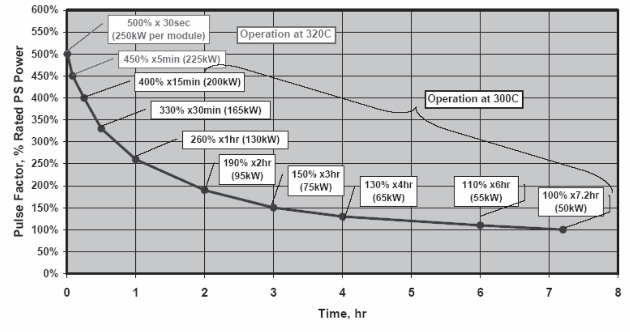

Fig. 11. Discharge characteristic of a 50 kW NaS battery [8]

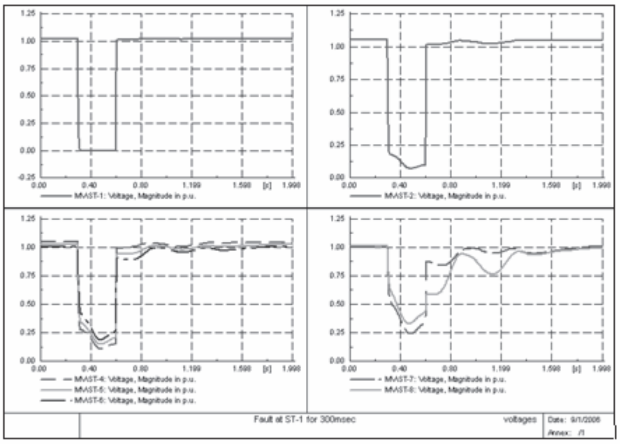

Fig. 12. Voltage profile of test network with storage system

close to the 150kV grid connection (at ST-4 busbar). From the discharge characteristic of NaS storage system, it can be found that total 6MW storage system is capable of supplying 10 MW load demand for 2 hours continuously. Each storage system is modeled as a DC voltage source along with a PWM inverter as shown in Figure 1.

6.3. Simulations results

A three phase fault of 300 msec duration is simulated at 150kV busbar ST-1 of the test network to study the influence of storage system on the network's voltage quality. The various busbar voltage profiles are shown in Figure 12 (along the vertical axis and are represented in p.u). The simulation is done for 2 sec and is plotted along the horizontal axis of Figure 12.

It can be noticed from Figure 12 that the various busbar voltages are in the range of 8–35% of the nominal voltages. Thus, the overall network voltage profiles are improved by the implementation of the storage systems in the network in comparison to Figure 8 and Figure 9.

It is also observed from the simulations that storage system is unable to provide complete voltage support during a short circuit event. So, the supply to most of the load points is interrupted during the fault interval. But after the fault is cleared, the storage system can support all the load demands for two hours and hence the load power supply interruption duration can be minimized.

7. CONCLUSIONS & RECOMMENDATIONS

From the various simulations on the test network, the following conclusions are drawn:

- A storage system in a hybrid grid augments the performance of a DG. The overall reliability of the network improves.
- Sustainable (wind based) DG alone contributes very less on improving the voltage quality of a network during a short circuit event.
- The storage system improves the busbar voltages during a fault which might however not always be enough to enhance the voltage quality of the network.
- Reliability analysis using "Monte Carlo" method is found to be efficient and suitable for analysis of time variant load and generation model and storage system in the network.
- Customer reliability indices in terms of power supply interruption are lower for upstream components than that of downstream components of a radial network (under the assumption that each feeder section is separately protected).
- NaS storage system can support both short and long duration power demands.
- Fast acting protective devices are required for achieving high benefits from the hybrid grid.

While conducting this research, it was observed that further study can be done on the following interesting areas:

- Reliability analysis considering DG can perform in island operation when an outage event occurs in the network.
- Influence of more DG in a weak grid during the short circuit event in the network component.
- Detailed analysis of equipment's voltage-tolerance curves to predict the customer loads reliability indices.
- Detailed modelling of a storage system including battery management philosophy for grid-connected and island operations.

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