World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:3, No:6, 2009

On the Reliability of Low Voltage Network with Small Scale Distributed Generators

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Open Science Index, Electrical and Computer Engineering Vol:3, No:6, 2009 publications.waset.org/3530.pdf

***Abstract*—**Since the 80s huge efforts have been made to utilize renewable energy sources to generate electric power. This paper reports some aspects of integration of the distributed generators into the low voltage distribution networks. An assessment of impact of the distributed generators on the reliability indices of low voltage network is performed. Results obtained from case study using low voltage network, are presented and discussed.

***Keywords*—**low voltage network, distributed generation, reliability indices

I. INTRODUCTION

IN the last 20 years the power system industry witnessed an important change in the conventional centralised paradigm of operation as a result of a large scale integration of distributed generation (DG) either at the medium voltage (MV) or at the low voltage (LV) distribution levels. In the last years this change became perceptible mainly due to the connection of large amount of generators at the MV level. In the years to come such a scenario is also going to happen in LV grids through the interconnection of small modular generation sources forming a new type of power system, the MicroGrid. The MicroGrids can be connected to the main power network or be operated autonomously if they are isolated from the power grid.

In terms of currently available technologies, the micro generation systems can include several types of devices as fuel cells, renewable generation as wind turbines or PV systems, micro turbines powered by natural gas or biofuells. One of the most promising applications of this new concept corresponds to the combined heat and power (CHP) applications leading to an increase of the overall energy effectiveness of the whole system.

New scenario of operation requires the development of applied research at several levels to benefit from the capabilities that these devices offer and develop efficient strategies to manage the MicroGrids.

Among others issues this includes micro source electrical modelling, power system LV operational impact analysis, monitoring control, power quality and network reliability, protection co-ordination and personal safety, communications, economical and electrical market driven procedures and finally definition of new interconnection standards.

Various investigations showed that DGs integrated into utilities' DNs could affect the host DNs in number of ways [1]÷[10]. Several papers reported the integration aspects of small DGs into the low voltage (LV) distribution network [3], [4], [7], [8], and [9]. The experience has shown that the integration of small DGs into DNs could create safety and technical problems. They may contribute to fault currents, produce voltage flickers, interfere with the process of voltage control, increase losses, deteriorate reliability of the system etc.

The objective of this study is an assessment of the impact of the DGs on the reliability indices of the LV network with small scale DGs. Results obtained from several case studies using real-life LV, are presented and discussed.

The paper is organised as follows: Section II describes the methodology applied for reliability assessment of the LV distribution network with DGs. In Section III a description of the test network is given, whereas in Section IV the results of various simulations with/without DGs are presented and discussed. Conclusions are given in the section V.

II. BACKGROUND

One of the integration aspects of small DGs into the low voltage (LV) distribution network is reliability analysis. The load point reliability study includes the following basic indices for each customer in the system: Mean time between failure (MTBF), Failure rate, Mean time to failure (MTTF), Annual outage time (total hours of downtime per year), Average outage time (MTTR), Annual availability, Expected energy not supplied per year (EENS), and Total damage cost in k$ per year due to failures (ECOST).

The system reliability indices, based on the basic indices are: System Average Interruption Frequency Index (SAIFI) (interruptions/customer-yr), System Average Interruption Duration Index (SAIDI) (hours/ customers-yr), Customer Average Interruption Duration Index (CAIDI) (hr/customer interruption), Average Service Availability Index (ASAI) and Average Service Un-Availability Index ASUI [11]. To calculate the load point reliability indices as well as system reliability indices, equipment failure rate and restoration time for each component including DG units have to be known.

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III. TEST NETWORK

Test network is a 0.4 kV real-life cable feeder consisting of 9 buses, 13 residential loads, 16 protection devices (LV switch 355-1000 A, 100 kA, in the substation and fuses in the bases), as well as 7 small synchronous DGs of CHP type, Total feeder length is 311 m. Fig. 1. Loading data are given in TABLE I, while network data including utility and DG contribution are given in TABLE II. The loading system as well as the generaton output is three-phase balanced. The total system loading is 169 kVA, with unity power factor and 0.4 loading factor, simulating night loading of the system, which enables power export of CHP units to the grid. Reliability data of the test system including utility, DGs, loads and cables, are given in TABLE III.

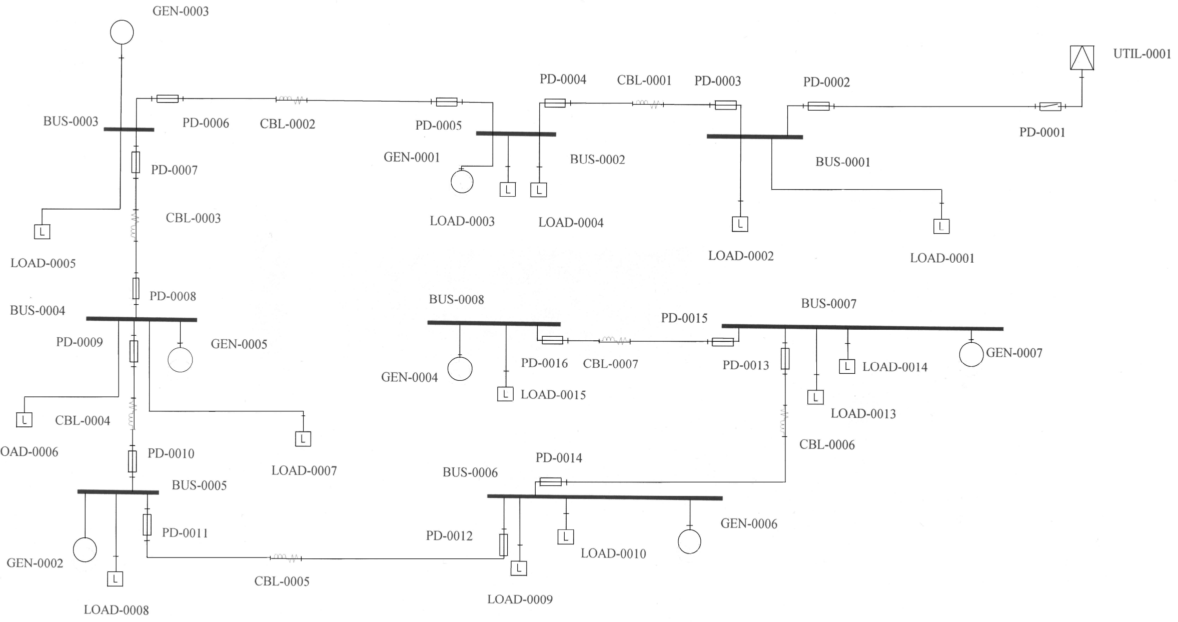

Fig. 1 Active low voltage distribution network.

TABLE I
THREE-PHASE SYSTEM LOADING

Load Name	Bus name	Load (kVA)	Load type
Load 0001	BUS 0001	20	heat unity
Load 0002	BUS 0001	12	general loads, rectifier unit
Load 0003	BUS 0002	14	general loads
Load 0004	BUS 0002	10	general loads, rectifier unit
Load 0005	BUS 0003	10	general loads
Load 0006	BUS 0004	14	general loads
Load 0007	BUS 0004	15	general loads, rectifier unit
Load 0008	BUS 0005	18	general loads
Load 0009	BUS 0006	10	general loads, rectifier unit
Load 0010	BUS 0006	14	general loads, rectifier unit
Load 0013	BUS 0007	15	lighting unit
Load 0014	BUS 0007	9	lighting unit
Load 0015	BUS 0008	8	general loads

TABLE II
SYSTEM DATA

Utility
Three phase contribution : 100 MVA, X/R=8.0
Line to earth contribution: 25 MVA, X/R=8.0
Positive sequence impedance (100 MVA base) = 0.124 + j 0.99 pu
Zero seq. impedance (100 MVA base) = 0.2481 + j 1.98 pu
V=1.00 pu
Synchronous Generator
Rated Voltage 380 V, power factor 0.9 lead, 1500 rpm, Connectrion: wye – ground,
Impedance data: Xd”= Xq”=Xo = 0.1500 pu,
rq = ro = 0.0100 pu,
IEC 61363 Data: Xd'=0.2900, Xd=2.75, Ra=0.0072 pu;
Td"= 26 ms, Td' = 420 ms, Tdc=93 ms
Steady state AC Decay Specification:
Neutral impedance: (0 + j 0) Ohms, Excitation limits: 1.3, Xdsat=1.60 pu, Vg=1.00 pu
Cables
Cooper, PVC Insulation, size 4 x 95 mm2,
Rated current 215 A;
Z_+ / Z- = (0.2431 + j 0.0771) Ohms / 1000 m;
Zo = (0.3865 + j 0.1959) Ohms / 1000 m;

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TABLE III
RELIABILITY DATA

Utility Reliability Data	
Type of circuit	IEEE single circuit
Permanent failure rate	1.9560 failure/year
Restoration time	1.32 hours
DG Reliability Data	
Failure rate	0.0135 failure/year
Restoration time	478 hours
Load Reliability Data	
Failure rate	0.9 failure/year
Repair time	0.9 hours
Replace time	2.0 hours
Cable Reliability Data	
Permanent failure rate	0.08760 failure/year/km
Repair time	7.6 hours
Switching time	0.5 hours

IV. APPLICATION

For the purpose of assessment how DGs affect the reliability of a typical three-phase cable LV network, several case studies are performed. In the first set of simulations, the network is treated as passive one, without DG, while in the second set, the network is considered as an active network, consisting of various numbers of DGs with different rated power. Special consideration was given to the evaluation of the performance of the local system after the fault in the substation was detected and isolated. In such a case the DGs supply the loads in the so called “island operation”.

Firstly, load demand analysis, three-phase power flow and device evaluation calculation in the passive network are performed. The simulation showed that there were no violations considering max voltage drop, cable rating, protection device coordination and arc flash protection. The first objective was to calculate load point reliability indices of the passive network, including Medium Time Before Fault (MTBF), Failure Rate, Average Outage Time (MTTR), Annual Outage Time, Annual Availability, and Expected Energy Not Supplied (EENS). Results of reliability study are presented in the TABLE IV. Calculated indices in the passive network are: EENS=1409.16 kWh/year, SAIFI=7.2026, interruptions/customer-yr, SAIDI=8.45 hr/customers-year), CAIDI =1.17 hr/customer interruption, ASAI=0.999036, and ASUI=0.000964.

In the next study the number of DGs and their rated power were varied and the impact on the reliability indices was observed, see TABLE V. The overall system performance indices such as DG contribution, max voltage drop, total system losses and feeder current reserve, are investigated. Obtained optimal DG commitment was in range of (0.12 ÷ 0.23) of total rated DG power, according to the objective function (minimizing generator cost).

The reliability study was firstly performed in the network with 7 DGs (10 kVA each) and the following indices were obtained: EENS=1629.25 kWh/year, SAIFI=8.0388 interruptions/customer-year, SAIDI=9.77 hr/customers-year), CAIDI =1.21 hr/customer interruption, ASAI=0.998885, and ASUI=0.001115. Obviously, all reliability indices are deteriorated. The reliability study was then repeated in the system with seven DGs (80 kVA each) and the results are presented in TABLE VI. Expected Energy Not Supplied (EENS) in such a system is 16.6 kWh/year, which is 85 times better indices comparing to the passive network. Just three of DGs (80 kVA each) significantly improved the EENS of the network (EENS=922.86 kWh/year). As it was expected, connecting 3 DGs (G1, G2 and G3) contribute to improvement of load point reliability indices in the first half of the feeder. However it was not expected to have deteriorated reliability indices in the rest part of the feeder, TABLE VII.

Special consideration in the reliability study was given to the local active network in island operation, after the fault in substation was detected and isolated. The simulation shows that major system performances during the island operation (voltage drop and section currents) were inside the system limits. Besides, protection device evaluation showed that operation of such a local network is safe (protection coordination and arc flash evaluation test have passed). Under these circumstances, seven DGs (30 kVA) in operation keep the EENS of the system very low (258,15 kWh/year), while four DGs (80 kVA) contribute to also very low energy not supplied EENS (311.5 kWh/year), TABLE VII.

Obviously, the proper placement and rated power of DGs can improve the reliability indices in the network even in the emergency regime (island operation). On the other side, large number of DGs with relatively small power contribution can deteriorate overall reliability indices. That is very important conclusion since one of the ambitions of the massive penetration of DGs in the LV network is improving the overall system reliability.

TABLE IV
Reliability analysis in the passive network (EENS=1409.16 kWh/yr)

Load	MTBF (yr)	Failure Rate (f/yr)	MTTR Average Outage Time (hr/yr)	Annual Outage Time (hr/yr)	Annual Availability (%)	EENS (kWh/yr)
Load 0001	0.5106	1.959	1.32	2.58	99.97051	51.67
Load 0002	0.5106	1.959	1.32	2.58	99.97051	31.00
Load 0003	0.2729	3.666	1.20	4.40	99.94973	61.65
Load 0004	0.2729	3.666	1.20	4.40	99.94973	44.03
Load 0005	0.1863	5.372	1.16	6.22	99.92896	62.23
Load 0006	0.1414	7.078	1.14	8.04	99.90827	112.50
Load 0007	0.1414	7.078	1.14	8.04	99.90827	120.54
Load 0008	0.1147	8.730	1.06	9.21	99.89481	165.86
Load 0009	0.0960	10.435	1.21	12.67	99.85541	126.66
Load 0010	0.0960	10.435	1.21	12.67	99.85541	177.32
Load 0013	0.0864	11.593	1.19	13.83	99.84217	207.39
Load 0014	0.0864	11.593	1.19	13.83	99.84217	124.43
Load 0015	0.0753	13.300	1.16	15.48	99.82324	123.87

TABLE V
DG commitment in the active network

DG rated power $S_{DG\ rated}$ (kVA)	7 x 10	7 x 30	7 x 80
DG power output S_{DG} (kVA)	16.2	25.7	79.2
S_{DG} / $S_{DG\ rated}$	0.23	0.12	0.14
Utility power output (kW, kVAr)	152.6 /-10.0	143.6 / -8.3	93.1 / -26.0

TABLE VI
Reliability analysis in the network with 7 DGs (80 kVA); total EENS=16.60 kWh/yr.

Load	MTBF (yr)	Failure Rate (f/yr)	MTTR Average Outage Time (hr/yr)	Annual Outage Time (hr/yr)	Annual Availability (%)	EENS (kWh/yr)
Load 0001	279.7882	0.004	0.57	0.00	99.9999	0.04
Load 0002	279.8717	0.004	0.57	0.00	99.9999	0.02
Load 0003	18.6536	0.054	2.59	0.14	99.9984	1.94
Load 0004	18.6536	0.054	2.59	0.14	99.9984	1.39
Load 0005	18.6545	0.054	2.59	0.14	99.9984	1.39
Load 0006	18.6549	0.054	2.59	0.14	99.9984	1.94
Load 0007	18.6549	0.054	2.59	0.14	99.9984	2.08
Load 0008	18.6549	0.054	0.50	0.00	99.9999	0.01
Load 0009	18.6554	0.054	2.59	0.14	99.9984	1.39
Load 0010	18.6564	0.054	2.59	0.14	99.9984	1.94
Load 0013	18.6554	0.054	2.59	0.14	99.9984	2.08
Load 0014	18.6564	0.054	2.59	0.14	99.9984	1.25
Load 0015	17.0988	0.058	2.53	0.15	99.9984	1.18

TABLE VII
EXPECTED ENERGY NOT SUPPLIED

Load	Regime					
	Passive network (No DG)	Active network G1÷ G7 7 x 10 kVA	Active network G1 ÷ G7 7 x 80 kVA	Active network (G1,G2,G3) 3 x 80 kVA	Island operation G1,G3,G5,G7 4 x 80 kVA	Island operation G1÷ G7 7 x 30 kVA
	EENS (kWh/yr)					
Load 0001	51.67	67.87	0.04	0.04	151.55	151.55
Load 0002	31.00	43.00	0.02	0.02	93.15	93.15
Load 0003	61.65	61.65	1.94	1.94	2.01	2.01
Load 0004	44.03	64.03	1.39	1.39	1.44	1.44
Load 0005	62.23	78.23	1.39	1.39	1.39	1.39
Load 0006	112.50	137.70	1.94	2.06	1.94	1.94
Load 0007	120.54	134.04	2.08	2.21	2.08	2.08
TABLE VII continued	Passive network (No DG)	Active network G1÷ G7 7 x 10 kVA	Active network G1 ÷ G7 7 x 80 kVA	Active network (G1,G2,G3) 3 x 80 kVA	Island operation G1,G3,G5,G7 4 x 80 kVA	Island operation G1÷ G7 7 x 30 kVA
	EENS (kWh/yr)					
Load 0008	165.86	201.86	0.00	0.15	0.21	0.0
Load 0009	126.66	153.66	1.39	160.35	1.55	2.08
Load 0010	177.32	215.12	1.94	224.50	2.17	1.94
Load 0013	207.39	219.54	2.08	229.58	2.29	2.08
Load 0014	124.43	128.03	1.25	134.06	1.39	1.25
Load 0015	123.87	124.25	1.18	165.16	50.42	1.18
Total	**1409.16**	**1629.25**	**16.60**	**922.86**	**311.58**	**258.15**

V. CONCLUSIONS

The development of MicroGrids is very promising for the electric power industry considering environmental, operation, investment, power quality and market driven issues. However, the development of MicroGrids still faces several challenges, difficulties and potential drawbacks.

This paper reports reliability aspect of integration of the DGs into the LV distribution networks. The study shows that optimal placement and rated power of the DGs can improve the reliability indices of the LV network even in the emergency regime (island operation). On the other side, large number of DGs with relatively small power contribution can deteriorate overall reliability indices. That is important conclusion since one of the ambitions of the massive penetration of DGs in the LV network is improving the overall system reliability.The real challenge for the future massive integration of the DGs into the LV distribution network will be developing a reliable and efficient MicroGrid Management System integrated with D-SCADA. Besides techno-economical analysis of the MicroGrids, showing the benefits to the system reliability is needed.

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