INVESTIGATION INTO THE POWER QUALITY AND RELIABILITY OF SUPPLY IN THE INDUSTRIAL NETWORKS WITH DISTRIBUTED GENERATION

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ABSTRACT

Various investigations showed that generators integrated into distribution networks could affect the host network in number of ways. This paper reports some aspects of integration of the synchronous generators of various types into the industrial networks. An assessment of impact of the distributed generators on the power quality and reliability of supply in the industrial applications is performed. Results obtained from case study using real-life industrial network are presented and discussed.

INTRODUCTION

Various investigations showed that DGs integrated into the distribution network could affect the host network in number of ways [1]-[9]. Numerous papers reported the technical and economic aspects of integration of DGs into the LV distribution networks. The experience and simulations have shown that the integration of DGs into LV distribution networks could create safety and technical problems.

The objective of this study is an assessment of the impact of the synchronous DGs of various types on the power quality and reliability supply in the industrial LV networks. In order to investigate the impact of DGs on system performance, load demand analysis, optimal power flow and device evaluation calculation, as well as harmonic analysis and reliability analysis in the passive and active network, are performed. Results obtained from several case studies using the real-life industrial network are presented and discussed.

BACKGROUND

The load point reliability study includes the following basic indices for each customer in the system [10]: 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 [10].

To calculate 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.

The *IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters* describes a method to quantify the harmonic distortion in the power system. The term Total Harmonic Distortion (THD) is defined for voltage distortion *V_THD* as follows:

$$V\_THD = \frac{\sqrt{V_2^2 + V_3^2 + .. + V_n^2}}{V_1} \tag{1}$$

where

V_1 is fundamental voltage level in per unit (pu),

$V_2 \ldots V_n$ are harmonic voltage level in pu.

The rms value for voltage is defined by:

$$V_{rms} = \left(\sum V_h^2\right)^{\frac{1}{2}} \tag{2}$$

where

$h_{1,2,3.....n}$ is maximum harmonic order; and

V_h is rms value of each harmonic voltage level.

Similar terms are defined for total branch current distortion *I_THD:*

$$I\_THD = \frac{\sqrt{I_2^2 + I_3^2 + .. + I_n^2}}{I_1} \tag{3}$$

where

I_1	fundamental current in pu,
$I_2, \ldots, I_n$	harmonic current level in pu.

The total rms branch current is:

$$I_{rms} = \left(\sum I_h^2\right)^{\frac{1}{2}} \tag{4}$$

where

I_h is rms value of each harmonic current level.

According to the IEEE Standard 519, current distortion limit for the harmonics of 11th order and lower is 12 %. Total current distortion limit *THD_I* is 15%. Individual voltage distortion limit is 3.0% and the total voltage distortion limit *THD_V* is 5 % for the systems <69 kV.

TEST NETWORK

Test network is a real-life 20 kV / 0.4 kV industrial underground network in Serbia. The network consists of 12 buses, 4 transformer stations 20/0.4 kV/kV, LV motor and non-motor loads and protection devices (MV circuit breaker in the substation, re-closers in the 20 kV buses, LV breakers and fuses), Fig. 1.

Four synchronous DGs are planned to be connected to the 0.4 kV side. The total system loading is 550 kVA with 0.8 power factor-lag. Load and harmonic sources data are given in Table I, while utility and DG contribution data as well as transformers and cable data are given in Table II. The loading system is three-phase balanced. Reliability data including utility, transformers, DGs, loads and cables, are given in Table III.

Several types of synchronous generators are considered: diesel, gas turbine and steam generators. In general, these machines can operate continuously or in the standby mode. In this study, continuous operation of DG units is investigated.

APPLICATION EXAMPLES

For the purpose of assessment how DGs affect the reliability and power quality of the 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 one, consisting of various numbers of DGs. Reliability and power quality analysis is performed by using *SKM® Systems Analysis, Inc* software.

Analysis of Passive Network

Firstly, load demand analysis, three-phase power flow and device evaluation calculation in the passive network are performed. There were no voltage violations and violations regarding cable rating, protection device coordination and arc flash protection.

The first objective of the study was to calculate load points and IEEE reliability indices of the passive network and the results are presented in Table IV. The second objective of the study was to analyse power quality in the passive network. The simulations show there was a violation of voltage and current high harmonics limits induced by loads which are the source of high harmonics (THD > 5%). The total voltage harmonic distortion *THD_V* was in the range (0.16-5.98) % with the maximum value observed in BUS 0006 due to AC drive.

The total current harmonic distortion *THD_I* is much higher, which was expected since the study case is typical industrial application. The total current harmonic distortion is especially highlighted in CBL 0003 (61.1 %) and CBL 0002 (32.6 %), see Table V. Transformer 20/0.42 kV XF2-0002 reduces the level of current harmonic distortion on the 20 kV side for almost 50 %. The total current harmonic distortion *THD_I* in the 20 kV bus bar in the substation is 24.6 % which is above the limit.

Analysis of Active Network

Obtained optimal DG commitment in the active network with four DGs was in the range of (10-14) % of the rated DG power, according to the objective function -minimizing generator cost. Total exported real power from the DGs is 72.8 kW while the exported reactive power from the DGs to the grid is 142.5 kVAr, see Table VI. The DGs in the considered case study reduced power losses, improved voltage profile and reactive power balance, and increased current reserve of the LV cables and MV feeder. However the DGs increased fault level and arc flash protection level.

The reliability study was performed in the network with one, two, three and four DGs in operation and the results are presented in Table VII. With the GEN 0001 connected to the BUS 0012, Expected energy not supplied (EENS) was 2501.7 kWh/year, which is 10 % more than in the passive network. Besides, all reliability indices deteriorated. The reliability study was repeated in the system with GEN 0001 and GEN 0002 (BUS 0003) operated and EENS in such a system was 4339.9 kWh/year. The reason for such deteriorating of system reliability is the connecting of gas turbine generator GEN 0002 in BUS 0003, with high failure rate (1.7276 failures per year).

Three DGs connected to the system (GEN 0001, GEN 0002 and GEN 003) improved the EENS comparing to the passive one for 26 % (EENS= 1654 kWh/year). The improvement of the reliability indices comes from the low failure rate of the steam generator GEN 0003 connected to the BUS 0006 (0.0135 failure/year). Connecting the fourth unit, gas turbine generator GEN 0004 to the BUS 0009, decreased EENS to 456.7 kWh/year, which is about five times less comparing to the passive network. Besides, all reliability indices were improved. Load point reliability indices in the network with 4 DGs are presented in Table VIII.

The next objective of the study was to evaluate power quality in the active network. The impact of four DGs on the total harmonic distortion *THD_V* was positive.

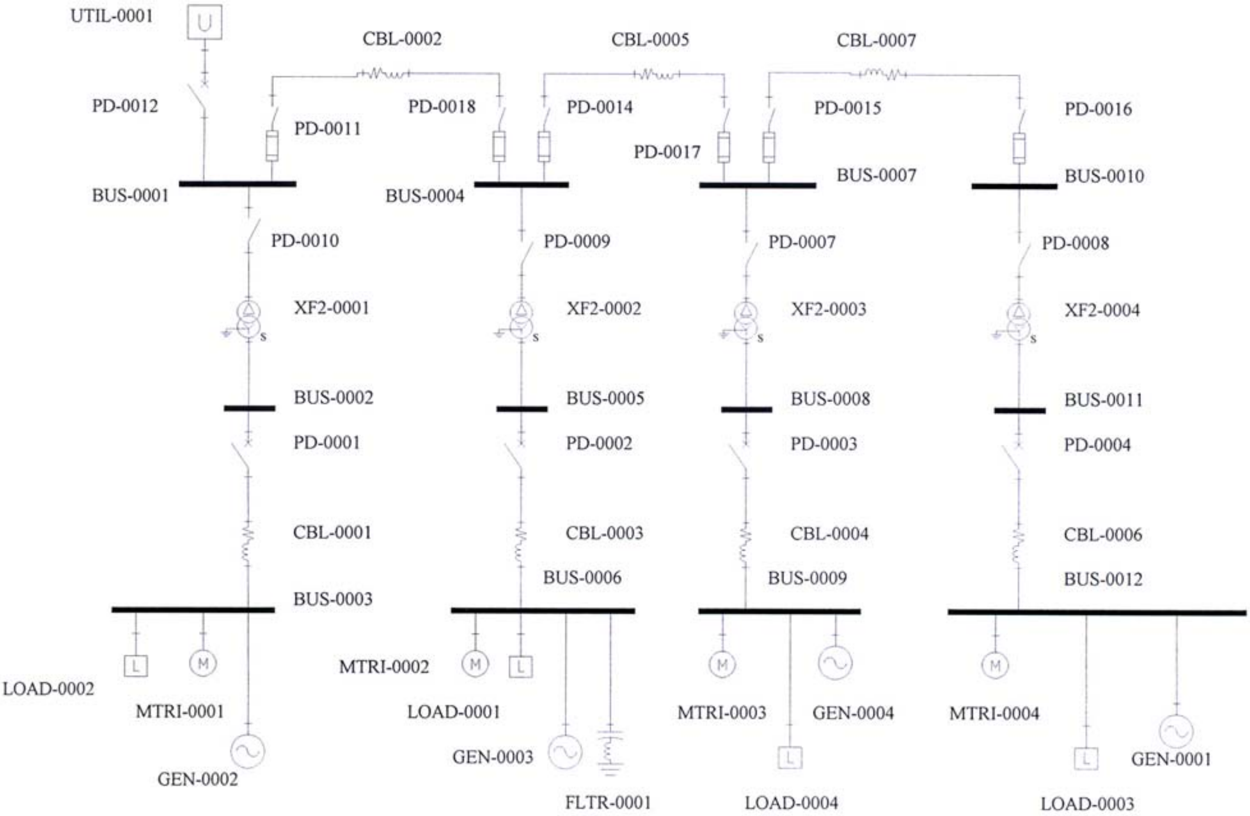

Fig. 1. Industrial distribution network.

TABLE I.
THREE-PHASE SYSTEM LOADING AND HARMONIC SOURCES

Load	Bus name	Load (kVA)	Number of customers	LF Current (A)	Harmonic source	THD %
Load 0001	BUS 0006	95	10	134.6	AC Drive	104.3
Load 0002	BUS 0003	45	12	63.5	ARC Furnace	7.27
Load 0003	BUS 0012	65	11	92.3	IEEE 6 Pulse	21.46
Load 0004	BUS 0009	75	14	104.8	IEEE 12 Pulse	6.53
MTRI 0001	BUS 0003	60	1	84.7	Induction motor - 6 pulse Dobinson	30.13
MTRI 0002	BUS 0006	70	1	99.1	Induction motor - IEEE 12 Pulse	6.53
MTRI 0003	BUS 0009	95	1	132.8	Induction motor - Six pulse classical	25.27
MTRI 0004	BUS 0012	45	1	63.9	Induction motor - IEEE 6 Pulse	21.46

TABLE II.
SYSTEM DATA.

Utility
Base voltage 20000 V
Three phase contribution : 500 MVA, X/R=0.125
Line to earth contribution: 150 MVA, X/R= 0.125
Positive sequence impedance (100 MVA base) = 0.024807 + j 0.198456 pu
Zero sequence impedance (100 MVA) = 0.033076 + j 0.264607 pu
Synchronous Generators
S_1=500 kVA, diesel
S_2=350 kVA, gas turbine
S_3=250 kVA, steam
S_4=150 kVA, gas turbine
Rated Voltage 420 V, power factor 0.9 lead, 1800 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
Transformers
20000/420 V/V,
Sr=1000 kVA
Primary full load amps 28.9 A
Secondary full load amps 1376.4
Tap 1.25 %
Connectrion: delta / wye – ground,
Impedance data:R_+=1. 0 %, X_+=5.6623 %,R_0=1.0 %, X_0=5.6623 %
LV Cables
Cooper, Insulation XLP4, size 4 x 95 mm2 + ground 25mm2
Rated current 215 A
Total length 299 m
Race Way Type Non - Magnetic
Z_+ / Z_- = (0.2431 + j 0.0925) Ohms / 1000 m
Zo = (0.3865 + j 0.2350) Ohms / 1000 m
MV Cables
Cooper, XLP1 Insulation, size 3 x 95 mm2 +ground 95 mm2
Rated current 335 A
Total length 1230 m
Race Way Type Non - Magnetic
Z_+ / Z_- = (0.2461 + j 0.1374) Ohms / 1000 m
Zo = (0.3912 + j 0.3496) Ohms / 1000 m.

TABLE III
RELIABILITY DATA

Utility	
Type of circuit	IEEE single circuit
Permanent failure rate	1.9560 failure/year
Restoration time	1.3 h

TABLE III continuation

DGs	
GEN 0001	Diesel
Failure rate	0.1235 failure/year
Restoration time	18.3 h
GEN 0002	Gas turbine
Failure rate	1.7276 failure/year
Restoration time	27.4 h
GEN 0003	Steam
Failure rate	0.0135 failure/year
Restoration time	478 h
GEN 0004	Gas turbine
Failure rate	0.1870 failure/year
Restoration time	6.2 h
Transformers	
Failure rate	0.0030 failure/year
Repair time	342.0 h
Replacement time	10.0 h
Cables MV	
Permanent failure rate	0.02011 failure/year/km
Repair time	19.0
Switching time	0.5
Cables LV	
Permanent failure rate	0.00659 failure/year/km
Repair time	11.2 h
Switching time	0.5 h

TABLE IV
RELIABILITY ANALYSIS OF PASSIVE NETWORK; TOTAL EENS= 2249.1 KWH/YR.

Load	Failure rate (f/yr)	MTTR Average outage time (hr)	Annual outage time (hr/yr)	Annual availability (%)	EENS kWh/yr
LOAD 0001	3.582	1.70	6.09	99.93046	462.96
LOAD 0002	2.851	1.62	4.63	99.94717	166.62
LOAD 0003	2.851	1.50	4.28	99.95114	222.58
LOAD 0004	3.583	1.39	5.00	99.94295	299.83
MTRI 0001	2.851	1.62	4.63	99.94717	222.15
MTRI 0002	3.582	1.70	6.09	99.93046	341.13
MTRI 0003	3.583	1.39	5.00	99.99295	379.79
MTRI 0004	2.851	1.50	4.28	99.95114	154.09

Namely the DGs decreased the total voltage distortion *THD_V* from 5.98 % to 4.99 %. However, the total current harmonic distortion limits *THD_I* were violated. The GEN 0003 in the BUS 0006 reduced the rms current in the CBL 0003 for 21 %, but increased the total harmonic distortion *THD_I* from 61.1 % to 66.6 %. That happens due to interference between the DGs and the sources of harmonic distortion.

In order to reduce the *THD_I* in the network, RLC filter FLTR-0001 in BUS 0006 (Qc=125 KVAr, *THD_I*=77.1 %) tuned to 5th harmonic order, was applied. The filter reduced *THD_V* in the BUS 0006 to 0.97 %, and kept the max *THD_V* on 1.79 % in the BUS 0003. With the filter in BUS 0006, the total current harmonic distortion *THD_I* in the 20 kV bus bar was reduced to 11.5 % which is under the limit (15 %). The total current harmonic distortion *THD_I* in the CBL 0003 was reduced to 12.4 %. Current distortion in the network with four DGs and the filter is presented in Table IX. To keep harmonic distortion *THD_I* under the limit, filters in all load buses should be applied.

TABLE V

CURRENT DISTORTION IN PASSIVE NETWORK, WITHOUT A FILTER

Bus name from	Bus name to	Device name	Voltage (V)	I_THD (%)	IEEE-519 (%)
BUS 0001	BUS 0002	XF2-0001	20000/420	16.09	15.0
BUS 0001	BUS 0004	CBL-0002	20000	32.62	15.0
BUS 0005	BUS 0006	CBL - 0003	420	61.09	15.0
BUS 0011	BUS 0012	CBL-0006	420	21.46	15.0

CURRENT DISTORTION IN THE NETWORK WITH 4 DGS AND FILTER FLTR-0001

Bus name from	Bus name to	Device name	Voltage (V)	I_RMS (A)	I_THD (%)
BUS 0002	BUS 0003	CBL-0001	420	102.16	19.92
BUS 0008	BUS 0009	CBL-0004	420	221.99	16.55
BUS 0011	BUS 0012	CBL-0006	420	89.04	28.75

TABLE VI

PERFORMANCE OF ACTIVE NETWORK (4 DGS)

	Pg (kW)	Qg(kVAr)	Sg(kVA)	Sg/Sgr(%)
GEN 0001	27.0	65.8	71.1	14.2
GEN 0002	14.9	44.9	47.3	13.5
GEN 0003	24.8	18.1	30.7	12.3
GEN 0004	6.1	13.7	15.0	10.0
Total GEN	72.8	142.5	164.1	-
UTIL 0001 (kW, kVAr)		P = 371.4	Q = 64.6	
Max VD %		2.1 (BUS 0012)		

TABLE VII

EXPECTED ENERGY NOT SUPPLIED (EENS) KWH/YEAR

Load	Regime				
	Passive network	Active network G1	Active network G1+G2	Active network G1+G2+G3	Active network G1+G2+G3+G4
LOAD 0001	462.96	657.38	488.02	78.33	78.49
LOAD 0002	166.61	163.88	38.01	39.96	38.74
LOAD 0003	222.58	53.41	54.03	54.08	53.42
LOAD 0004	299.83	431.28	341.67	456.65	61.57
MTRI 0001	222.15	218.51	50.25	51.10	51.65
MTRI 0002	341.13	484.39	2963.93	57.76	57.84
MTRI 0003	379.79	546.29	546.29	1199.73	77.99
MTRI 0004	154.09	36.97	37.41	37.44	36.98
Total	**2249.1**	**2501.7**	**4339.9**	**1656.4**	**456.7**

TABLE VIII

LOAD POINT RELIABILITY INDICES OF ACTIVE NETWORK (4 DGS); TOTAL EENS= 456.7 KWH/YR.

Load	Failure Rate (f/yr)	MTTR Average Outage Time (hr)	Annual Outage Time (hr/yr)	Annual Availability (%)	EENS kWh /yr
LOAD 0001	0.005	197.45	1.03	99.98821	78.49
LOAD 0002	0.020	54.04	1.08	99.98772	38.74
LOAD 0003	0.004	291.37	1.03	99.98827	53.42
LOAD 0004	0.003	314.80	1.03	99.98829	61.57
MTRI 0001	0.020	54.04	1.08	99.98772	51.65
MTRI 0002	0.005	197.45	1.03	99.98821	57.84
MTRI 0003	0.003	314.80	1.03	99.98829	77.99
MTRI 0004	0.004	291.37	1.03	99.98827	36.98

TABLE IX

CONCLUSIONS

This paper reports important aspects of integration of distributed generation into the industrial networks - power quality and reliability of supply. The simulations show that proper choice and placement of the DGs can significantly improve the reliability indices in the industrial networks. On the other side, the DGs with relatively small power contribution and high failure rate can deteriorate overall reliability. This is important conclusion since one of the ambitions of the high penetration of DGs in the LV network is improving the overall system reliability.

The DGs in the considered network decreased the total voltage distortion improving the overall power quality. Besides, the DGs decreased rms currents in the LV cables and contributed to reactive power compensation. However the DGs increased the total harmonic distortion *THD_I* in the LV network.

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