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Photovoltaic Renewable Energy Systems for Power Quality Improvement of Distribution Networks

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Abstract-- The present paper aims to improve the power quality of Distribution Network using decentralized photovoltaic renewable energy systems. A control technique for controlling the active and reactive power of PVs through power electronic converters is designed. The essential feature of the proposed control technique is that, the reactive power as a function of bus voltage relation called Q(U) is built and utilized. The objective of PV active and reactive power regulation is to minimize Distribution Network power losses and to achieve the bus voltage level stability. The effect of penetration level of PVs on power losses and voltage regulation is studied. The studied electrical Distribution network consists of eight MV buses and nineteen LV buses with PV Renewable Energy Systems. Also, the Distribution Network has both underground cables and Over Head Transmission line systems. The Distribution Network with the proposed control technique is simulated over a wide range of operating conditions using DIgSILENT Power Factory Software.

The network performance is tested over a wide range of loading factors and different ratings of PV renewable energy sources through different scaling factors. The digital simulation results show that the power quality of Distribution Network is improved in terms of power losses minimization and bus voltage regulation.

Keywords- decentralized generators, distribution network, renewable energy system, reactive power control, energy losses, and voltage profile.

I. INTRODUCTION

The distributed generation (DG) units like photovoltaic (PV), Wind, Diesel engine, Fuel cell etc., has many advantages [1]. Inserting of DG in the distribution network can cause loss reduction, voltage regulation enhancement and voltage stability improvement. [1-4]. The optimal performance of DG units was determined for minimal loss and allowing all bus voltage level within permissible limits. There are disadvantages with connection of DG in distribution network such as overvoltage conditions and increasing grid loss. [2-5]. Therefore, it could reasonable to integrate adequate value of DG to the utility grid at appropriate locations to improve the voltage profile, voltage stability enhancement and reducing active and reactive losses. [6-9]. To achieve the distribution network optimal performance, there are reactive power control devices and storage systems can be utilized with DG units. The reactive power (VAR) control with characteristics of fast response may be based on the use of reliable high-speed power electronics, analytical tools, and modern control techniques [10-14].The reactive power management of the DG can play a role in the distribution network voltage profile as well as in the network losses in medium voltage MV and low voltage LV network [15-19].The present article reviews the benefits of penetrating renewable DG units such as solar power, photovoltaic (PV), hydro power and wind turbines. that are directly connected at or near the load points in the distribution systems at the medium voltage or LV. Renewable DG units can play many significant roles in the economic, technical and environmental operation of a power system. The benefits of renewable DG technologies have changed the operation of the distribution system. This has reduced energy and power losses, improved system reliability and improved voltage profile.

II. THE STUDIED ELECTRICAL DISTRIBUTION NETWORK

This test system consists of eight MV buses, four distribution transformers 20 / 0.4 KV MV / LV and nineteen LV buses distributed on four feeders which:

Feeder-1 and Feeder-4 are the same except the Feeder-1 has three DG units.

Feeder-2 has OHTL, cable connections and two DG units, one PV system and another is wind turbine generator (WTG-1).

Feeder-3 has OHTL only with one wind turbine generator (WTG-1) and there is no load in this feeder.

The electrical parameter data of the studied system of Fig. (1) present in Table (1), Table (2), Table (3) and Table (4).

Table (1): Transformers Data

Transformer	Rated Power (S_n)	U_{prim}/U_{sec}	impedance (%Z)	Vector Group
TR_01, TR_02, TR_03, TR_04	630 kVA	20/0.4 kV	4 %	DYn11

Table (2): Transmission Line Data

	Voltage Level	Rated Current	R_1	X_1	Material
MV OHTL	20 kV	0.5 kA	0.41 Ω/km	0.366 Ω/km	AL
LV OHTL	0.4 kV	1.0 kA	0.90 Ω/km	0.303 Ω/km	Copper
LV Cable	0.4 kV	0.7 kA	0.93 Ω/km	0.083 Ω/km	Copper

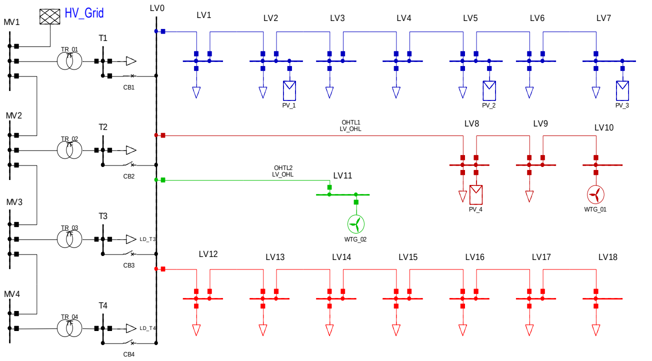


Fig. (1): The schematic diagram of the Distribution network under study.

Table (3): Connections and line parameters of studied LV distribution network

Line Name	From Node	To Node	Type	R1 Ω/km	X1 Ω/km	Length Km
LN_0_1	LV0	LV1	LV_Cable	0.93	0.083	0.02
LN_1_2	LV1	LV2	LV_Cable	0.93	0.083	0.08
LN_2_3	LV2	LV3	LV_Cable	0.93	0.083	0.05
LN_3_4	LV3	LV4	LV_Cable	0.93	0.083	0.05
LN_4_5	LV4	LV5	LV_Cable	0.93	0.083	0.08
LN_5_6	LV5	LV6	LV_Cable	0.93	0.083	0.05
LN_6_7	LV6	LV7	LV_Cable	0.93	0.083	0.07
LN_0_12	LV0	LV12	LV_Cable	0.93	0.083	0.02
LN_12_13	LV12	LV13	LV_Cable	0.93	0.083	0.08
LN_13_14	LV13	LV14	LV_Cable	0.93	0.083	0.05
LN_14_15	LV14	LV15	LV_Cable	0.93	0.083	0.05
LN_15_16	LV15	LV16	LV_Cable	0.93	0.083	0.08
LN_16_17	LV16	LV17	LV_Cable	0.93	0.083	0.05
LN_17_18	LV17	LV18	LV_Cable	0.93	0.083	0.07
LV8_LV9	LV8	LV9	LV_Cable	0.93	0.083	0.02
LV9_LV10	LV9	LV10	LV_Cable	0.93	0.083	0.08
OHTL1	LV8	LV0	OHL_LV	0.9	0.303	0.4
OHTL2	LV11	LV0	OHL_LV	0.9	0.303	0.2

Table (4): Connections and Load parameters of studied LV Distribution Network

Name	Power (kW)	Terminal (Bus)	Apparent Power (kVA)	Current (A)	PF	Profile Type	Value at 12Pm (p.u)
LD_01	5	LV1	5.26	7.60	0.95	Professional Profile	0.8795
LD_02	25	LV2	26.32	37.98	0.95	Domestic Profile	0.6743
LD_03	9	LV3	9.47	13.67	0.95	Domestic Profile	0.6743
LD_04	20	LV4	21.05	30.39	0.95	Professional Profile	0.8795
LD_05	6	LV5	6.32	9.12	0.95	Domestic Profile	0.6743
LD_06	15	LV6	15.79	22.79	0.95	Domestic Profile	0.6743
LD_07	12	LV7	12.63	18.23	0.95	Professional Profile	0.8795
LD_08	20	LV8	21.05	30.39	0.95	Professional Profile	0.8795
LD_09	30	LV9	31.58	45.58	0.95	Professional Profile	0.8795
LD_12	5	LV12	5.26	7.60	0.95	Professional Profile	0.8795
LD_13	25	LV13	26.32	37.98	0.95	Domestic Profile	0.6743
LD_14	9	LV14	9.47	13.67	0.95	Domestic Profile	0.6743
LD_15	20	LV15	21.05	30.39	0.95	Professional Profile	0.8795
LD_16	6	LV16	6.32	9.12	0.95	Domestic Profile	0.6743
LD_17	15	LV17	15.79	22.79	0.95	Domestic Profile	0.6743
LD_18	12	LV18	12.63	18.23	0.95	Professional Profile	0.8795
LD_T1	200	B1	210.53	303.87	0.95	Professional Profile	0.8795
LD_T2	300	B2	315.79	455.80	0.95	Domestic Profile	0.6743
LD_T3	230	B3	242.11	349.45	0.95	LD_3 Characteristic	1.0000
LD_T4	10	B4	10.53	15.19	0.95	LD_4 Characteristic	0.5000

III. CONTROL METHOD OF THE ACTIVE/REACTIVE ENERGY LOSSES AND VOLTAGE VARIATION RANGE

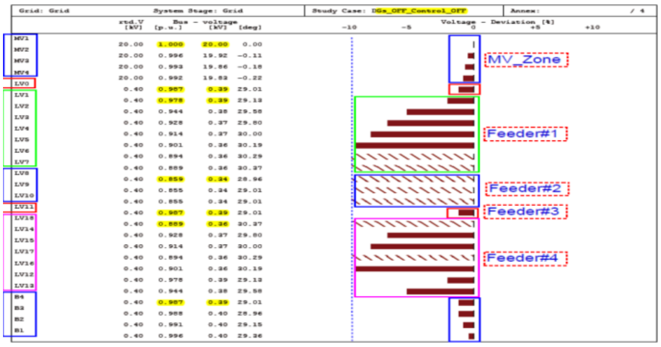
In this test system, control technique is the reactive power as a function of bus voltage relation called Q(U) is built and utilized by using PV system and DG units to minimize Distribution Network power losses and to achieve the bus voltage level stability. The controller technique is simulated by using DIgSILENT Power Factory Software.

Description of the Control Method of case study which the proposed control method can be classed by three cases:

Case_1: Digital Simulation Results of DN without DG Units.

The DGs are deactivated in this scenario (in OFF state) to segregate between the performance of the system with and without DG units. In Fig. (1) illustrates voltages and loading of each feeder of the DN without DGs at 12PM trigger time. It is clear that there is unacceptable voltage violation in the DN feeders (voltage drops to 0.86p.u).

Fig. (2) provides the detailed DigSILENT output result report for the bus voltage deviation when all DGs are OFF and Control algorithm also is OFF.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Grid: Grid              System Stage: Grid      Study Case: DGs_OFF_Control_OFF      Annex:        / 4
          rtd.V      Bus - voltage                     Voltage - Deviation [%]
          [kV]    [p.u.]    [kV]    [deg]      -10        -5        0        +5        +10
MV1       20.00    1.000   20.00    0.00
MV2       20.00    0.996   19.92   -0.11
MV3       20.00    0.993   19.86   -0.18
MV4       20.00    0.992   19.83   -0.22
LV0        0.40    0.987    0.39   29.01
LV1        0.40    0.978    0.39   29.13
LV2        0.40    0.944    0.38   29.58
LV3        0.40    0.928    0.37   29.80
LV4        0.40    0.914    0.37   30.00
LV5        0.40    0.901    0.36   30.19
LV6        0.40    0.894    0.36   30.29
LV7        0.40    0.889    0.36   30.37
LV8        0.40    0.859    0.34   28.96
LV9        0.40    0.855    0.34   29.01
LV10       0.40    0.855    0.34   29.01
LV11       0.40    0.987    0.39   29.01
LV18       0.40    0.889    0.36   30.37
LV14       0.40    0.928    0.37   29.80
LV15       0.40    0.914    0.37   30.00
LV17       0.40    0.894    0.36   30.29
LV16       0.40    0.901    0.36   30.19
LV12       0.40    0.978    0.39   29.13
LV13       0.40    0.944    0.38   29.58
B4         0.40    0.987    0.39   29.01
B3         0.40    0.988    0.40   28.96
B2         0.40    0.991    0.40   29.15
B1         0.40    0.996    0.40   29.36
```

Fig. (2): Bus voltage Deviation when all DGs OFF and Control algorithm OFF

The time sweep analysis (for complete day time period) for the maximum and minimum voltages of all terminals of the

MV_Zone and the LV Feeders of DN without DG units are performed and its simulation results are shown in Fig. (3).

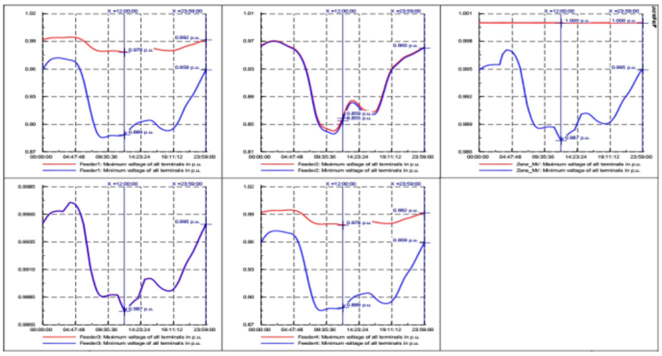


Fig. (3): Maximum/Minimum voltages of all terminals for the MV Zone and the LV Feeders of DN without DG units during complete day

Also, the voltage magnitude of the outmost 0.4kV bus for each LV Feeder of DN (at buses: LV_7, LV_10, LV_11& LV_18) were done and the results are given in Fig. (4).

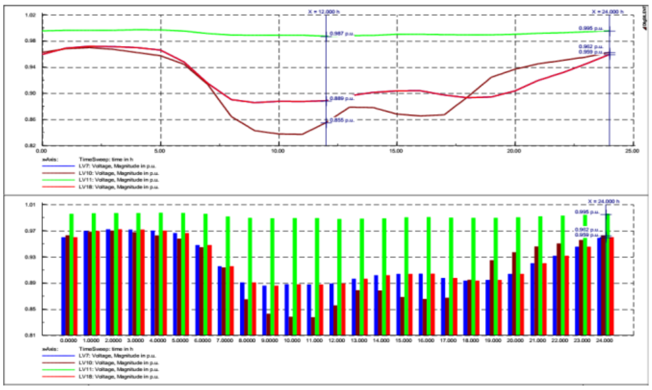


Fig. (4): The voltage magnitude of the outmost bus for the LV Feeders of DN without DG units during complete day (LV_7, LV_10, LV_11& LV_18)

The active/reactive power losses of the MV Zone and the LV Feeders are given in in Fig. (5).

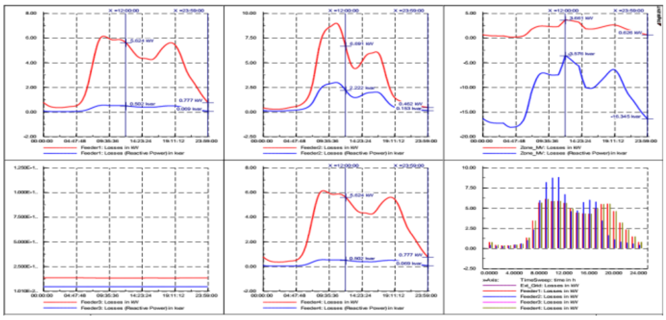


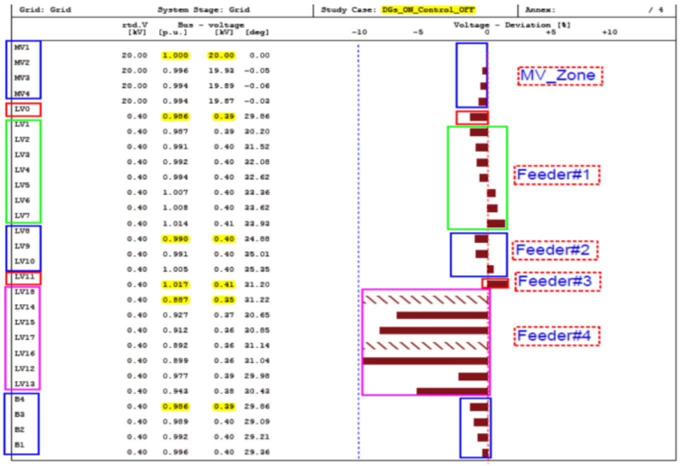
Fig. (5): Active and Reactive Power Losses for the MV Zone and the LV Feeders of DN without DG units during complete day

Case_2: Simulation Results of DN with DG Units without Reactive Power Control of DG Inverters (Operator setting)

In this Simulation, all DG units are activated to be (in ON state). The network parameters and loads values are fixed in all cases of study. The active/reactive power setting points of the DG units are controlled manually by the DN operator regardless of bus voltage values at PCC with DGs. Based on these settings (32kW and 10kvar under excited in this scenario) the generation profiles are assigned.

In fig. (1) the voltages and loading of each line feeder of the DN in the presence of DG units at a specific trigger time i.e at 12PM and the Q (U) control is deactivated. It is clear that the voltage profiles of the DN feeders containing DGs were improved (i.e FD_1, FD_2 and FD_3) while FD_4 voltage profiles still has violation in voltages. Fig. (6) provides the detailed DigSILENT output result report for the bus voltage deviation when all DGs are ON and automatic control algorithm is OFF.

The time sweep analysis (for complete day time period) for the maximum and minimum voltages of all terminals of the MV_Zone and the LV Feeders of DN in the presence of DG units are performed and its simulation results are shown in Fig. (7).



Grid: Grid | System Stage: Grid | Study Case: DGs_ON_Control_OFF | Annex: / 4

	rtd.V [kV]	Bus - voltage [p.u.]	[kV]	[deg]
MV1	20.00	1.000	20.00	0.00
MV2	20.00	0.996	19.93	-0.05
MV3	20.00	0.994	19.89	-0.06
MV4	20.00	0.994	19.87	-0.03
LV0	0.40	0.986	0.39	29.86
LV1	0.40	0.987	0.39	30.20
LV2	0.40	0.991	0.40	31.52
LV3	0.40	0.992	0.40	32.08
LV4	0.40	0.994	0.40	32.62
LV5	0.40	1.007	0.40	33.36
LV6	0.40	1.008	0.40	33.62
LV7	0.40	1.014	0.41	33.93
LV8	0.40	0.990	0.40	34.88
LV9	0.40	0.991	0.40	35.01
LV10	0.40	1.005	0.40	35.35
LV11	0.40	1.017	0.41	31.20
LV18	0.40	0.887	0.35	31.22
LV14	0.40	0.927	0.37	30.65
LV15	0.40	0.912	0.36	30.85
LV17	0.40	0.892	0.36	31.14
LV16	0.40	0.899	0.36	31.04
LV12	0.40	0.977	0.39	29.98
LV13	0.40	0.943	0.38	30.43
B4	0.40	0.986	0.39	29.86
B3	0.40	0.989	0.40	29.09
B2	0.40	0.992	0.40	29.21
B1	0.40	0.996	0.40	29.36

Fig. (6): Bus voltage Deviation when all DGs ON and Control algorithm OFF

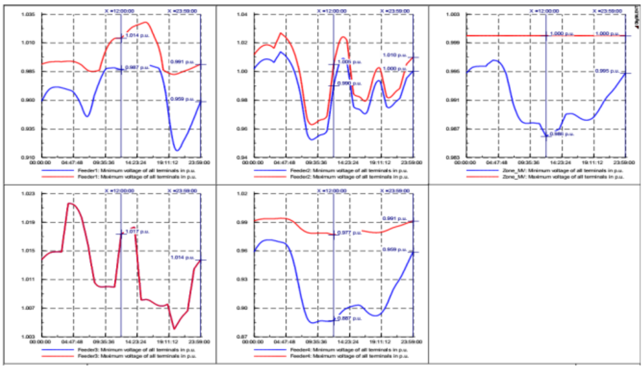


Fig. (7): Time sweep results for Maximum/Minimum voltages of all terminals of the MV Zone and the LV Feeders of DN with DG units and the Q (U) control is deactivated

Also, the voltage magnitude of the outmost 0.4kV bus for each LV Feeder of DN (at buses: LV_7, LV_10, LV_11& LV_18) were done and the results are given in Fig. (8).

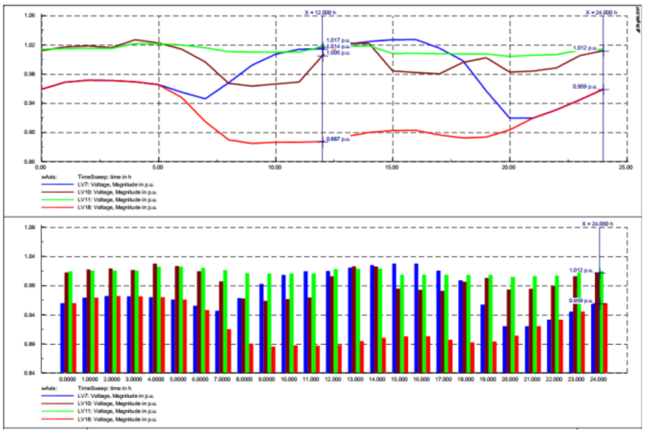


Fig. (8): Time sweep results for the voltage magnitudes of the outmost bus of the LV Feeders of DN with DG units and the Q (U) control is deactivated (LV_7, LV_10, LV_11& LV_18)

The active/reactive power losses of the MV Zone and the LV Feeders are given in in Fig. (9).

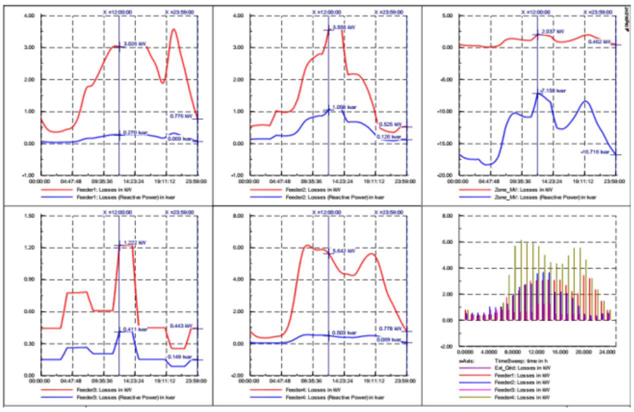
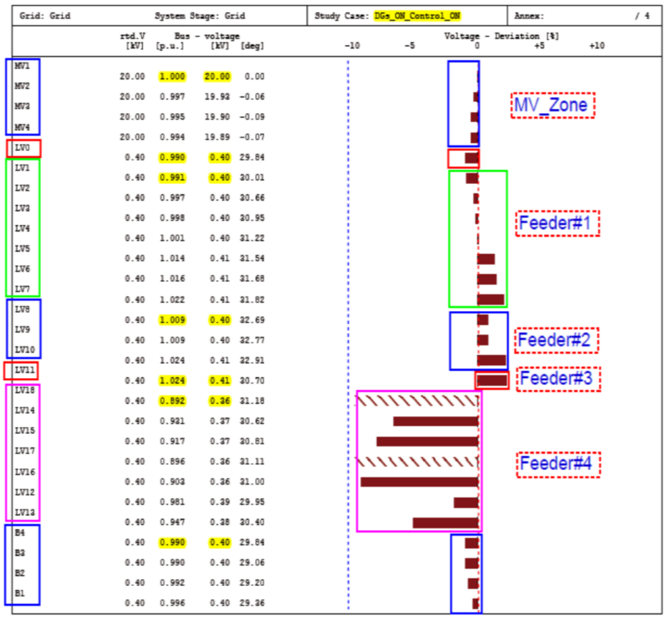


Fig. (9): Active and Reactive Power Losses for the MV Zone and the LV Feeders of DN with DG units and the Q (U) control is deactivated

Case_3: Voltage Control with Reactive Power from DG Inverters (Automatic setting)

When the DGs and Q (U) control are both ON. It is seen that voltage values of DN feeders containing DGs are within acceptable limits. FD_4 has a high voltage drop. It indicates also voltage and loading values of each line feeder at 12PM trigger time. Fig. (10) provides detailed DigSILENT output result report for the bus voltage deviation when all DGs ON and Control algorithm ON.



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Grid: Grid          System Stage: Grid        Study Case: DGs_ON_Control_ON       Annex:            / 4

                rtd.V      Bus - voltage                       Voltage - Deviation [%]
                [kV]   [p.u.]    [kV]   [deg]        -10        -5         0        +5        +10
MV1
                20.00  1.000    20.00    0.00
MV2
                20.00  0.997    19.93   -0.06
MV3
                20.00  0.995    19.90   -0.09
MV4
                20.00  0.994    19.89   -0.07
LV0
                 0.40  0.990     0.40   29.84
LV1
                 0.40  0.991     0.40   30.01
LV2
                 0.40  0.997     0.40   30.66
LV3
                 0.40  0.998     0.40   30.95
LV4
                 0.40  1.001     0.40   31.22
LV5
                 0.40  1.014     0.41   31.54
LV6
                 0.40  1.016     0.41   31.68
LV7
                 0.40  1.022     0.41   31.82
LV8
                 0.40  1.009     0.40   32.69
LV9
                 0.40  1.009     0.40   32.77
LV10
                 0.40  1.024     0.41   32.91
LV11
                 0.40  1.024     0.41   30.70
LV18
                 0.40  0.892     0.36   31.18
LV14
                 0.40  0.931     0.37   30.62
LV15
                 0.40  0.917     0.37   30.81
LV17
                 0.40  0.896     0.36   31.11
LV16
                 0.40  0.903     0.36   31.00
LV12
                 0.40  0.981     0.39   29.95
LV13
                 0.40  0.947     0.38   30.40
B4
                 0.40  0.990     0.40   29.84
B3
                 0.40  0.990     0.40   29.06
B2
                 0.40  0.992     0.40   29.20
B1
                 0.40  0.996     0.40   29.36
```

Fig. (10): Bus voltage Deviation when all DGs ON and Control algorithm ON

The time sweep simulation analysis (for complete day time period) of MV_Zone and LV Feeders in the presence of DG units and Q (U) control were done and the results are depicted and classified as follows:

1- Fig. (11) represents the maximum and minimum voltages of all terminals.

2- Fig. (12) shows the outmost LV bus voltage magnitude for each Feeder.

3- Fig. (13) shows active/reactive power losses of MV_Zone and LV Feeders.

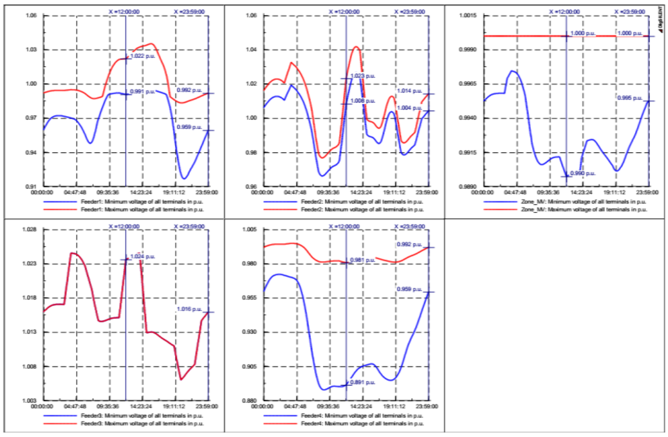


Fig. (11): Maximum/Minimum voltages of all terminals of the MV Zone and the LV Feeders of DN with DG units and the Q (U) control is Activated

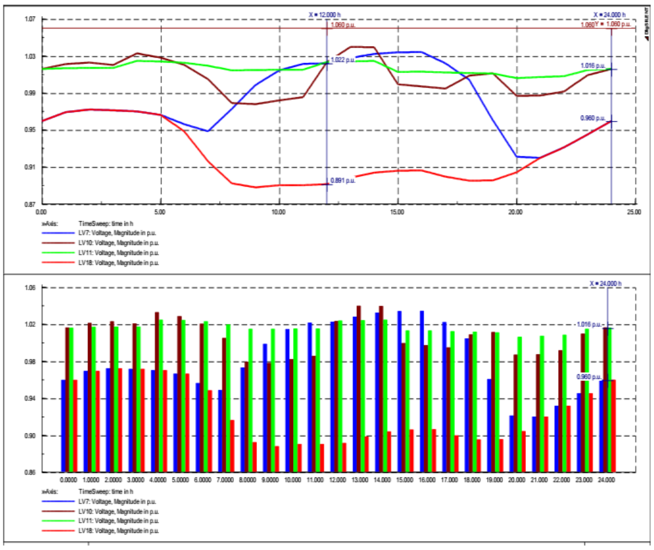


Fig. (12): The outmost bus voltage magnitude for LV Feeders of DN with DG units and the Q(U) control is Activated (LV_7, LV_10, LV_11& LV_18)

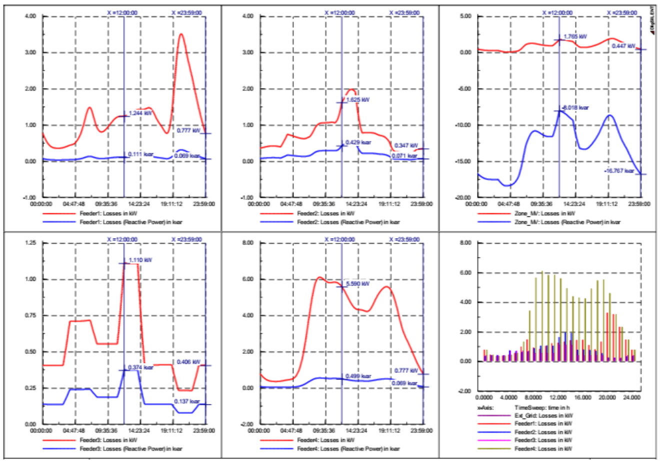


Fig. (13): Active/Reactive Power Losses of MV_Zone and the LV Feeders of DN with DG units and the Q (U) control is Activated

IV. COMPARISON OF THE DN PERFORMANCE FROM SIMULATION RESULTS

The feasibility and effectiveness of the proposed control method can be validated and verified if comparing is done in the three case studies as follows:

Case_1 (standalone DN): when DG units are OFF and Control is OFF.

Case_2 (Operator setting): when DG units are ON and the automatic Control technique Q (U) is OFF.

Case_3 (Automatic setting): when DG units are ON and the automatic Control technique Q (U) is ON.

The Active/Reactive energy losses comparison of the DN system including LV Feeders and MV_Zone in the three different cases during 24 hours period is shown in table (5). These values indicate that about 27% and 43% decrease of energy losses in case_2 and case_3 respectively with respect to case_1; and 20% decrease of energy losses in case_3 with respect to case_2 as in table (6).

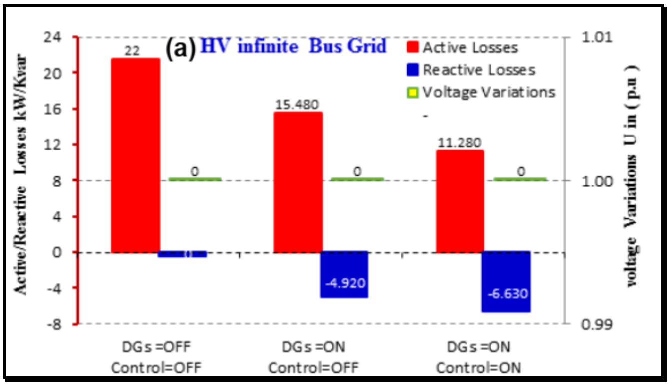
Table (5): Comparison of Active Energy Losses of the DN in the three different cases during 24 hours time period

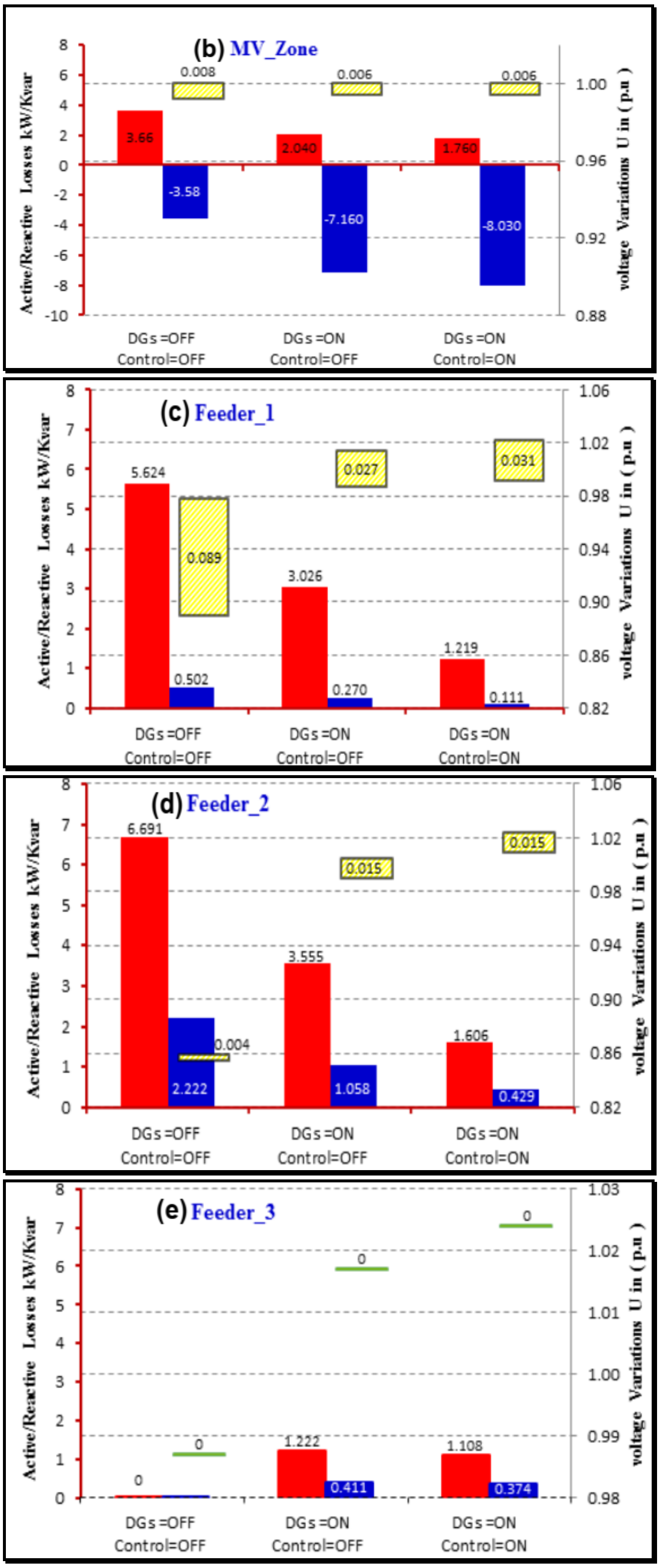
During one day	Case_1 (standalone DN)	Case_2 (Operator Setting)	Case_3 (Automatic Setting)
	DGs =OFF Control=OFF	DGs =ON Control=OFF	DGs =ON Control=ON
Total Ext. Infeed (kWh)	12920.546	10600.822	10557.834
Total Generation (kWh)	0	2243.200	2243.200
Total load (kWh)	12635.82	12635.820	12635.820
Total Losses (kWh)	**284.735**	**208.209**	**165.223**

Table (6): The % of Active Energy Losses of the DN in the three different cases during 24 hours time period

With Respect To	**% of Energy Losses Reduction**		
	Case_1 (standalone DN)	Case_2 (Operator Setting)	Case_3 (Automatic Setting)
	DGs =OFF Control=OFF	DGs =ON Control=OFF	DGs =ON Control=ON
Case_1	**-**	**27%**	**43%**
Case_2	**27%**	**0**	**20%**

Active/Reactive power losses and voltage variation range are given in Fig. (14) for the three simulated cases. Fig. (14.d) clearly shows that reactive power losses are highest in Line 2 (when observing only the LV network) due to long OHTL_1. Comparison of losses, both active and reactive, also shows one interesting difference between losses in the LV and MV networks. Active power losses in the LV network (FD_1 & FD_2) are on average by an approximate factor of 2 higher than losses in the MV_Zone (MV_Zone / LV Feeder).





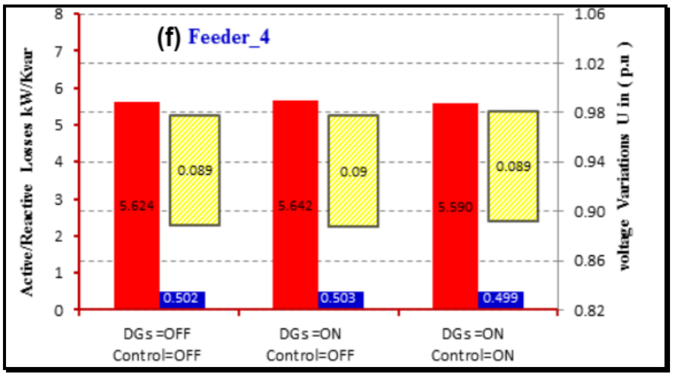


Fig. (14): Active/Reactive Power Losses and Voltage Variations along LV Feeders & MV Zone of DN in the three different cases at 12Pm trigger time

Table (7) provides the Active/Reactive Power Losses of the HV infinite Bus Grid in the three different cases. It is noticed that the load losses are positive while the no-load reactive power losses are negative. The negative sign of reactive power shown in Fig. (14.a) and Fig. (14.b) indicates that reactive power is delivered/injected to the HV infinite Bus grid. That negative sign caused by the no-load capacitive charging current of the long MV OHTL.

Table (7): The total Active/Reactive Power Losses of HV infinite Bus Grid in the three different cases

The HV Infinite Bus Grid Losses	Load Losses		No-Load Losses		Total Losses	
	kW	kVar	kW	kVar	kW	kVar
Case_1: (DGs =OFF and Control=OFF)	21.6	18.47	0	-18.82	21.60	-0.35
Case_2: (DGs =ON and Control=OFF)	15.48	13.95	0	-18.86	15.48	-4.92
Case_3: (DGs =ON and Control=ON)	11.28	12.25	0	-18.88	11.28	-6.63

V. CONCLUSIONS

Reactive power losses of an MV_Zone are higher than reactive power losses of a LV feeder. This is due to the fact that in the MV networks the X/R ratio of a line is much higher than in the LV thus reactive power, which passes through the MV network, causes more losses than when it passes through the LV network. And of course, vice-versa applies for the relationship of the active power losses in the LV network, where X/R ratio of a line is much lower than in the MV network.

There is a tendency of lower losses and good voltage levels in the overhaul DN, when the reactive power of DGs is controlled. It is obviously that without DG units, the voltage will fluctuate between nearly (0.99 to 0.89 p.u) with network low voltage conditions, while with DG units or Q (U) control strategies of DGs, the voltage is fluctuated with less range around (1p.u ± 0.02p.u) in LV Feeders and between (0.994±1.0p.u) in MV_Zone, because this approach allows injection/absorption of reactive power and then improving the DN voltage profile.

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