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Analytical Investigation of DG Allocation on Power System Operation

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Abstract

This paper investigates the effects of large scale integration of distributed generation (DG), particularly wind system and photovoltaic system (PV), on power system steady state operation. The performance of power system with connecting DGs at different locations with different sizes is investigated from the economic and technical point of view. The total power loss is considered as a measure for the economical side where the voltage profile and total distortion harmonics (TDH) are considered as a technical decision for selecting the optimal location and size of DGs. Variety of configurations are analyzed and discussed. IEEE 30-bus test system is used to analyze the impact of DG on power system operation. The generation level of DGs is intended to meet the future increase in demand and provide the acceptable level of spinning reserve. Connecting DGs at the best locations are compared with connecting traditional steam power generation units from the view point of steady state operating conditions. The affecting on voltage profile, system losses and harmonic contents are compared in case of connecting DG compared with connecting traditional generation unit at the same buses. The results show that when the DGs connected at the best locations, the voltages profiles are improved and the power loss reduced where the THD slightly increased in case of connecting DGs. The results proves that the power system dynamic stability improves with connecting DG units at best locations.

Keywords — DG units, PV system, Wind turbines generation, Power system Harmonics, Power quality.

INTRODUCTION

Distributed generation (DG) becomes a vital option to meet the rapid increase in power demand. The allocation of DG units and the uncertainty associated with the generating level can significantly affect the steady state as well as dynamic performance of the power system. Proper size and location of connecting DG units have a significant effect on power system steady state and dynamic operation [1]. DG allocation at the best location is an important aspect for a steady, reliable and efficient power system operation. The voltage profile improvement, power loss reduction, and reactive power compensation are the main contributions of DG integration in radial distribution feeders as well as the voltage security margin improvement [2]. Many methods are used to solve a multi-objective function for appropriate allocations of DG units in power system considering power loss minimization, enhance reliability and voltage profiles [3]. The impact of wind energy based DG units had been investigated talking into account operational constraints.

A combination of squirrel cage and doubly-fed induction generator based wind system are used to obtain a unity power factor combined system of generation in order to increase the level of wind power extraction [4]. Iterative method is used to determine wind farm maximum size at certain location while minimizing the negative impact on power system voltage stability margins [5]. The voltage stability problem is investigated in case of high penetration level of PV system and an auxiliary reactive power supply consists of inverter and capacitor bank is suggested to improve reactive power capability of PV systems. The proposed method scheme investigates the reduction of harmonic contents due to switching transients [6].

DG units installations will effect on the power quality due to the existence of converters, especially for weak or rural grids as well as the wind turbines themselves create power pulsation on the system [7]. Harmonic contents associated the integration of DG units cause the reduction of power quality, equipment's long life and a reduction in the efficiency. The impacts on power quality can be reduced by using variable speed operation of turbine using transistor converters and accurate power controllers [8,9]. A comparison between variable speed WTs and fixed speed WT considering the voltage fluctuations and harmonics distortion are presented in [10,11].

This paper conducts the optimal allocation of DG units to anticipate load increase, particularly wind and PV system in power system regarding total power loss minimization considering voltage profile enhancement. Then the harmonic analysis is performed based on the THD for selected optimal location. Different scenarios are used to supply the required power which include concentrated wind or PV system and distributed wind or PV system. The DG units are installed at preselected set of candidate busses to select the optimal location according to total power loss minimization and operating voltage limits. IEEE30-bus test system is used where a case of a (80+j20) MVA DG units are connected to supply the load increase while maintaining the system spinning reserve. The rest of the paper investigates the effect of DG units' locations and sizes on the THD and comparison between the behavior of the system with connecting a traditional steam power station and DG units. The analysis has been implemented and simulated using ETAP software.

MODELING OF DG UNITS

There are many types of DG units where wind and PV systems are the most extensive integration to power grid and will be considered in this study. The wind system based doubly fed induction generation (DFIG) is implemented. Figure. 1 presents a general schematic diagram for integration of DG units with power system at a selected candidate busses. Each DG unit associated with control systems to adjust the output active power and reactive power according to the system states to achieve secure and economic operation of power system. System operator should schedule the available generation to anticipate the estimated loads keeping a sufficient hot spinning reserve to enhance system security and service continuity.

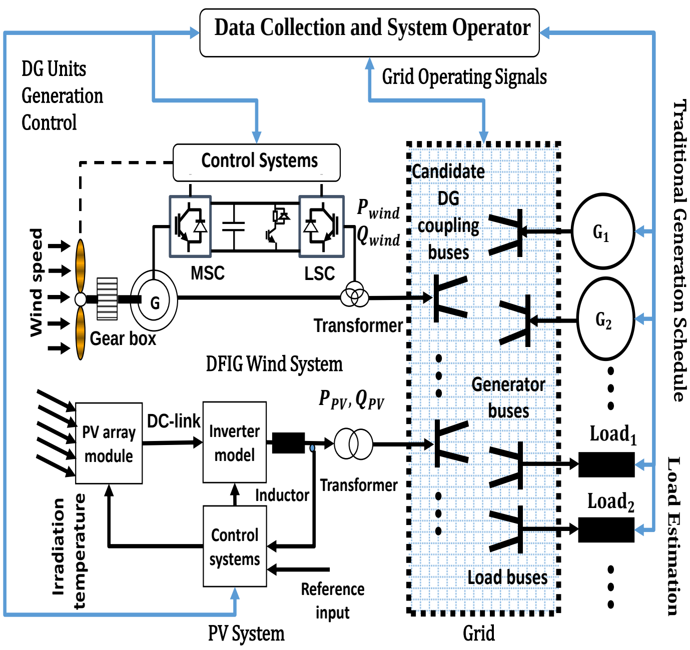


Figure. 1: Power system with DG units

Modelling of Wind system based on DFIG

Wind systems can be either operate at fixed or variable speed. The wind system is modeled in ETAP software as MVAR control type 3 using of DFIG with AC/DC/AC rotor side converter where the stator is connected directly to the grid through transformer as shown in Figure. 2. DFIG has the capability to control the terminal voltage and injected active and reactive power through the integrated the line side converter (LSC) and the machine side converter (MSC) controls. The control of active power and reactive power is achieved independently through air gap flux and generated output torque of the DFIG.

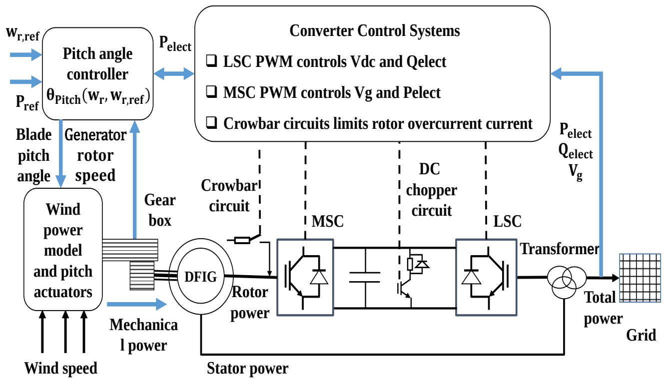


Figure. 2: DFIG based wind system

LSC controls the power flow between the DC bus and the AC side by the DC voltage level variation using charging and discharging of capacitor, which provides reactive current for supporting the grid by of the reactive power. MSC controls terminal voltage (reactive power) and active power of the DFG independently to track the characteristic of the generator for optimal power generation depending on the wind speed. MSC allows controlling the amplitude, frequency and phase angle of the rotor voltage. The pitch angle control is a common which has been used to keep the rotational speed and output power of the generator within the nominal limits. [12]

The switching process in the inverter provides a fundamental voltage at the slip frequency and low frequency harmonics are included in the electric signals. Switching process causes a pulsating air gap torque and voltage fluctuations on the system bus bar. In addition, speed fluctuations and pitch angle control produce a pulsating torque which transfer from rotor to stator side of the machine. Therefore, impact of wind system integration on the level of total harmonic distortion (THD) need to be investigated during wind system allocation. Increasing THD tends to several undesired conditions such as power quality deterioration, overheating and power loss [13].

An equivalent controlled current injection model is used to model the DFIG in ETAP software.

Modelling of PV systems

ETAP modulates the PV system as a renewable energy source. The PV system cosists of a number of PV arraies and associated inverters to generated AC voltage according to the grid terminal voltage. The output power of each array and voltage can be controlled using the number of connected series and parallel panels (modules). Each panel consists of many series connected solar cells. The selected panel is a multi-crystalline. The number of series and parallel connected panels in the array depends on the power rating of PV system and terminal voltage. Table I presents the characteristics of selected PV panel.

Table 1: The characteristics of selected PV panel

Number of cells	54	
maximum power delivered	205	watt
irradiance levels	1000	Watt/m2
maximum peak power voltage	27.19	volt
open circuit voltage	32.97	volt
Panel efficiency	14	%
maximum peak power current	7.89	A
short circuit current	8.33	A

The inverter should be able to carry the rated power of the PV array in addition to the expected short circuits power. The type of inverter and associated harmonics due to switching process is important to investigate the system harmonic analysis. The parameters of each integrated array and inverter presented in Table 2.

Table 2: The parameters of the integrated array and inverter

Number of series connected panels	15	
Number of parallel connected panels	15	
DC output voltage of array		
DC output power of array		
Inverter efficiency	90	
Short circuit contribution of inverter	150%	
Minimum power factor	0.8	
Maximum power factor	0.95	

Typical-IEEE harmonic model of 18 pulse used to represent the harmonic injection due to switching process. The optimal location of DG units should be determined based on the power system operating condition. The performance analysis depends on a sensitivity factor for system losses, voltage profile and harmonic analysis.

Sensitivity Factors Analysis

i. Line loss sensitivity factor

The loss sensitivity factor is the total power losses in all lines (N_{line}) in the power system.

$$S_P = \frac{1}{N_{line}} \sum_{i=1}^{N_{line}} P_i \tag{1}$$

ii. Bus voltage sensitivity factor

The absolute average error is used to select the proper DG size and location from the candidate solutions. The bus voltage sensitivity factor can be formulated as:

$$S_V = \frac{1}{N_b} \sum_{i=1}^{N_b} \left| \frac{V_i - V_i^{ref}}{V_i^{ref}} \right| \tag{2}$$

where V_i^{ref} is the reference voltage of each bus and N_b is the total number of busses.

iii. System harmonic distortion sensitivity factor

The maximum total harmonic distortion (THD) of buss voltages is used as a sensitivity factor to evaluate the effect of DGs units' integration on the level of harmonic contents in the electric signals.

$$S_{THD} = max(THD_1, THD_2, \cdots THD_{N_b}) \tag{3}$$

$$THD_i = \frac{\sqrt{\sum_{n=2} V_n^2}}{V_i} \tag{4}$$

CASE STUDY

The proposed analytical method for optimal allocation of DG units applied in the IEEE 30-bus test system. A single-line diagram of the test power system under study is shown in Fig. 3 [15]. The base case total demand is (303.180 +j140.723) MVA. The total available generation is (350+j230) MVA. The load is assumed to be increased by 20% of the rated power (363.82+j168.87) MVA. The DG units are installed to cover the load increase and keep a sufficient level of 50 MW spinning reserve power.

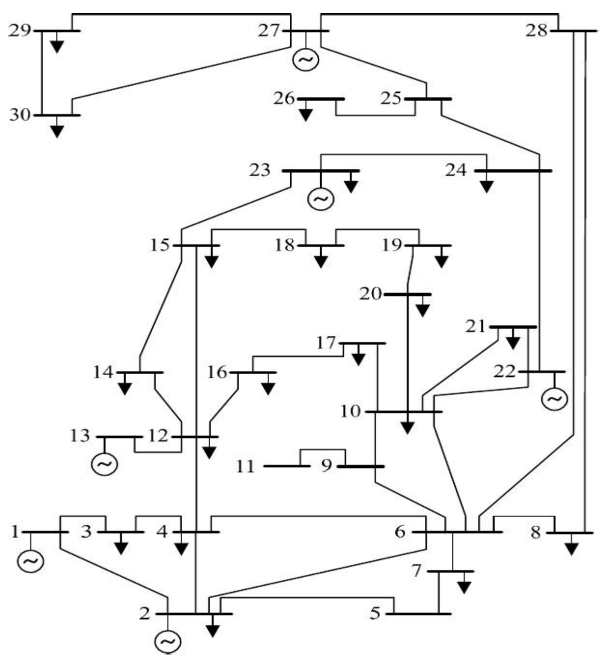


Figure. 3: A single-line diagram of 30-bus system

DG Integration Impact on System Behavior

Four different configurations investigated:

Case 1: DGs units (wind or PV) are concentrated at single location.

Case 2: Distributed wind farms at two different locations.

Case 3: Distributed PV units at two different locations.

Case 4: Hybrid DG units (wind and PV) at two different locations.

A variety of system configurations are analyzed to determine the candidate best locations of connecting DG units. The system behavior with connecting traditional steam power units with the same rated power of DG units are considered as base case operation and used to evaluate the behavior of the system with connecting DG units.

Case 1. Effects of concentrated DG units on the system behavior

DG units (wind or PV) of 80+j20 MVA rating are selected to anticipate the increase in demand and satisfy the minimum required spinning reserve. The DG units are located at different system busses to specify the candidate best location based on the sensitivity factor. At base case without connecting the DG units, the power loss is 30.229+j54.3 MVA, the voltage sensitivity factor is 8.404 % and THD is 6.06 p.u. Table 3 presents the sensitivity factors associated with connecting DG units at different busses in the test system.

Table 3: Sensitivity factors using concentrated DGs

BUS NO.	P_Loss		S_V		S_THD		VMIN	VMAX
	PV	Wind	PV	Wind	PV	Wind		
1	25.42	25.42	5.63	5.63	7.41	5.93	91.13	101.00
2	20.76	20.76	3.98	3.98	6.95	6.32	92.92	101.00
3	19.69	19.69	3.17	3.17	9.41	6.21	93.94	102.12
4	17.60	17.59	2.50	2.50	7.14	6.32	94.77	103.20
5	15.09	15.08	2.25	2.25	6.13	6.04	95.00	102.53
6	16.15	16.15	1.95	1.95	6.96	6.46	95.66	103.29
7	15.57	15.57	1.93	1.93	6.98	6.32	95.67	103.05
8	16.21	16.20	1.87	1.87	6.84	6.39	95.63	103.25
9	24.26	24.27	2.47	2.47	5.50	5.52	94.84	102.40
10	24.36	24.37	2.23	2.24	5.81	5.92	95.03	102.62
11	54.85	54.90	5.55	5.56	5.63	5.89	91.30	101.00
12	25.65	25.66	2.85	2.85	5.26	5.38	94.36	103.53
13	54.87	54.92	5.69	5.70	5.32	5.83	91.20	101.00
14	27.99	27.99	3.11	3.11	10.18	5.44	94.20	107.18
15	25.42	25.42	2.51	2.52	6.01	5.46	94.53	103.26
16	26.19	26.19	2.83	2.83	8.43	5.46	94.42	103.40
17	25.17	25.17	2.50	2.50	6.17	5.67	94.78	102.63
18	26.32	26.32	2.61	2.61	10.28	5.40	94.48	104.40
19	25.91	25.91	2.58	2.57	9.74	5.45	94.59	103.71
20	25.81	25.81	2.47	2.47	8.87	5.48	94.65	103.24
21	24.55	24.55	2.09	2.10	6.07	5.09	95.00	102.61
22	24.68	24.68	2.09	2.09	6.40	4.85	95.00	102.61
23	26.66	26.67	2.54	2.55	10.43	5.12	94.44	104.58
24	25.64	25.64	2.09	2.09	15.04	4.59	94.77	102.81
25	26.86	26.87	2.32	2.33	11.24	5.16	94.55	103.86
26	35.01	35.03	3.80	3.81	30.18	5.60	93.43	114.52
27	16.45	16.45	1.70	1.70	8.17	5.99	95.60	103.23
28	24.74	24.75	2.20	2.20	7.41	5.10	94.81	102.33
29	29.26	29.27	3.02	3.03	20.87	5.57	94.02	107.62
30	29.04	29.05	3.09	3.09	20.84	5.60	94.03	108.68

As shown from Table 3, the candidate busses that have the bus voltage deviation within limits of ±5 % voltage deviation are highlighted. Each of the candidate buses is a suitable location for connecting the DG units. The selection of the best location is performed based on the ranking of candidates busses based the total power losses. The best location is selected based on the voltage sensitivity factor and system harmonic distortion sensitivity factor. A mathematical equation relates the three variables can be formulated by:

$$F = C_1 P_{Loss} + C_2 S_V + C_3 S_{THD} \qquad (5)$$

The weight factor in the function selected according to the importance of each sensitivity factor ($C_1 = 0.3, C_2 = 0.4, C_3 = 0.3$). Fig. 4 presents the values of the weight faction corresponding to the PV and wind allocation at candidate busses.

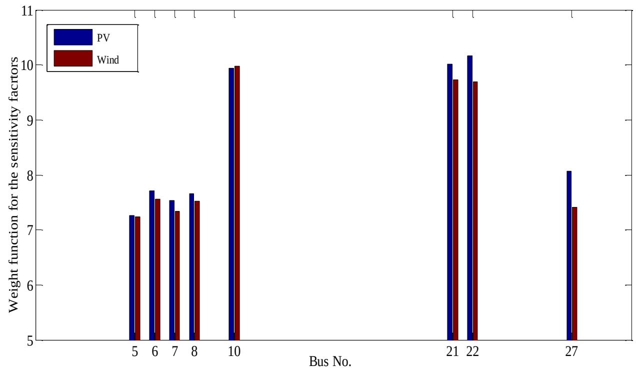


Figure. 4: The weight function with concentrated DGs

Selected location for connecting concentrated PV or wind system is bus 5. The two busses are in the same geographical region. The voltage profile with connecting the concentrated PV unit compared with base case presented in Fig. 5.

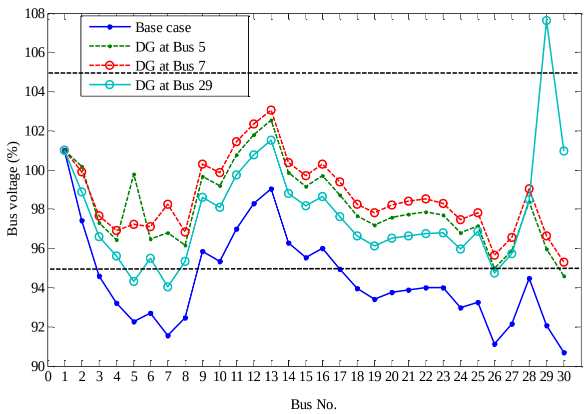


Figure. 5: The voltage profiles with connecting concentrated PV system at selected buses

The voltage profiles are within limits with connecting the concentrated PV unit at bus 5 and bus 7.

Case 2. Effects of distributed DG units on system behavior

The study of the effects of distributed DG units (distributed wind or PV systems) on steady state power system behavior and harmonic contents conducted using similar units. Two DG units with (40+j10) MVA each are located at the candidate buses which selected in the previous section as the best locations for connecting DGs. The weight function based on sensitivity factors used to select best locations of connecting different DG types. The best results presented in Table 4-Table 7.

Table 4: Best configurations of two similar PV units based on weight function

DG1_PV	DG2_PV	P_Loss	S_V	S_THD	Weight function
Bus 5	Bus 27	14.145	1.603	5.449	6.520
Bus 6	Bus 5	14.209	1.782	5.492	6.623
Bus 7	Bus 22	14.565	1.708	5.716	6.767
Bus 8	Bus 5	14.077	1.716	5.690	6.617
Bus 10	Bus 21	15.26	1.898	4.286	6.622
Bus 21	Bus 5	14.028	1.679	5.742	6.603
Bus 22	Bus 8	15.080	1.670	4.912	6.666
Bus 27	Bus 5	14.145	1.603	5.449	6.520

Table 5: Best allocation of two similar PV (fixed at certain bus) and wind system

DG1_PV	DG2_Wind	P_Loss	S_V	S_THD	Weight function
Bus 5	Bus 7	14.275	1.831	6.192	6.873
Bus 6	Bus 5	14.415	1.803	4.989	6.542
Bus 7	Bus 5	14.265	1.823	4.388	6.325
Bus 8	Bus 5	14.284	1.736	5.020	6.486
Bus 10	Bus 5	14.427	1.728	5.829	6.768
Bus 21	Bus 5	14.234	1.690	5.878	6.710
Bus 22	Bus 5	14.301	1.675	5.887	6.726
Bus 27	Bus 5	14.352	1.620	5.011	6.457

Table 6: Best allocation of two similar wind (fixed at certain bus) and PV system

DG1_Wind	DG2_PV	P_Loss	S_V	S_THD	Weight function
Bus 5	Bus 7	14.265	1.823	4.388	6.325
Bus 6	Bus 10	15.564	1.718	5.702	7.067
Bus 7	Bus 8	14.772	1.650	5.605	6.773
Bus 8	Bus 6	15.421	1.714	5.801	7.052
Bus 10	Bus 27	17.727	1.660	8.983	8.677
Bus 21	Bus 27	17.556	1.626	6.722	7.934
Bus 22	Bus 27	17.610	1.615	6.320	7.825
Bus 27	Bus 5	14.363	1.630	7.607	7.243

Table 7: Best configurations of two-wind DG units

DG1_Wind	DG2_Wind	P_Loss	S_V	S_THD	Weight function
Bus 5	Bus 8	14.502	1.764	6.142	6.899
Bus 6	Bus 5	14.638	1.832	6.456	7.061
Bus 7	Bus 5	14.479	1.855	7.783	7.421
Bus 8	Bus 5	14.502	1.764	6.142	6.899
Bus 10	Bus 5	16.930	1.867	8.229	8.294
Bus 21	Bus 5	16.749	1.747	5.829	7.472
Bus 22	Bus 5	16.800	1.742	5.450	7.372
Bus 27	Bus 5	14.570	1.648	6.762	7.059

From the results, the best integration consists of PV system at bus 7 and wind system at bus 5. The results with two DG units are comparable with the results with concentrated DG unit. A comparison between the base-case, best location with concentrated unit and best locations of two DG units presented in Table 8.

Table 8: A Summary for best locations and base case

Case study	P_Loss	S_V	S_THD	Weight function
Base case without DG units	30.229	8.404	6.06	14.2483
One PV unit at bus 5	15.09	2.5	6.13	7.366
One wind unit at bus 5	15.09	2.5	6.04	7.339
Two DG units (PV at bus 7 and wind at bus 5)	14.265	1.823	4.388	6.325

The best configuration based on the weight function is the integration of PV system and wind system at bus 7 and bus 5 respectively. The configuration produces a less power loss, less voltage sensitivity factor and less maximum total harmonic distortion. The voltages profiles at all buses with connecting DG units at best locations for the base case, connecting concentrated DG unit at bus 5 and distributed DG units (wind system at bus 5 and PV at bus 7) are presented in Fig. 6.

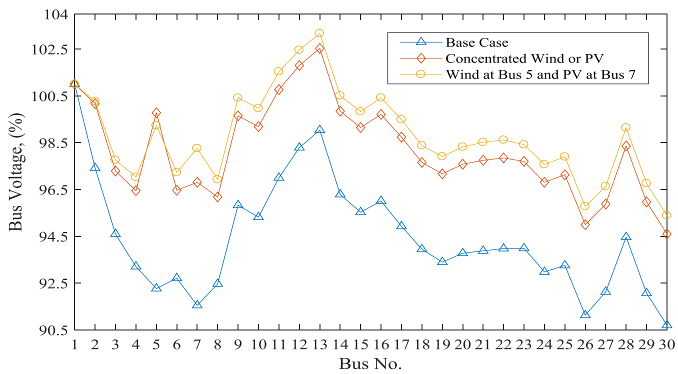
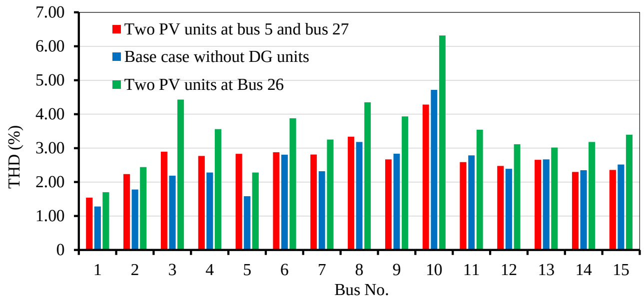


Figure. 6: Voltage profile with PV at best location

Fig. 6 presents that the voltages profiles improved with connecting DG units at best location while the distribution of DG units is the best result.

Case 3. Harmonic contents in the waveforms

The harmonic contents due to distributed DG units will differ from type to another due to the power electronic devices associated with each type. Fig. 6-Fig. 9 present the total harmonic distortion at selected busses at different cases of study



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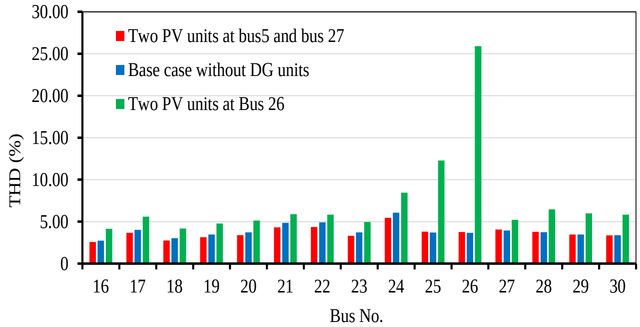

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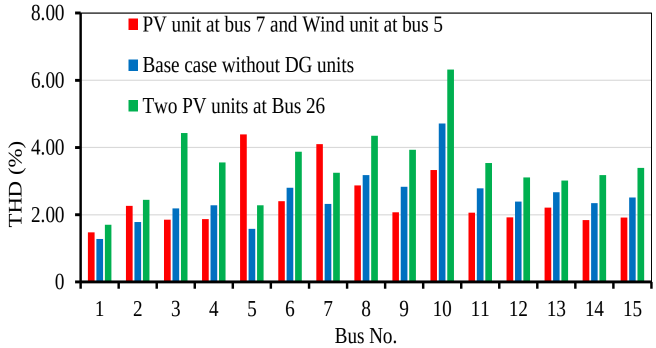
Figure. 7: THD in case of distributed two PV units



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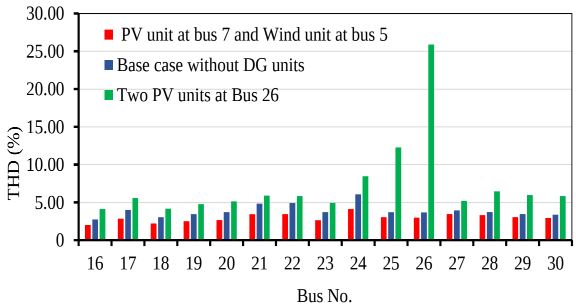
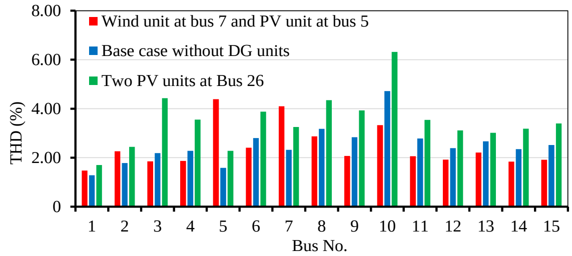


(b)

Figure. 8: THD with PV at bus 7 and wind at bus 5



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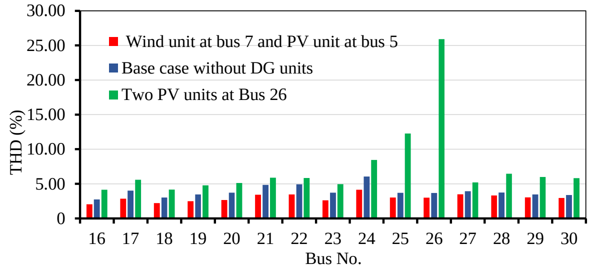

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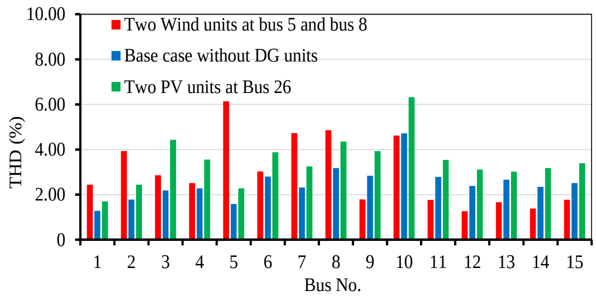
Figure. 9: THD with wind at bus 7 and PV at bus 5



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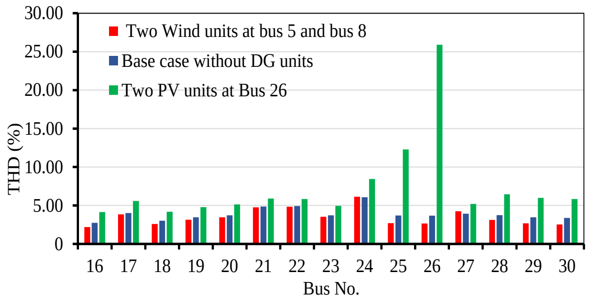

(b)

Figure. 10: THD in case of distributed two wind units

As show in the previous figure, with connecting DG units at random locations such as connecting PV at bus 26, the injected harmonics are increased at all buses. The selection of best location considering the harmonic sensitivity factors reduces the injected harmonic. Fig. 11 presents the THD at randomly selected buses in the base case with no DG integration and different optimal DG allocations in the studied four cases.

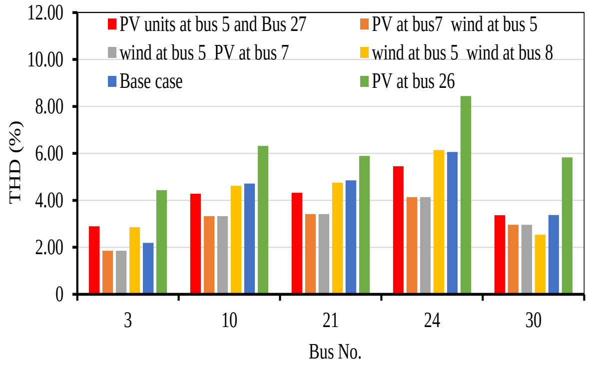

Figure. 11: THD at randomly selected buses in base case and the different four studied cases

Case 4. Impact of large penetration of wind energy on power system stability

The effect of DGs on power system dynamic stability analysed when DG units connected at optimal locations in the four different combination in the previous section following a three-phase short circuit. The minimum time clearing fault considered as 150 milliseconds where the protection system should be activated to isolate the fault.The system generators should be able to survive without loss of synchronism.

Considering the fault at one of the critical buses (Bus 10) without DG integrations, the system is transiently unstable as shown in Figure. 12. The generators at buses 11 and 13 are going to unstable and oscillatory mode following the fault.

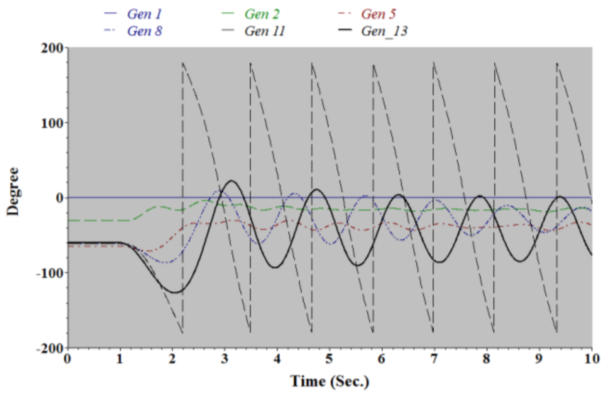

Figure. 12: Generators relative power angles with 150 three-phase short circuit at bus 10

Considering case of wind systems at bus 5 and bus 8 as a case study for the effect of connecting DGs at best locations, the system is going to stable mode following the clearance of the fault as shown in Figure. 13. The injected power from wind systems at the selected best location near the critical fault location improves the system dynamic behavior.

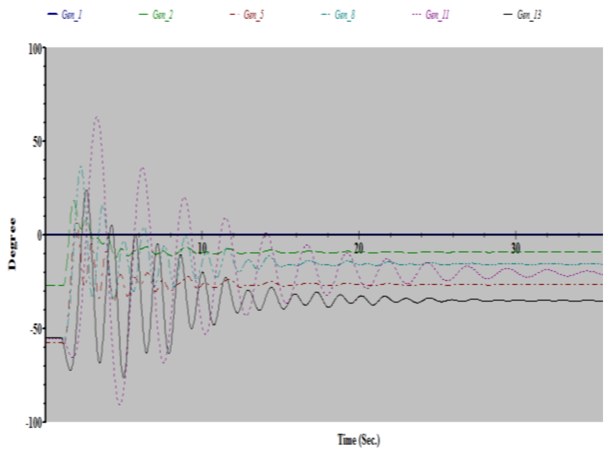

Figure. 13: Generators relative power angles

CONCLUSION

Integrations of DG units in power system at random locations can deteriorate the voltage profiles and effect on the power quality in addition to increases the harmonic contents. Combining different types of DGs may lead to improve the steady state power system operation and reduce the losses. The best location of connecting of DG units is selected based on the sensitivity factors (Line loss sensitivity factor, Bus voltage sensitivity factor, and System harmonic distortion sensitivity factor). A weight function is used to combine the sensitivity factors for selecting the best location. The connection of DG units compared with connecting traditional generation unit from the view point of selected sensitivity factors and the results show that the voltages profiles are improved, the harmonic contents are decreased and the power system losses are reduced. The proposed analytical approach is tested and validated using standard IEEE 30 bus test system with its all loads are increased by 25%. The DG units are used to supply the load increased and the required spinning reserve. The results had illustrated that the best location of concentration DG units are obtained when a wind DG unit with 80+j40 MW had connected at bus 5. The active power loss is reduced from 30.229 MW to 15.09 MW, the voltage sensitivity factor is enhanced from 8.404 % to 2.25 % while the THD is changed from 6.06 to 6.04. The best location with distributed two DG units with 40+j20 MW each had connected at buses 5 (wind type) and at bus 7 (PV type) respectively. The active power loss is reduced to14.265 MW, the voltage sensitivity factor is enhanced to 1.823 % while the THD is decreased to 4.388. Therefore, the DG allocation is greatly effect on power system operation. The results prove that power system dynamic stability improved with connecting the DGs at the best locations as well as the voltage profiles and power quality. The optimal allocations of DGs systems relieve the power system operation where the loads rescheduled among generators, which reduce the system congestions.

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