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Voltage Sags Assessment in Distribution Systems Using Distributed Generation

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***Abstract*— In distribution systems the most critical disturbance is the interruption of the power service. However, the main concern for end-users is the mal-operation produced by voltage sags. The presence of distributed generation (DG) modifies the radial configuration of distribution systems and imposes new challenges to be evaluated concerning to the assessment of voltage stability, the performance of protection system, the active power generation and consequently the behavior of voltage sags. This paper shows the influence on voltage sag characteristics by the presence of DG in the IEEE-13 bus test feeder. The analysis is performed by using a random generation of disturbances using a MATLAB routine and simulated in ATP/EMTP software tool. Several case studies in the test system taking into account different locations and sizes of DG unit are presented.**

***Index Terms*— voltage sags, distributed generation (DG), power quality, modeling, IEEE-13, ATP/EMTP.**

I. INTRODUCTION

IN recent years, natural resource conservation and environmental protection issues have caused an increase in the use of green technologies and renewable sources for electric power generation. The Distributed Generation (DG) can be defined as the strategic use of small or medium scale power generation units based on renewable and traditional sources, which are connected to the electrical networks [1].

There are several advantages when DG units are installed. These can be technical, economic, environmental and even political. Although the costs associated with DG are still high, these generation units could be a solution when a high reliability in power service is required, or when the construction of transmission lines and large power plants is not supported by end-users [2]. However, the installation of DG sources imposes new challenges to the radial operation of distribution systems. In fact, the DG represents change not in the system topology, but in the direction of power flow and voltage levels. This impact depends on size, type and location of DG units [3].

Voltage sags are the most important power quality (PQ) disturbance that many industrial, commercial and residential users faced it [4]. They are short-duration reductions in RMS voltage at power frequency between 10% and 90% of the nominal value with durations from half-cycle to a few seconds. These disturbances produce mal-operation or interruption on sensitive equipment, in many occasions leads to complete interruptions of the industrial process and affect the proper operation of power and distribution systems [5].

Study of sags has increased the interest on mitigation methods to preventing or reducing their effects. Usually, DG helps to mitigate voltage sags because increases the short circuit power in distribution networks, increases voltage profiles of nodes in fault condition and also helps to maintain the voltages during the fault [2], [6]. In addition, a factor as the DG penetration level can modify the system behavior with respect to voltage sags.

Characteristics of voltage sags in a distribution network can be affected by the presence of DG. For this reason, the response of IEEE-13 distribution system using different DG penetration levels for voltage sags mitigation is analyzed in this paper. To understand DG unit operation and the distribution system response, modeling and digital simulations are made using ATP/EMTP. To speed up the simulation, no protection devices have been included and the effect of transformer simulation will be neglected.

The ATP/EMTP model of IEEE-13 node test feeder and its main features are detailed in section II. In section III the method used to identify the critical buses of the test system is briefly explained. Section IV presents the case studies obtained by a scheme of random generation of disturbances. The ATP/EMTP model of the DG unit and its parameters is shown in section V. In section VI, the simulation results and analysis of DG impact on test system, under voltage sag condition, is performed. Finally in section VII, the conclusions of this work are presented.

II. DESCRIPTION AND MODELING OF THE TEST SYSTEM

In order to analyze the DG impact on voltage sags in distribution systems, simulations have been performed on IEEE-13 node test feeder. This system consist of 13 buses which are interconnected by means of 10 lines (three and single phase lines), one generation unit, one main $\Delta - Y$ transformer to 115/4.16 kV, one in-line $Y - Y$ transformer to

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4.16/0.480 kV, one voltage regulator unit, two shunt capacitor banks, unbalanced spot and distributed loads [7]. On the other hand, in steady-state the IEEE 13-bus system present three types of disturbances: (a) voltage imbalances, (b) load unbalance and (c) reactive power flows. Fig. 1 shows the scheme of the IEEE-13 bus test feeder.

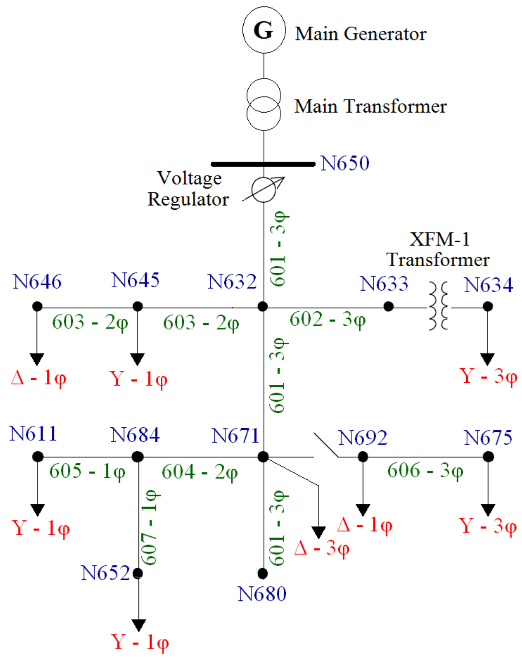

Figure 1. Scheme of IEEE-13 node test feeder

Although several types of tools have been used to simulate voltage sags, the present work has been based on the development of models in ATP/EMTP. The capability of this tool to the voltage sags analysis is shown in [2], [8].

III. IEEE-13 Critical Buses Identification

Critical bus of a system is a load connection point where the occurrence of faults will lead to the reduction in voltage at all nodes of the system. To analyze how much the IEEE-13 bus test feeder is affected by the occurrence of a fault in a specific bus, the following local function is used

$$L_{Fb} = \sum_{i=1}^{13} \sum_{j=1}^{3} (V_{pre-ij} - V_{fault-ij})^2 \qquad (1)$$

Where, F is the fault type according to the Table 1, b is the bus where the fault is produced, i is each bus in the system, j is the phase, V_{pre-ij} is the pre-fault voltage in p.u. and $V_{fault-ij}$ is the voltage in p.u. in fault condition. The use of a squared difference in Eq. (1) prevents negative values in the local function when $V_{fault-ij} > V_{pre-ij}$.

For each bus of IEEE-13 system simulations for all fault types connecting an impedance-to-ground equal to zero are performed. In total 102 cases have been simulated considering that the test system is unbalanced and some nodes just have a single-line or two-lines.

In this work, an overall function (O) to assess the complete effect that each bus has on the others buses in the IEEE-13 system is proposed. This function is given by

$$O_b = \sum_{F=1}^{11} L_{Fb} \qquad (2)$$

Where, L_{Fb} is the local function for each fault condition F in the bus b. Table 2 presents the overall functions of IEEE-13 buses organized in descendent order.

TABLE I
FAULT TYPES

Fault type	Involved phases	Fault code (A)
single line-to-ground (LG)	A	1
	B	2
	C	3
line-to-line (LL)	AB	4
	BC	5
	AC	6
Double line-to-ground (2LG)	AB	7
	BC	8
	AC	9
Three line (3L)	ABC	10
Three line-to-ground (3LG)	ABC to-ground	11

Since the overall function is a parameter that totalizes the effect of local functions by fault type, a critical bus can be considered as the one with the largest overall function. In the case of IEEE-13 bus test feeder, the most critical is bus 650 with an overall function $O_{671} = 187.13$. By other hand, the less critical is bus 611 which overall function is $FG_{652} = 5.61$.

TABLE II
OVERALL FUNCTIONS FOR IEEE-13 BUS TEST FEEDER

Affected Node	Overall function
650	187.13
632	165.59
633	133.19
671-692	127.58
675	113.69
680	101.02
634	49.61
645	33.94
684	32.07
646	28.70
652	6.66
611	5.61

To analyze the response of the test system in presence of voltage sags using DG, in this paper five buses with the largest overall function are selected. These buses are 632, 633, 671, 675 and 680. The bus 650 is not taken into account as critical bus due to its relevance and proximity to principal generator, because any fault on this bus will produce the system collapse. However, depending on the number of nodes in the system for other case study can be used different selection criteria.

IV. Case Studies

Voltage sags features at bus of interest are predicted applying a method of stochastic generation of disturbances based on the distribution system model and statistical data of faults [5]. This method selects different fault positions (critical buses identified in section III), the fault type and the fault resistance taking into account statistical data about faults in the electrical system. In addition, the method assumes that sags are originated only by faults, and they are rectangular.

Stochastic generation of disturbances is implemented using a Matlab® routine, generating random numbers with a density of probability. The total of 200 voltage sag conditions are simulated on the IEEE-13 bus test feeder. The parameters used in simulations are the following:

- Location of fault: the fault may occur at any critical node (632, 633, 671, 675 and 680) or at any line that connect the critical nodes. This paper assumes that the fault position in each line may occur in three positions (25%, 50% and 75%). The density function for nodes and lines is 65% and 35%, respectively. Fig. 2 shows with a dashed line the selected critical zones of IEEE-13 system.
- Probability of fault types: LG:75%, LL: 15%, 2LG: 6%, 3L and 3LG: 4%
- Fault resistance: 8 different values between 0.19Ω and 0.85Ω are established. The fault resistance is selected by an uniform density function.

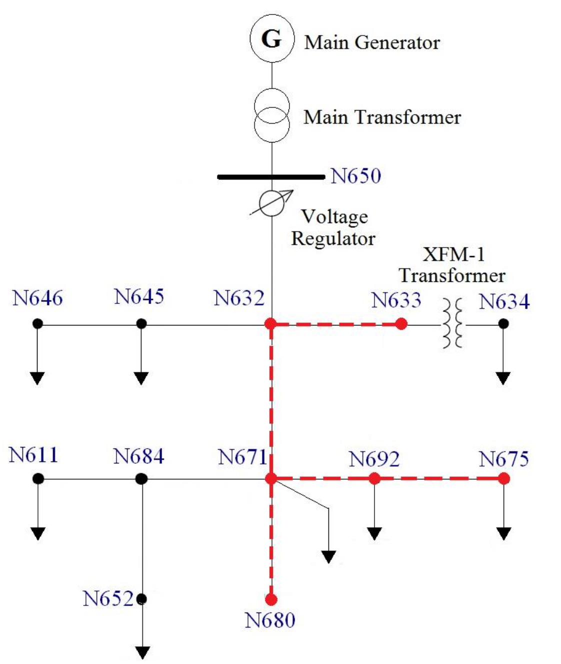

Figure 2. Critical zones of IEEE-13 node test feeder

For each simulation, the results of the fault configurations are used to estimate the local function using Eq. (1). Table 3 presents three worst voltage sag conditions, i.e. the cases with the largest local function. Each selected case corresponds to a general fault type. These are the case studies where the influence of DG units on voltage sags will be evaluated.

TABLE III
CASE STUDIES FOR DG UNIT IMPLEMENTATION

Case	Fault Position	Fault Type	Resistance Value [Ω]	Local Function
1	N671	LG – 1	0.19	9.396
2	50% Line 632-671	2LG – 9	0.19	12.495
3	N675	3L – 10	0.38	10.067

V. ATP/EMTP Model of the Distributed Generation Unit

In this paper, only one distributed source is installed. This DG unit is a medium power synchronous generator, whose ratings and electric parameters are shown in Table 4. In simulations this generator will be connected to all buses of IEEE-13 system.

TABLE IV
ELECTRICAL PARAMETERS OF THE SYNCHRONOUS GENERATOR

Parameter	Value
Rated Frequency	60 Hz
Rated Voltage	4.16 kV
Number of poles	2
Armature resistance: Ra	0.0015 p.u.
Armature leakage reactance: Xl	0.1300 p.u.
Zero-sequence reactance: Xo	0.1000 p.u.
d-axis synchronous reactance: Xd	0.9500 p.u.
d-axis transient reactance: Xd'	0.1400 p.u.
d-axis sub-transient reactance: Xd"	0.1350 p.u.
q-axis synchronous reactance: Xq	0.9200 p.u.
q-axis transient reactance: Xq'	0.2100 p.u.
q-axis sub-transient reactance: Xq"	0.1400 p.u.
d-axis open circuit transient tine constant: Tdo'	4.300 s
d-axis open circuit sub-transient tine constant: Tdo"	0.032 s
q-axis open circuit transient tine constant: Tqo'	0.850 s
q-axis open circuit sub-transient tine constant: Tqo"	0.050 s

No information about the mechanical behavior of the generator is provided, for this reason a single representation in ATP/EMTP simulations is used. However, to choice the best generator model, transient and stable state simulations are considered. This is important because in transient conditions, as the occurrence of voltage sag, the machine must behave as stable as possible during the fault to compensate its effects.

VI. Simulation Results

A. *Base case: The original system conditions*

Initially, IEEE-13 bus test feeder has been verified without install the distributed generation unit. In this case the original system is simulated in ATP/EMTP to analyze the magnitudes and angles of pre-fault voltages presented in [7].

Table 5 shows a comparison between the original IEEE-13 system conditions and the results provided by simulations. This table illustrates that all voltages of IEEE-13 system presented in [7] have a value between 0.938 and 1.053 in p.u., while IEEE-13 bus voltages obtained from ATP/EMTP have a value between 0.965 and 1.052 in p.u. Maximum absolute error obtained from simulations is 3.4%. This error shows the validity of the distribution system modeling.

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TABLE V
SIMULATION RESULTS COMPARISON FOR IEEE-13 SYSTEM

NODE	VOLTAGE [p.u] IEEE-13 REPORT			VOLTAGE [p.u] IEEE-13 FROM ATP		
	A	B	C	A	B	C
650	1.000	1.000	1.002	0.966	0.973	0.965
632	1.021	1.042	1.017	1.016	1.044	1.003
633	1.018	1.040	1.042	1.013	1.042	1.001
634	0.994	1.022	0.996	0.989	1.024	0.982
671	0.990	1.053	0.978	0.995	1.050	0.972
680	0.990	1.053	0.998	0.995	1.050	0.972
675	0.938	1.055	0.976	0.991	1.052	0.974
692	0.990	1.053	0.978	0.995	1.050	0.972
645	---	1.033	1.016	---	---	1.001
646	---	1.031	1.013	---	1.033	0.999
684	0.988	---	0.976	0.993	---	0.970
611	---	---	0.974	---	---	0.968
652	0.982	---	---	0.988	---	---

B. Case studies using DG unit under voltage sag conditions

In order to analyze the DG unit influence on voltage sags features in IEEE-13 test system, the following procedure is developed in the case studies defined in section IV:

- Step 1: Analyze the test system under sag conditions before the connection of the DG unit.
- Step 2: Define the penetration levels (PL): in this paper three levels with respect to the total power of the system are selected (low: 20%, medium: 50% and high: 100%).
- Step 3: Connect the synchronous generator at each tree-phase bus of IEEE-13 system (dispersion level) and change the penetration level in order to find a solution in which the local function is the smallest possible.
- Step 4: Analyze the impact of location and penetration level of DG unit on voltage sags features.
- Step 5: Compare the results between the system with and without DG installation.

1) Case 1: voltage sag at bus 671

Voltage sag occurred at bus 671 is due to a single-line-to-ground fault (type 1) with a resistance of 0.19 Ω. This condition has a local function of 9.396 and produces a voltage sag of 0.163 p.u. on phase A. Voltages of phase B and C are 1.258 and 1.139 p.u., respectively.

Fig. 3 illustrates the impact of location and penetration level of DG unit on local function obtained from ATP/EMTP. For this condition, the size of DG has a low influence on voltage sag severity. From simulations, the lowest local function obtained is 6.398 connecting the DG unit at bus 675 with a medium penetration level.

The RMS voltage per phase at the node 671 before and after the connection of DG unit is shown in Table 6. Note that DG unit connection contributes to mitigate voltage sag on phase A. The DG unit connection improves the voltage of bus 671-phase A (affected phase) reaching a value of 0.547 p.u.

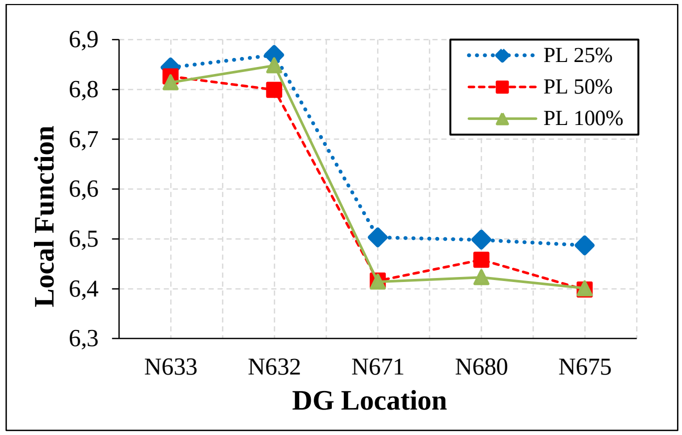

Figure 3. Local function vs. DG location and dispersion level for case 1

TABLE VI
VOLTAGE COMPARISON AT BUS 671 FOR CASE 1

	Voltage [p.u]		
	Phase A	Phase B	Phase C
Without DG	0.163	1.258	1.139
With DG	0.547	0.981	1.190

2) Case 2: voltage sag at line 632-671

In this case, a two-line-to-ground fault (type 9) at 50% of line between 632 and 671 buses with a fault resistance of 0.38 Ω is simulated. This scenario is the most critical of 200 random cases with a local function of 12.495. The fault produces at point of fault a voltage sag of 0.241 p.u. on phase A and 0.233 p.u. on phase C, while the voltage of phase B is 1.281 p.u.

Behavior of local function with respect to location and penetration level of DG unit is shown in Fig. 4. The lowest local function obtained from simulations is 9.529 connecting the DG unit with a high penetration level at bus 671.

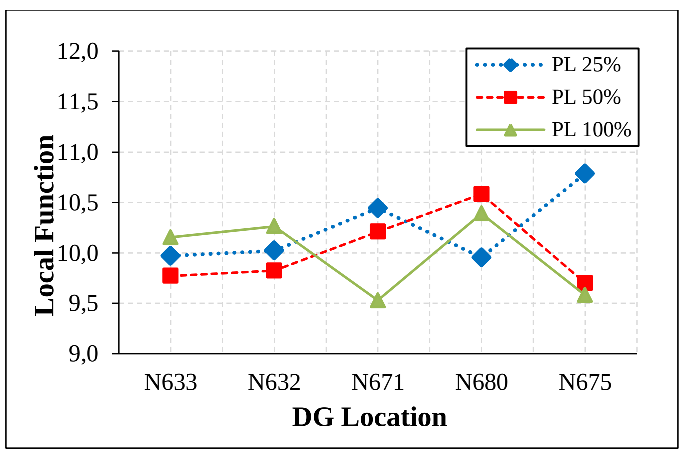

Figure 4. Local function vs. DG location and dispersion level for case 2

Table 7 presents the RMS voltage at 50% of line 632-671 before and after the connection of DG unit. Note that the presence of DG unit contributes to reduce the voltage sag severity. In this case, the voltage of phases A and C increase about 25% and 28%, respectively.

TABLE VII
VOLTAGE COMPARISON AT 50% OF LINE 632-671 FOR CASE 2

	Voltage [p.u]		
	Phase A	**Phase B**	**Phase C**
Without DG	0.241	1.281	0.233
With DG	0.489	1.199	0.517

3) Case 3: voltage sag at bus 675

Average voltage sag of 0.378 p.u due to a three line fault (type 10) at bus 675 with a fault resistance of 0.38 Ω is presented. Fig. 5 shows the influence of location and DG penetration level on the local function. The best location of DG unit using a high penetration level is bus 680. With this configuration LF is reduced from 10.067 to 6.379.

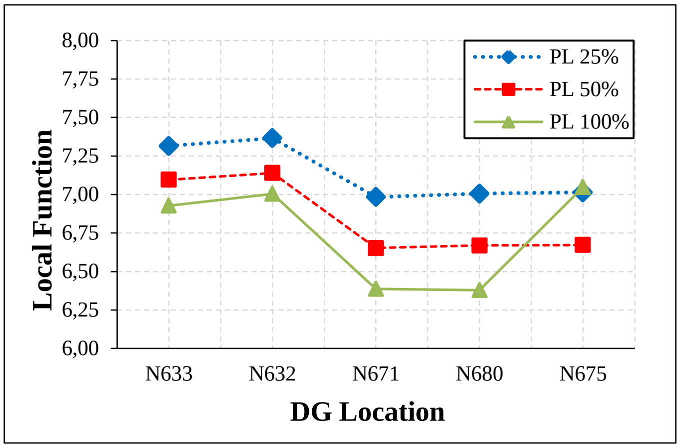

Figure 5. Local function vs. DG location and dispersion level for case 3

The RMS voltage at bus affected by sag condition with and without the DG unit is presented in Table 8. Note that the voltage sag depth at bus 675 decrease about 23% with respect the reference value (pre-fault voltage) connecting DG unit.

TABLE VIII
VOLTAGE COMPARISON AT BUS 675 FOR CASE 3

	Voltage [p.u]		
	Phase A	**Phase B**	**Phase C**
Without DG	0.362	0.429	0.344
With DG	0.591	0.635	0.579

C. Results analysis

Results from simulations show that local function and voltage profile of IEEE-13 bus test feeder are improved when DG is installed. Impacts of DG on voltage sag assessment depend on characteristics of DG as follows:

- An increase of DG size in the test system leads to a reduction voltage sags severity in almost all buses of system. In those cases where the voltage sag is occurred at system bus, the best results can be obtained with a medium or high penetration level. However, in general terms when multiple-phase are involved in voltage sag condition the size of DG decrease the local function and voltage sag severity. By other hand, if the voltage condition involves a single-phase, the size of DG has influence on voltage sag severity by decreasing the local function slightly as seen in Fig. 3.
- With respect to the location of DG unit, if the new generator is installed at any three-phase bus of the test system the voltage profiles can be improved. However, downstream-installed DG can improve voltage profile of system and reduce the voltage sag severity better than upstream-installed DG.

VII. CONCLUSIONS

In this paper, the influence of a distributed generation unit on voltage sags features caused by faults in the IEEE-13 test system has been analyzed. Also, in order to evaluate the impacts of its installation, the location and size of the new synchronous generator have been taken into account. Besides, a method to identify the critical buses based on random generation of disturbances, the system model and statistical data of faults was applied.

For the cases studies, it was observed that the presence of DG unit has a positive effect on the system, contributes to reduce the voltage sags impact and improves the voltage profiles in all system. Simulation results show that DG unit should be installed closed to bus affected by voltage sag. The new DG unit at a downstream location of principal generator shows better performance than an upstream location. In case studies 2 and 3, the inclusion of a 1.25 MVA DG unit improves the performance of voltage profile connecting this generator at buses 675 and 680, respectively. In addition, under one-single voltage sag conditions the impact of DG unit size is not significantly different.

Developed features and graphic advantages available in ATP/EMTP were used to conduct all aspects of the DG implementation, the IEEE-13 system modeling and to carry out several simulation results. This work is still under development, the next steps in research should consider the influence of protection schemes to find more accurate results and the optimal location to connect the DG unit.

REFERENCES

[1] M. Bollen, *Integration of Distributed Generation in the Power System*, 1st Edition. New Jersey, USA: Wiley-IEEE Press, 2011, p. 524.
[2] J. Martinez-Velasco and J. Martin-Arnedo, “EMTP model for analysis of distributed generation impact on voltage sags,” *IET Gener. Transm. Distrib.*, vol. 1, no. 1, pp. 112–119, 2007.
[3] S. Surisunthon and T. Tayjasanant, “Impacts of distributed generation’s locations, sizes, operation modes and transformer connections on voltage sag assessment,” in *2011 IEEE Region 10 Conference - TENCON 2011*, 2011, pp. 893–897.
[4] R. C. Dugan, M. F. McGranaghan, and H. W. Beaty, *Electrical Power Systems Quality*, 3rd Edition. India: McGraw-Hill, 2012, p. 580.
[5] M. Bollen, *Understanding power quality problems. Voltage Sags and Interruptions*, 1st Edition. New York: Wiley-IEEE Press, 2013, p. 672.
[6] L. Zheng, Y. Zhang, and L. Lin, “Studies on Voltage Sag in Distribution Network Containing Distributed Generations,” in *Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific*, 2012, pp. 1–5.
[7] IEEE Distribution System Subcomitte, “IEEE 13 Node Test Feeder Report,” 2001.
[8] J. Martinez and J. Martin-Arnedo, “Voltage sag studies in distribution Networks-part I: system modeling,” *IEEE Trans. Power Deliv.*, vol. 21, no. 3, pp. 1670–1678, Jul. 2006.