DISCRIMINATION AND ASSESSMENT OF VOLTAGE SAG IN DISTRIBUTION NETWORKS

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ABSTRACT

In this paper, the system under study, which is located in the region of North Cairo Electricity Distribution Company (NCEDC), has been monitored for 171 days. Voltage sags occurred during these days have been recorded for the purpose of discrimination and assessment. The system under study has been simulated in MATLAB/SIMULINK environment in order to study the causes of voltage sag (faults, transformer energizing, load switching and induction motor starting). The simulation has been done to find out the actual causes of the phenomena considering system construction and operating scenarios. A two-dimensional chart has been used to identify the origin of voltage sags via the single-event characteristics (sag magnitude, sag duration). Simulation results and recorded voltage sags have been allocated on one chart. The allocation showed that there is an overlap between voltage sags due to single line to ground faults (SLGF) and voltage sags due to transformer energizing in distribution networks. The magnitude of 2^{nd} order harmonic current (I_2) as a percentage of the fundamental current (I_1) was proposed as a discriminating tool to resolve the overlap mentioned above. Finally, single-event indices and site indices for the recorded voltage sags have been calculated.

INTRODUCTION

The term sag (dip) is defined in IEEE Standard 1159-1995 as "A decrease to between 0.1 and 0.9 Pu in rms voltage or current at the power frequency for duration of 0.5 cycle to 1 min" [1].
According to the results of the EPRI Distribution Power Quality (DPQ) study conducted several years ago, only 3% of events experienced by distribution grid industrial customers were outages. The vast majority of the offending “events” were found to be short duration disturbances, primarily voltage sags and momentary loss of power [2].
The causes of voltage sags are faults, induction motor starting, transformer energizing, load switching [3].
A large number of single events (sags) have been recorded during the monitoring period of the system under study which is located in an industrial zone causing tremendous trips for industrial loads.
Simulation results showed that actual causes of voltage sag occurring in the system under study were faults and transformer energizing (inrush current).
Allocating both measurements and simulation results on one chart illustrates that there is an overlap between voltage sags due to faults and transformer energizing in distribution networks.
Transformer inrush is described by IEC 60076-8 as the phenomenon:
"When a transformer is suddenly energized with full system voltage, a random saturation phenomenon may occur, which is usually referred to as an inrush current". The inrush current has a high degree of asymmetry and is harmonically rich due to it being created by saturation of the transformer’s magnetic circuit. The fundamental component contributes towards only 50% of the overall inrush current. The other main component in this case is the 2^{nd} harmonic current. In addition, there is a large DC offset component which contributes significantly to the peak component [4].
Calculating the area under the curve of 2^{nd} order harmonic in fault current and inrush current resulting from simulation illustrates that there is a big difference between the two values which can be used as a discriminating tool.
Voltage sag indices are a mean of presenting the performance at sites and system levels. The site indices describe the power quality at a given location of a power system whereas the system indices describe the performance of the whole system or a set of sites [5].
In this paper, voltage sag assessment was done through the computation of a number of single-event indices and a number of site indices for the system under study, these indices were computed based on the line-to-line voltage sags recorded during the monitoring period.

SYSTEM DESCRIPTION

The system under study consists of two sub-systems:
Transmission system with nominal voltage (220, 66KV) and distribution system with nominal voltage (22, 0.4KV).

Transmission system description

Transmission system under study consists of two transformers connected in parallel, each one is (125MVA, 220/66KV, Z%:11%, Y earthed /Y earthed). The primary side, named Bus00, has a nominal voltage (220KV) and the secondary side, named Bus0, has a nominal voltage (66KV). Bus0 feeds Bus1 with nominal voltage (66KV) through an over head transmission line (OHTL) which has a (43.95Km) length.

Distribution system description

Distribution system under study is a part of the local medium voltage (MV) network with nominal voltage (22KV), feeding industrial customers. The power transformer feeding the system, named T2, is (25MVA, 66/22KV, Z%:12%, Δ/Y earthed through a resistance 20Ω), its primary side is connected to Bus1 and secondary side is connected to Bus2 (nominal voltage 22KV). The system under study consists of a bus-bar named Bus3, fed from T2 through two parallel feeders start from Bus2 and end at Bus3, each feeder has a (6.5Km) length, consists of three single-core cables, cross-sectional area 400mm^2, aluminium conductor, aluminium tape armour, cross-linked polyethylene insulation, (3*1*400, AL, ATA, XLPE) connected through two circuit breakers (C.Bs) at the beginning and the end of each feeder. Bus3 feeds five outgoing radial feeders through C.Bs, all outgoing cables are three-core cables, cross-sectional area 240mm^2, aluminium conductor, double steel tape armour, cross-linked polyethylene insulation (3*240, AL, DSTA, XLPE. The overall number of transformers (kiosks) connected to Bus3 is twenty four distribution transformer (22/0.4KV) with rated power range from 300KVA to 2000KVA, all transformers are Δ/Y, solidly earthed and Z% is according to IEC 60076-5:200. The longest outgoing feeder has a (2.197Km) length and feeds eight transformers with rated power (1, 0.5, 1, 1, 1.5, 0.5, 0.5, 1) MVA.

VOLTAGE SAG MEASUREMENTS

The system under study has been monitored over (171days) to record voltage sags, the power quality analyzer used was (Chauvin Arnoux C.A 8334B) and the monitoring point was one of the two incomings to (Bus3). The power analyzer has been connected to the monitoring point via the measuring cell where the nominal voltage is (110V). Figure 1 illustrates the recorded voltage sags.

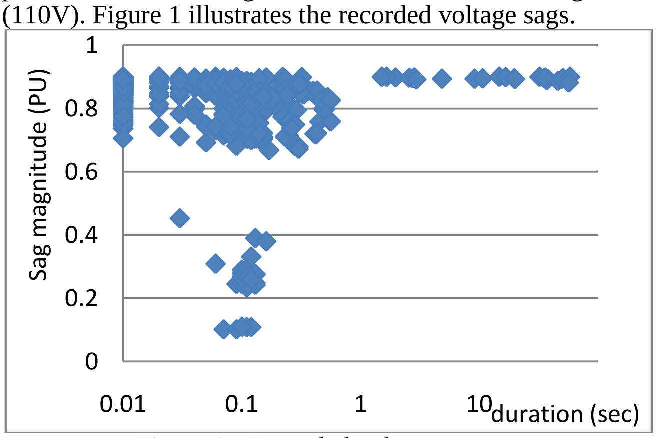

Figure 1 - Recorded voltage sags

VOLTAGE SAG SIMULATION

The system under study has been simulated using MATLAB/SIMULINK environment to study the causes of voltage sag as follow:

Faults

Faults may occur in distribution level or transmission level. Therefore, simulation has been done for faults which may occur in the two levels.

Faults in distribution level

Due to the medium voltage (MV) cables construction, the majority of faults may be considered single line to ground faults (SLGF). Figure2 illustrates SLGF simulation results, considering the following assumptions:
Fault resistance (0Ω, 10Ω or 20Ω), fault location (at each kiosk feeding point along the longest outgoing feeder) and fault incipient angle (0°, 36°, 54°or 90°).

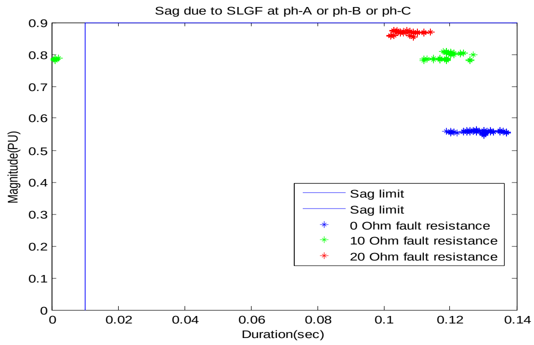

Figure 2 - SLGF simulation results

Faults in transmission level

Transmission system under study is an OHTL. Therefore, faults that have been simulated were single line to ground fault (ph A-G), double line to ground fault (ph A-B-G) and line to line fault (ph A-B). Figures 3, 4 illustrate transmission fault simulation results considering the following assumptions:
Fault resistance (0Ω, 5Ω or 10Ω), fault location (at distance of 0.1*L, 0.9*L from Bus0), where L is the length of the OHTL and fault incipient angle (0°, 36°, 54° or 90°).

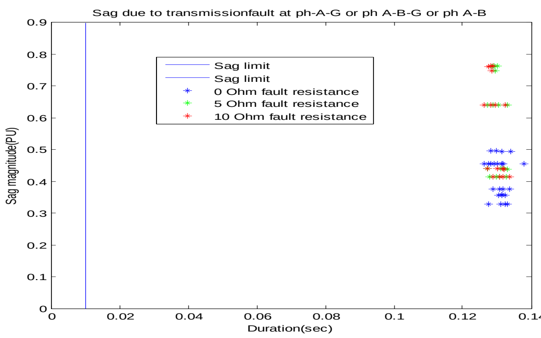

Figure 3 - Simulation results of transmission faults according to fault resistance

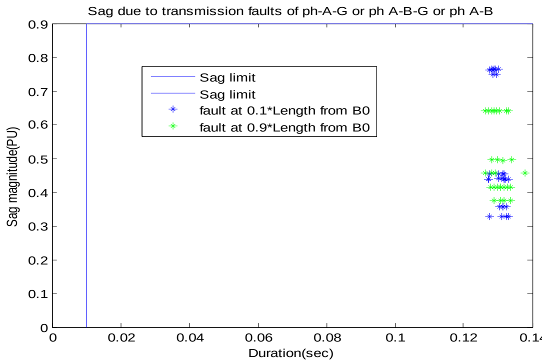

Figure 4 - Simulation results of transmission faults according to fault location

Transformer energizing

Generally, transformer inrush currents are mainly determined by the power-on angle and the magnitude and direction of the original residual flux [6]. Figure 5 illustrates simulation results considering the follow assumptions:
The sum of rated power in (MVA) of energized transformers is 0.5MVA, 1.5MVA, 2.5MVA, 3.5MVA, 4.5MVA, 5.5 MVA or 6.5MVA, switching on angles (0°, 36°, 54° or 90°) and the residual flux value at switching off angles (0, π/6, π /3 or π /2).

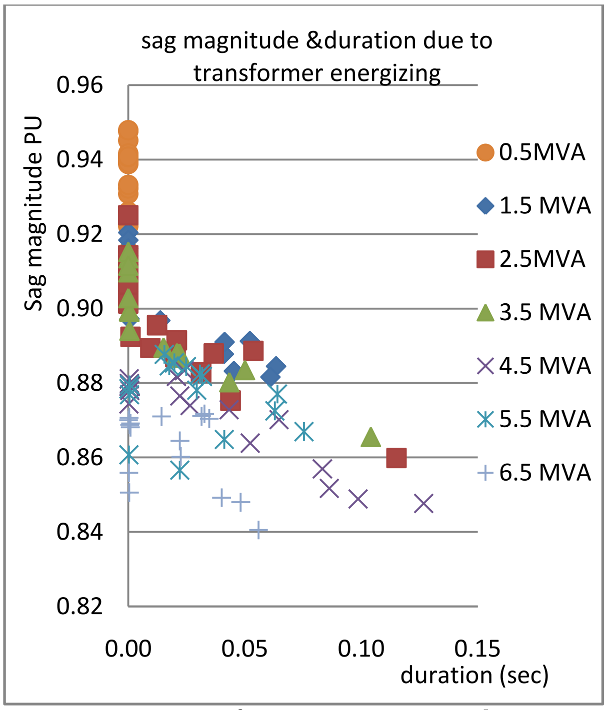

Figure 5 - Transformer energizing simulation

Load switching

Assuming a pre-switching voltage of 0.95 pu (average value during monitoring period) of nominal voltage (22KV) at the monitored bus-bar (Bus3) and switching on a load of 3.949 MVA (maximum load fed from T2). Figure 6 illustrates voltage profile due to switching on a load of 3.949 MVA.

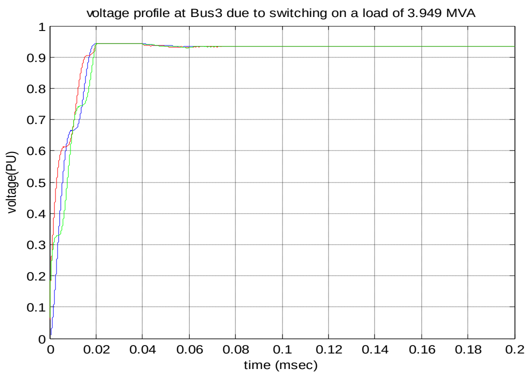

Figure 6 - Voltage profile due to switching on a load of 3.949 MVA

Induction motor (IM) starting

After surveying customers fed from the system under study, it is found that induction motors (IM) with rated power of 18 (KW) and more usually use soft starting methods to start the motor. Therefore, the simulated motor in this study has rating of (22.5 KVA) and assumed (0.9 pf). Figure 7 illustrates voltage profile due to switching on 22.5 KVA induction motor

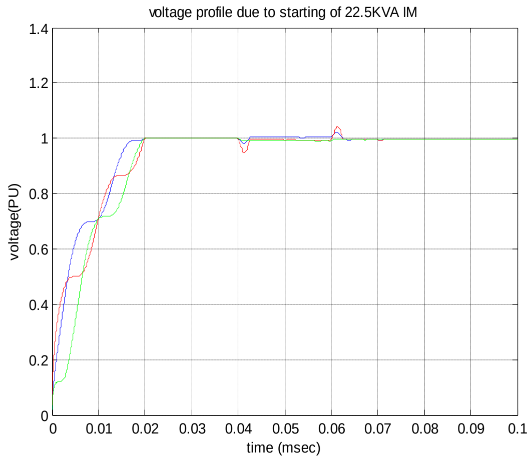

Figure 7 - Voltage profile due to switching on 22.5 KVA induction motor

VOLTAGE SAG DISCRIMINATION

Allocating both recorded voltage sags and simulation results on one chart, figure 8 shows that there is a region of overlapping between voltage sags due to distribution faults and due to transformer energizing which means that identifying voltage sag origin using sag magnitude and sag duration only is not enough.

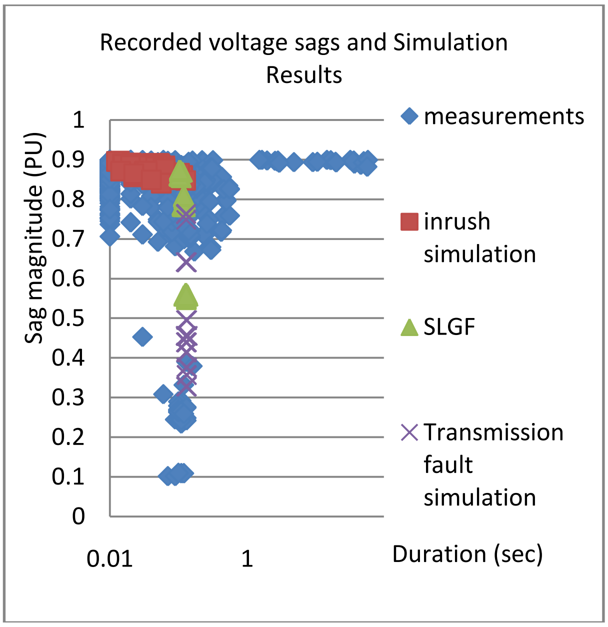

Figure 8 - Recorded voltage sags and simulation results

Figure 9 illustrates the wave shape of (I_2) for SLGF current and inrush current in (PU)
By calculating the area under each curve it was found that:
Area under SLGF curve = 49.3020
Area under transformer energizing curve = 661.0158
Also from simulation results:
Maximum % of I_2/I_1 for SLGF=7.48%.
Minimum % of I_2/I_1 for transformer energizing=19.92%.
Therefore, the percentage of I_2/I_1 can be used as a discriminating tool.

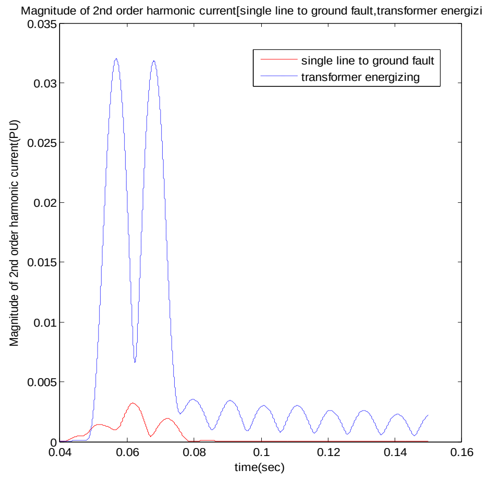

Figure 9 - 2nd order harmonic of SLGF and transformer energizing currents.

The application of this concept for discrimination was shown in figure 10 where the addition of this third axis completely resolves the overlap between voltage sag due to faults and transformer energizing.

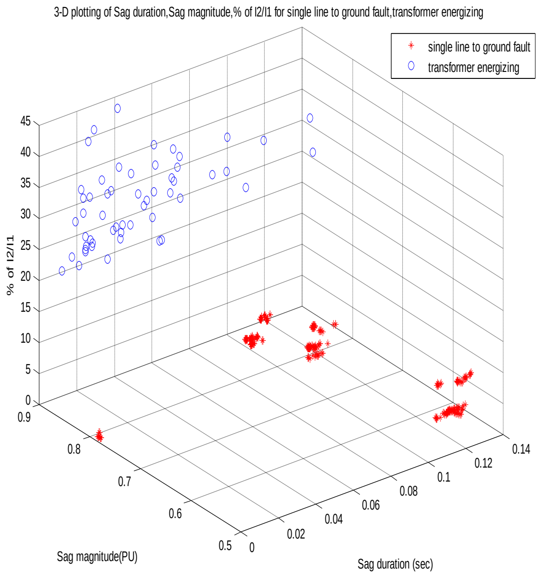

Figure 10 - Plotting of voltage sag &% of I_2/I_1 for SLGF and transformer inrush current

Table 1 - A sample of VDA, event duration and voltage sag energy index (E_{vs})

Sample of sags (P-P)				
Duration	Value	PU	$1-PU^2$	E_{vs}
0.03	107.5	0.8884	0.2107	0.0063
0.02	101.4	0.8380	0.2977	0.0060
0.01	108.8	0.8991	0.1915	0.0019
0.01	105.2	0.8694	0.2441	0.0024
0.01	104.2	0.8611	0.2584	0.0026
0.01	106.3	0.8785	0.2282	0.0023
0.01	105.2	0.8694	0.2441	0.0024
0.01	107.3	0.8867	0.2136	0.0021
0.01	106.4	0.8793	0.2268	0.0023
0.01	108	0.8925	0.2033	0.0020
0.01	107.4	0.8876	0.2122	0.0021
0.01	108.7	0.8983	0.1930	0.0019
0.01	108.1	0.8933	0.2019	0.0020
0.01	108.7	0.8983	0.1930	0.0019
0.16	102.3	0.8454	0.2852	0.0456
0.01	108.8	0.8991	0.1915	0.0019
0.01	106.1	0.8768	0.2311	0.0023
0.01	107.2	0.8859	0.2151	0.0022
0.01	108.7	0.8983	0.1930	0.0019
0.07	12.3	0.1016	0.9897	0.0693
0.09	12.3	0.1016	0.9897	0.0891
0.02	108.7	0.8983	0.1930	0.0039
0.05	106.7	0.8818	0.2224	0.0111
0.06	106.7	0.8818	0.2224	0.0133
0.04	107	0.8842	0.2180	0.0087
0.08	104.8	0.8661	0.2498	0.0200
0.09	104.8	0.8661	0.2498	0.0225
0.11	104.9	0.8669	0.2484	0.0273
0.1	106.1	0.8768	0.2311	0.0231
0.1	106	0.8760	0.2326	0.0233
0.1	106	0.8760	0.2326	0.0233
0.08	106.5	0.8801	0.2253	0.0180
0.08	106.2	0.8776	0.2297	0.0184
0.09	106.3	0.8785	0.2282	0.0205
0.01	108.7	0.8983	0.1930	0.0019
0.01	107.7	0.8900	0.2078	0.0021
0.06	106	0.8760	0.2326	0.0140
0.01	107.5	0.8884	0.2107	0.0021
0.01	107.9	0.8917	0.2048	0.0020
0.01	108.3	0.8950	0.1989	0.0020
0.01	108.3	0.8950	0.1989	0.0020

VOLTAGE SAG ASSESSMENT

As mentioned above, voltage sag assessment has been done through the computation of single-event indices and site indices for the system under study which were computed based on the line-to-line voltage sags recorded during the monitoring period.

Single-event indices

The selected single-event indices are voltage dip amplitude (VDA), event duration and voltage sag energy index (E_{vs}).
Table 1 shows a sample of VDA, event duration and calculated voltage sag energy index (E_{vs}) according to the following equation

$$E_{vs} = \int_0^T \left\{ 1 - \left(\frac{U(t)}{U_{nom}} \right)^2 \right\} dt$$

Where T: sag duration in sec.
$U(t)/U_{nom}$: sag magnitude in PU.

Site indices

Based on the recorded line-to-line voltage sags the following site indices were calculated.

SARFI 90 =(NE/D)*30
= 184.0351

Where NE: the number of recorded voltage sag events during monitoring period (1049).
D: the number of monitoring days (171).

Sag energy index (SEI) $= \sum_{i=1}^{n} \mathrm{Evs}(i) = 136.17$

Average sag energy index (ASEI) $= (1/n) * \sum_{i=1}^{n} \mathrm{Evs}(i)$
=0.1298

Where n: the number of recorded events during monitoring period (n=1049).
Unfortunately, there is no international standard specifying permitted ranges for theses site indices.

CONCLUSION

Based on the results of this work, the following conclusions can be drawn:

From simulation results

In case of distribution faults, voltage sag magnitude is mainly affected by the magnitude of fault resistance. Voltage sag duration is mainly affected by the fault clearing time.
In case of transmission faults, voltage sag magnitude is affected by fault resistance magnitude, fault type and fault location. Voltage sags duration is affected by fault clearing time.
In case of transformer inrush, energizing a transformer of 0.5MVA rated power doesn’t cause any voltage sag, energizing transformers of 1.5MVA or 2.5MVA or 3.5MVA rated power may cause voltage sags depending on the switching on angle and the residual flux value, energizing transformers of 4.5MVA, 5.5MVA or 6.5MVA rated power will cause voltage sags at any switching on angle and any residual flux value. Voltage sag durations also depend on the switching on angle and the residual flux value. Therefore, the number of voltage sags caused by transformer energizing can be reduced by energizing each transformer individually or decreasing the number of transformers which are energized together in every switching on operation.

From comparison of simulation results and recorded measurements

It is found that voltage sag characterization using sag magnitude and sag duration is not enough to release the overlap between voltage sags due to distribution system faults and that due to transformer energizing. Therefore, using the percentage of (I_2/I_1) as a discriminating tool to resolves the overlap between voltage sags due to transformer energizing and distribution system faults is a powerful method.
Most of recorded voltage sags are due to transformer energizing and distribution faults. Therefore, the system performance can be greatly improved if the number of voltage sags due to transformer energizing and distribution faults are decreased.

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