An Investigation into the Impact on Voltage Sag due to Faults in Low Voltage Power Distribution Systems

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Abstract - Voltage sags are the most widespread quality issues affecting distribution systems. This paper describes in some detail the voltage sag characteristics due to different types and locations of fault in a practical low voltage power distribution system encountered in the UK. The results not only give utility engineers very useful information when identifying parts of the system most likely to pose problems for customer equipments, but also assist the facility personnel to make decisions on purchasing power quality mitigation equipment.

Keywords: power quality, voltage sag, distribution systems, voltage unbalance

1. Introduction

A voltage sag, as defined in the IEEE Std. 1346-1998 [1], is a momentary decrease in the rms voltage magnitude, usually caused by a remote fault somewhere on the power system, with a duration ranging from half a cycle to a few cycles (less than one second). The longer the voltage sag lasts, the more probable the chances of malfunction of customer equipments.

Voltage sags are the most widespread quality issues affecting distribution systems, especially in industry where losses incurred can reach very high values. Even a short and shallow voltage sag can cause the dropout of a whole factory; this can result into a long and costly delay for the full plant to recover, some times several hours. In general, it is normal to consider voltage sags being the cause of between 70% to 90% of the industrial power quality problems [2]. Accurate estimates of sag magnitude and duration probabilities help system designers to select appropriate equipment specifications for critical processes. The acquired sag information can be used by the utility engineers to understand the 'weak locations' (ie, areas of vulnerability) of the electrical supply system and to assist the wanagement personnel to take decisions on purchasing power quality mitigation equipment.

Faults cause voltage sags that can disrupt proper functioning of sensitive equipment and these problems are likely to continue until such time as equipment is manufactured to be less sensitive. Since the utility faults cannot be eliminated completely, solutions to the voltage sag problems on the utility side include fault prevention activities and modification to fault clearing practices and on the customer side, a power line conditioning equipment is required to be used to provide ride-through capability for highly sensitive loads. Modest change in equipment specifications through design practices also provides the equipment ride-through capability [2,3].

This paper describes the voltage sag characteristics in a practical low voltage distribution system. The distinct features of voltage sags and unbalance are summarized including factors influencing the voltage sag magnitude, such as, different types of fault, fault locations, loading conditions, etc.

2. General Methodology for Determining Voltage Sags in Electrical Power Systems

A better understanding of the voltage sag characteristics of the electrical power system offers the opportunity to evaluate alternative system configurations and small modifications in equipment specifications can reduce the number of nuisance outages due to voltage sag. Hence there is a definite need for utility companies to provide more information concerning voltage sags to their customers in today's competitive environment.

A voltage sag is principally described by two essential characteristics, magnitude and duration. The magnitude is determined by the electrical distance to the fault and the duration by the fault clearing time. However, a fault in a power system not only leads to a drop in voltage magnitude, but also to a change in phase angle of the voltage (jump in phase angle). This so called phase angle jump can be calculated as the argument of the complex voltage.

The impact of sag depends on equipment sensitivity. For a faulted radial system, one can calculate the voltage sag at the point of interest by using the impedance divider

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principle. These are some of the major factors that influence the voltage sag magnitude [4,5]:

1) *Fault location:* any fault closer to the substation produces a more severe sag than when the fault is far from the substation.
2) *Types of fault:* three phase (3LF) and Single line to ground fault (SLGF) are normally considered in the analysis; this is so by virtue of the fact that the former has the maximum impact on voltage sag and the latter is the most common type of fault. However, two phase and two phase to ground faults (LLF, LLGF) are also included in this paper.
3) *Effect of transformer connections:* three phase transformer connected delta/star or star/delta alters the unbalance in voltage sags in the three phases.

General methodology for voltage sag analysis basically consists of: 1) *load flow*: a load flow program representing the existing or modified system is required; 2) *voltage sag calculation*: a standard short circuit program is utilized for this purpose.

3. Model of the Distribution System Studied

The model developed herein is based on the MATLAB power systems blockset and parameter data from a UK Electricity Company.

The system is illustrated in Fig 1. Feeder 1 has three loads. The lengths of the cables between loads are all 1 km. Feeder 2 has four loads. All the loads connect with the busbar through transformers and 1 km cables. The main power transformers are Star/Star to earth through a 'tank'. The 'tank' acts as a tertiary delta winding providing a path for zero-sequence currents. The distribution transformers connecting the loads to the main distribution line are all delta/star to earth, as shown in Fig. 1.

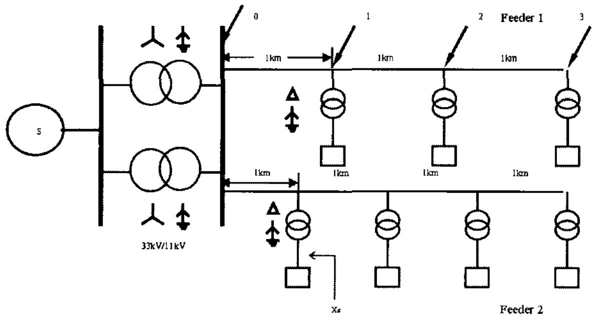

Fig. 1 system structure

3.1 Types of Load

The types of load connected are respectively, static, dynamic, and a mixture of the two, for calculating their impact on the voltage sags for a particular type of fault. All the static loads (the first three loads from the source side) on feeder 2, the healthy feeder, are static loads rated at 1 MVA with a power factor (pf) of 0.9 lagging. The dynamic load (the 4th load) is a 1 MVA asynchronous induction motor with 0.85 lagging pf and 85% efficiency. On feeder 1, the faulted feeder, the first two loads (from the source side) are 1 MVA static loads with a 0.9 lagging pf; the third load is a mixture of static and dynamic, the former rated at 1 MVA and 0.9 lagging pf and the latter, a 1 MVA asynchronous induction motor with 0.85 lagging pf and 85% efficiency.

The faults occur respectively at positions 0 (bus bar), 1, 2 and 3 on feeder 1. The types of fault comprise of: (i) single phase to ground, (ii) two phase to ground, (iii) phase to phase and (iv) three phase to ground. The measurement position is on the load side on feeder 2 (e.g. at Xs). Voltage profiles measured at other customer sides are very similar to those at point Xs.

3.2 System Parameters

Source: V=33 kV, resistance 5.687 ohms.
Main transformer: S=23 MVA, f=50 Hz (base)
Winding 1: V=33 kV, R1=0.002pu, L1=0.2pu
Winding 2: V=11 kV, R2=0.002pu, L2=0.2pu
Winding 3: V=2 kV, R3=0.005pu, L3=1pu
Cable:
Resistance R1= 0.01951ohm/Km, R0=0.02088 ohm/Km
Inductance L1=0.25465 mH, L0=0.38897 mH
Capacitance C1=12.74e-8 F, C2=7.751e-8 F
Customer side Transformer: S= 1 MVA
Winding 1: V=11 kV, Rp=0.001pu, Xp=0.0288pu
Winding 2: V=220 V, Rs=0.001pu, Xs=0.0288pu
Magnetizing Branch: Rm=500pu, Xm=500pu.
Motor Parameters: Pn= 30 HP, Vn= 220V, Fn = 50 Hz
Stator: Rs=0.0435 ohm, Ls= 2.0 mH
Rotor: Rr= 0.0816 ohm, Lr=2.0 mH
Mutual Inductance: Lm=69.31 mH
Inertia time constant H = 1.4 s.

4. A Summary of the Results

The simulation results can be divided according to the types of fault. In the case of dynamic loads, the majority of results given in this paper are only for 50% motor loads.

4.1 Single Line to Ground Fault (SLGF)

The single line-to-ground fault is the most common type of fault and importantly, through a delta-star transformer, it is transformed into a two-phase voltage sag; in this case, the voltage sag should be looked upon as a case of unbalanced transient supply to the loads. The results presented herein are when a single line to ground fault occurs at different positions on Feeder 1.

Fig. 2 illustrates the voltages at the busbar when a single line to ground fault occurs on phase A at the busbar (position 0). The remnant voltage of phase A is close to zero. When a single line to ground fault occur at different positions, the remnant voltage of phase A is non zero since there is an impedance between the busbar and fault positions.

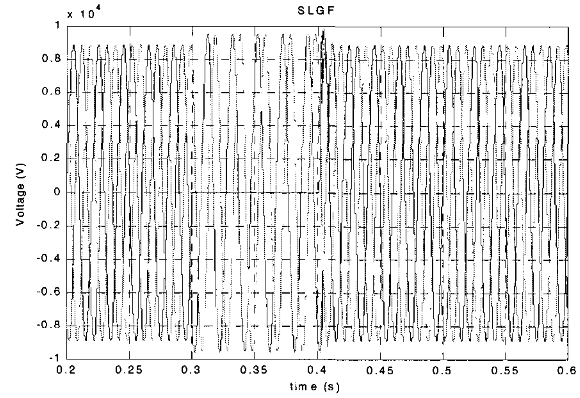

Fig. 2 Busbar voltages when a SLGF occurs at position 0

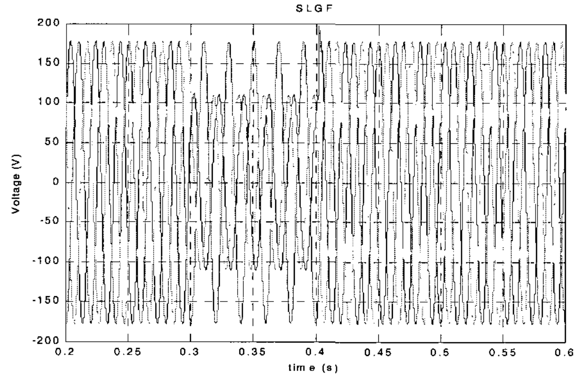

Fig. 3 Customer side voltages when a SLGF occurs at position 0

The voltage changes on the customer side (ie, point Xs) are depicted in Fig. 3 (SLGF at position 0). These voltage waveforms interestingly show that although the fault is on the A phase, the healthy C-phase voltage also experiences almost the same voltage dip as the faulted A phase. The magnitude of the healthy B phase voltage, however, remains unchanged. This phenomenon can be directly attributed to the delta/star transformer connection for the customer load. As would be expected, on the delta connected primary side, the line voltages AB, BC and CA are the same as the phase voltages A, B, and C. This effectively means that when the faulted A-phase voltage collapses, there is a direct impact on the C-phase voltage on the secondary side of the customer transformer. It should be noted that if the fault were to be, say, on the B phase, then the impact of this fault would be on the A-phase voltage ie, this voltage on the secondary side of the customer transformer would also show a dip.

The RMS magnitudes of the three phase voltages are plotted in Fig. 4. These values are calculated using a complete cycle of data. Fig. 5 shows that the dips are a function of fault locations or the electrical distance between the busbar and the fault position. The descending slope of all the dips is the same but the level of dips is slightly different.

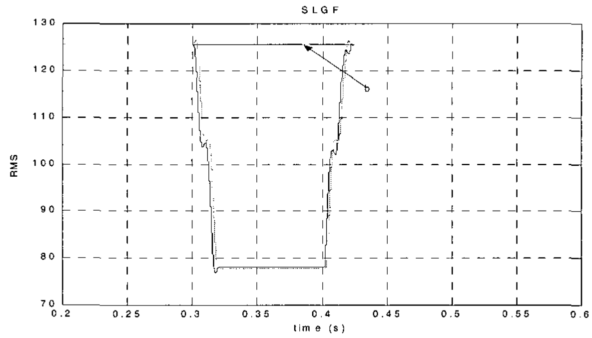

Fig. 4 RMS voltages of the three phases

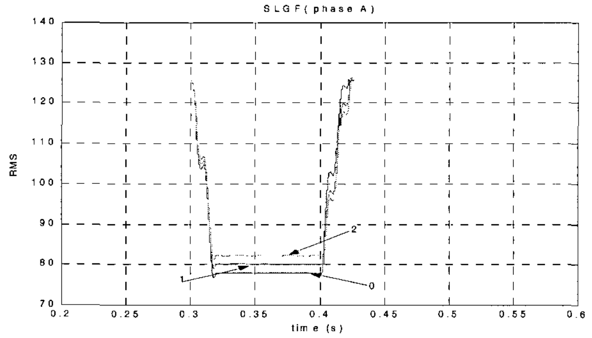

Fig. 5 RMS voltage changes following different fault locations (phase A)

4.2 Two phase-to-ground Faults (2LGFs) and phase-phase Faults

When a double line-to-ground fault occurs, the voltage waveforms are the expected signals ie, a collapse in the two faulted phases A and B (see Fig 6). However, the profiles on the customer side through the delta/star transformer have quite unique characteristics as shown in Fig 7. It can be seen that whilst the faulted A phase voltage collapses to a near zero value, the other faulted phase (B) and the healthy phase C have almost identical magnitudes during the period of the fault; this is depicted in Fig 8 which shows the RMS voltages of the three phases. This rather peculiar phenomena can be directly attributed to the transformer connection for the customer load. It can be shown mathematically that for this type of fault, the V_{AB} voltage collapses to near zero and hence the A phase voltage on the secondary side also collapses to zero. However, the B and C phase voltages on the secondary side are almost identical in magnitude but are of opposite polarity. Fig 9 typifies the RMS voltage profiles on the customer side (ie, at point Xs in Fig 1) of the B and C phases respectively, for different fault locations.

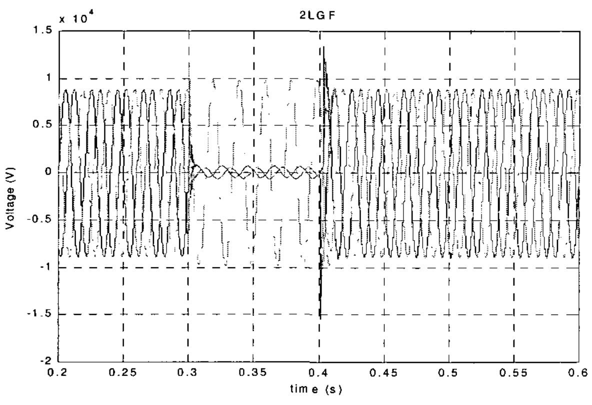

Fig. 6 Bus bar voltages during LLGFs

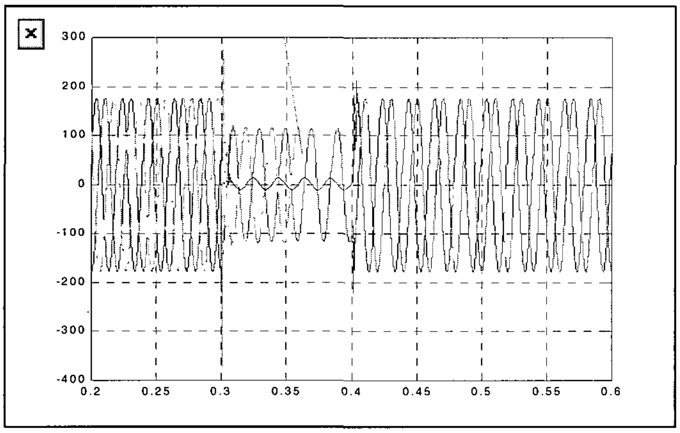

Fig. 7 voltages on the custom side

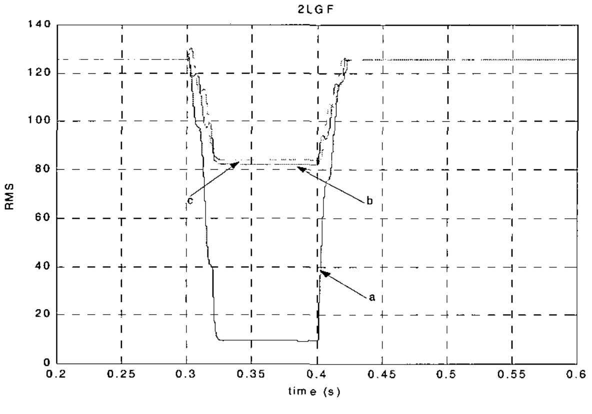

Fig. 8 RMS voltages of three phases

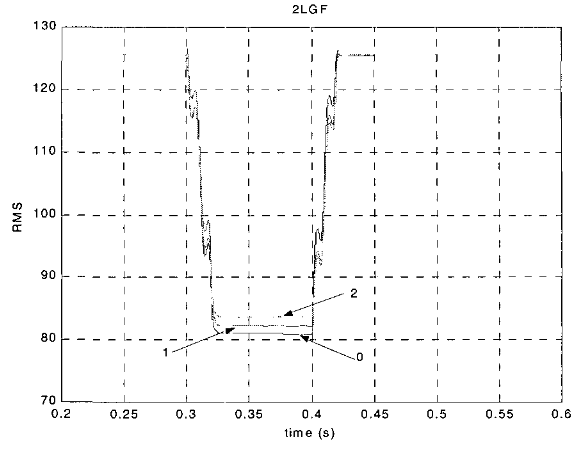

Fig. 9 RMS changes following different fault locations (phase B or C)

Although not shown here, the results for a phase to phase fault clear of ground are identical to those shown for a two-phase-ground fault. This would be expected by virtue of the fact that the delta winding of the transformer acts as a trap for the zero sequence current associated with the two-phase-ground fault, thereby forcing the voltage profile for this type of fault to mimic a phase–phase fault on the customer side of the load.

4.3 Three-phase-to-ground Faults (3LGFs)

As would be expected, the voltage signals are balanced on all the three phases for this type of fault ie, there is voltage collapse on all the three phases. Unlike the previous unbalanced fault, in this case the RMS voltage profiles are more or less identical on the customer side of the load (at point Xs in Fig 1), as depicted in Fig 10 which shows the changes in RMS voltage magnitudes, following different fault positions.

The effect of motor behaviour on the voltage profiles can be quite significant and therefore cannot be ignored. One such example is given herein. The mixed load on the customer side on feeder 1, the faulted feeder, is changed to 100% motor load. A three phase fault occurs respectively at positions 0, 1, 2, 3, from the busbar on feeder 1. Only the RMS voltage profiles at measurement point Xs are illustrated. Like before, the profiles at other points on feeder 2 are very similar to that at point Xs. In comparison to Fig 10, Fig 11 shows that the voltage profiles do not drop very vertically due to the presence of the motor. The energy stored in the motor needs time to release. Thus the voltage drop curve is quite different from those that have an impedance load in conjunction with the motor load. When such an impedance load exists, it sets up a circuit path for the motor to release the stored energy. However, when the fault is cleared, the voltage recovers very quickly.

This is so because the voltage at the busbar is controlled by the source.

In order to ascertain the full impact of motor load on voltage sag, in particular its effect on the descending slope of the sagging voltage, more extensive studies need to be performed with a much larger volume of motor loads connected into the system.

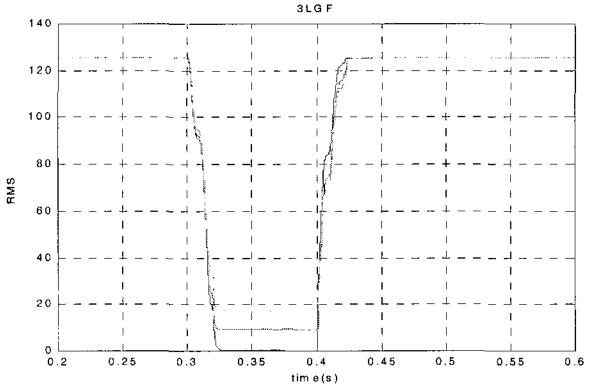

Fig. 10 RMS changes following different fault locations

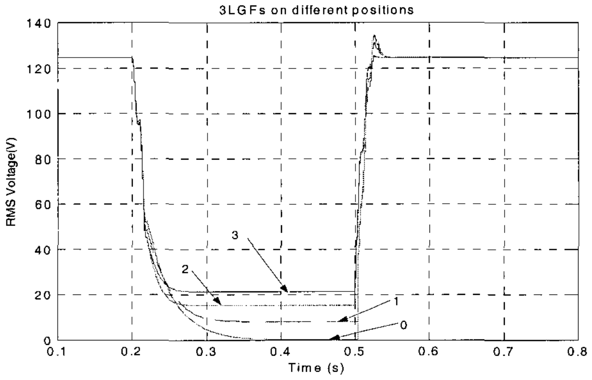

Fig. 11 Voltage profiles when 3LGFs occur at different positions

5. Conclusions

The results presented in this paper clearly show that voltage sags are unbalanced during single phase to ground and two-phase faults, with and without ground involved. The characteristics of sags are also distinctly different between these two types of fault. Only voltage sags associated with three phase faults are symmetrical. The overall conclusions drawn from the study are as follows:

1) **Single phase to ground faults (SLGFs):**When a single phase (A phase) to ground faults occur at different positions on feeder 1, the voltage dips on phases A and C on the customer side are the same but are much more severe than for phase B. This effectively means that for single-line-ground faults, there are always two phases that are affected on the secondary side of the delta/star customer load transformer.
2) **Two phase to ground and phase to phase faults (LLGFs and LLFs):** When, for example, two phases (A and B) to ground or phase-to-phase faults occur, phase A voltage on the customer side drops very significantly, but the B and C phase voltage drops are much smaller than the for the A phase. Moreover, the voltage dips for LLGFs are higher than those for SLGFs and unlike the latter, all three phases are affected.
3) **Three phase faults:** All the three phase voltages drop by the same level. Moreover, the farther the fault position is from the busbar, the lesser is the voltage drop. In other words, the voltage dips on the customer side are directly proportional to the dips at the busbar which in turn are proportional to the distance to fault from the busbar. The effect of motor behaviour on the voltage profiles on the customer side shows some interesting results but this aspect of the work needs some further investigation.

The forgoing study can not only give utility engineers very useful information about potential problems (including areas of vulnerability) that could adversely affect proper functioning of customer equipments but also assist the facility personnel to make decisions on the purchase of power quality mitigation equipment that would reduce the voltage dips to acceptable levels.

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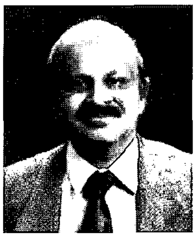

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