

THEORETICAL INVESTIGATION OF ACCIDENTAL CONTACT BETWEEN DISTRIBUTION LINES OF DISSIMILAR VOLTAGE

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Abstract

A theoretical study is presented of the consequences of accidental contact between conductors at different voltage levels. This study was done to complement previous experimental and simulation work [1] and confirmed the previous findings that the distribution transformer holds down the voltage at the point of contact to a value below the nominal lower voltage level. Two cases are examined (a) contact downstream and (b) contact upstream of the distribution transformer location. The theory is applied to some of the experimental and simulation cases examined in [1] and to other case studies.

1. INTRODUCTION

Faults involving contact between distribution lines of dissimilar voltage (also called intermix faults) are not common and their consequences are often misunderstood. They cannot be analysed using the per unit system because of cross-connection of voltage levels which prevents appropriate base quantities being specified. Hence absolute component values must be used. Intermix faults are examined here using simple network analysis.

A typical single phase intermix situation is shown in Figure 1. Up to three stages can be identified for the progression of such an intermix fault:

Stage 1: Initial transient (up to several hundred microseconds).

When the conductors first touch, a short-duration wavefront will travel along the lower voltage line, generating reflections at each point of discontinuity e.g. tee-offs. The magnitude of this initial wavefront will depend on the point on the voltage waveform at which the fault occurs – it will be the difference between the instantaneous voltages on the higher voltage and lower voltage conductors at the moment they first touch. This transient rapidly dies out due to the damping inherent in distribution network.

Stage 2: Steady state situation with lower voltage fuses intact (hundreds of milliseconds).

After the initial transient dissipates, steady state fault conditions are achieved for voltage and current, being determined by the distribution transformer. Transformer action will hold the voltage at the transformer lower voltage terminals to a value slightly lower than normal operating voltage on two of the three phases. This steady state situation has

been investigated experimentally by Chong and Bodger [1] and it is this stage that is examined in this paper.

Stage 3: Steady state situation after the lower voltage fuse has operated (hundreds of milliseconds to seconds).

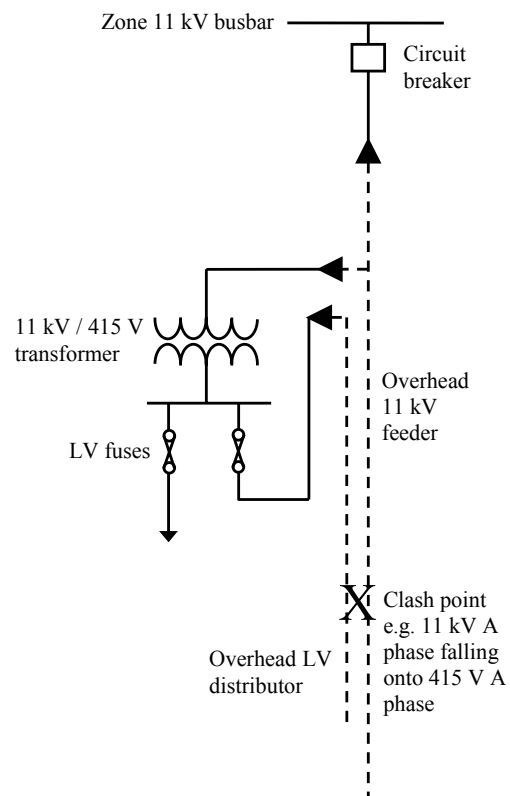


Figure 1: A typical single phase intermix situation.

Stage 2 conditions only exist until the lower voltage fuse on the faulted phase operates at which time the voltage on the faulted phase rapidly rises to the higher voltage (line-earth voltage). This last stage

does not always occur depending on the magnitude of the lower voltage fault current and the speed of operation of the higher voltage protection relays at the zone substation (refer to Section 4 below).

Two theoretical Stage 2 situations are examined in this paper (a) when the conductor contact is downstream of the distribution transformer location, away from the zone substation, and (b) when contact is upstream of the distribution transformer location, towards the zone substation. The theoretical results are applied to some of the experimental and simulation cases examined in [1] and to other case studies.

2. THEORETICAL ANALYSIS

2.1 Downstream Clash

A conductor clash away from the zone substation downstream of the distribution transformer location can be simplified to the single-phase circuit shown in Figure 2.

The impedance of the LV conductors to the clash point has been referred to the primary of the distribution transformer and lumped together with the transformer impedance to give Z_{LV} . Z_S is the source impedance upstream of the transformer tee-off, Z_{MV} is the MV line impedance between the tee-off and the clash point, and $n:1$ is the transformer turns ratio.

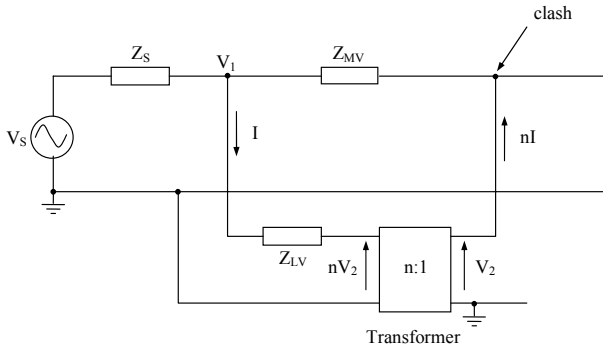


Figure 2: Simplified circuit for downstream conductor clashing.

Considering the transformer primary and secondary currents and ignoring load currents:

$$nI = \frac{V_2 - V_1}{Z_{MV}} = n \times \frac{V_1 - nV_2}{Z_{LV}}$$

Re-arranging:

$$\frac{V_1}{V_2} = \frac{Z_{LV} + n^2 Z_{MV}}{Z_{LV} + nZ_{MV}}$$

Defining
$$\alpha = \frac{Z_{LV} + n^2 Z_{MV}}{Z_{LV} + nZ_{MV}}$$

then

$$V_1 = \alpha V_2 \quad \dots(1)$$

By KCL at node V_1 :

$$\frac{V_s - V_1}{Z_s} = I - nI = (1 - n)I \quad \dots(2)$$

Now as before:

$$I = \frac{V_1 - nV_2}{Z_{LV}} = \frac{(\alpha - n)V_2}{Z_{LV}} \quad \dots(3)$$

Using (1) and substituting (3) into (2):

$$\therefore \frac{V_s - \alpha V_2}{Z_s} = \frac{(1 - n)(\alpha - n)V_2}{Z_{LV}}$$

Re-arranging:

$$V_2 = \frac{V_s}{\alpha + \frac{(n-1)(n-\alpha)Z_s}{Z_{LV}}} \quad \dots(4)$$

Equations (1), (3) and (4) can now be used to solve for the fault parameters. Equation (4) will give the voltage at the clash point and Equation (3) will give the transformer primary current from which the fault current can be calculated. Protection operating times can then be assessed.

For practical distribution networks, α will generally lie between 1 and 2. It is determined solely by local network and transformer parameters being dominated by the value of Z_{LV} .

2.2 Upstream Clash

A derivation similar to that in Section 2.1 can be performed for the case where the conductor clash is upstream of the distribution transformer location. This situation is shown in Figure 3.

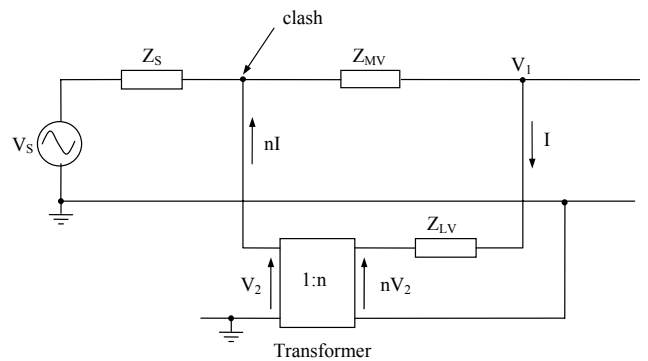


Figure 3: Simplified circuit for upstream conductor clashing.

Considering the transformer primary current and ignoring load currents:

$$\frac{V_2 - V_1}{Z_{MV}} = \frac{V_1 - nV_2}{Z_{LV}}$$

Re-arranging:

$$\frac{V_1}{V_2} = \frac{Z_{LV} + nZ_{MV}}{Z_{LV} + Z_{MV}}$$

Defining $\beta = \frac{Z_{LV} + nZ_{MV}}{Z_{LV} + Z_{MV}}$

then

$$V_1 = \beta V_2 \quad \dots(5)$$

By KCL at node V_2 :

$$\frac{V_s - V_2}{Z_s} = I - nI = (1 - n)I \quad \dots(6)$$

Now as before:

$$I = \frac{V_1 - nV_2}{Z_{LV}} = \frac{(\beta - n)V_2}{Z_{LV}} \quad \dots(7)$$

Using (5) and substituting (7) into (6):

$$\therefore \frac{V_s - V_2}{Z_s} = \frac{(1 - n)(\beta - n)V_2}{Z_{LV}}$$

Re-arranging:

$$V_2 = \frac{V_s}{1 + \frac{(n - 1)(n - \beta)Z_s}{Z_{LV}}} \quad \dots(8)$$

As before, Equation (8) will give the voltage at the clash point and Equation (7) will give the transformer primary current from which the fault current can be calculated.

For the upstream clash, the value of β is always very close to 1 for practical networks being dominated by Z_{LV} (as was found for the value of α). The transformer impedance together with the LV distributor impedance referred to the transformer primary will always be much larger than nZ_{MV} or Z_{MV} .

3. CASE STUDIES

3.1 Experimental Work of Chong and Bodger

A previous investigation by Chong and Bodger [1] has indicated that intermix faults pull down the voltage at the fault point to a value less than or equal to the lower network voltage. The theoretical

formulas developed above were applied to the experimental part of this study.

Chong and Bodger set up a simple, single phase, 230 V laboratory experiment to measure the voltages and currents associated with downstream intermix faults. The circuit consisted of two radial network arms fed from a single phase power supply. Each network arm consisted of a lumped R-L model of a distribution feeder with nominal impedance of $50 + j25 \Omega$, and a load resistance of 450Ω . A 230/24 V transformer was inserted into one network arm to simulate conversion of the load voltage on that arm to a lower voltage. A switch was connected between the secondary of the transformer and the other network arm. An intermix fault could then be simulated by closing the switch. Figure 4 shows the circuit layout arrangement.

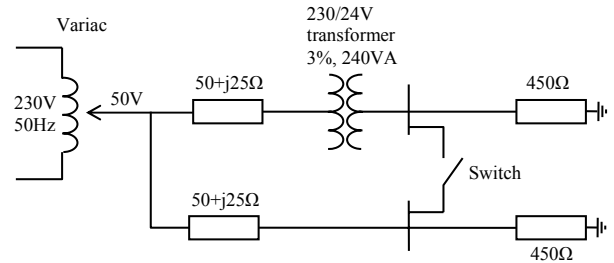


Figure 4: Experimental circuit used by Chong and Bodger [1]

From the circuit, the following can be determined:

$$n = 230/24 = 9.58$$

$$Z_{MV} = 55.9\Omega$$

$$Z_{LV} = 59.15\Omega \text{ (including } 6.6\Omega \text{ for the transformer)}$$

$$Z_s = 0.1\Omega \text{ (stated by Chong and Bodger)}$$

$$V_s = 50V$$

Using these values, α was found to be 8.73. This is much greater than is found for practical distribution networks due to the large values of impedance used to represent the network arms so that circuit currents could be kept low.

Using Equation (4), $V_2 = 5.7V$.

This gives good agreement with the measured voltage at the intermix point which was 5.6V (pulled down from 49.5V).

The current in the secondary of the transformer due to the intermix was also calculated using Equation (3). This current had a value of 0.79A which was 6.6 times the load current flowing in the network arm without the transformer before the intermix. Unfortunately this current could not be compared with the measured value as there appeared to be an error in the reported value. 1.36A was said to flow in the network arm without the transformer during the

intermix causing a 44V drop across the $50+j25\Omega$ impedance which is clearly impossible.

3.2 Practical Networks

3.2.1 Downstream Clash

A typical 11 kV overhead network was examined to find the line-neutral voltage and fault current at the intermix point for a single phase 11 kV/415 V downstream clash for a range of fault locations. The network investigated is shown in Figure 5.

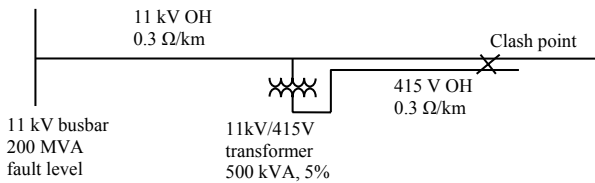


Figure 5: Typical overhead distribution network used to examine intermix faults.

For the purpose of the investigation, the transformer was located at 2, 4, 6, 8 and 10 km from the zone substation and the intermix fault was considered at a distance from the transformer of 50 to 300 m. The line-neutral voltage calculated at the fault point is given in Figure 6 (nominal voltage is indicated in red) and the fault current generated is shown in Figure 7.

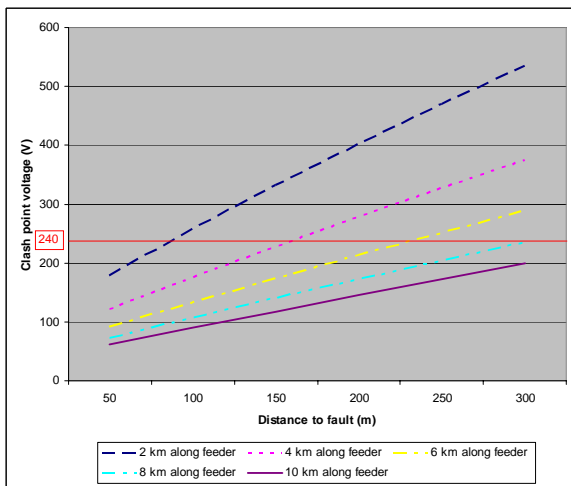


Figure 6: Line-neutral voltage at clash point for downstream faults

It can be seen from Figure 6 that the voltage at the fault point increases linearly with distance from the transformer and at a greater rate the closer the transformer is to the zone substation.

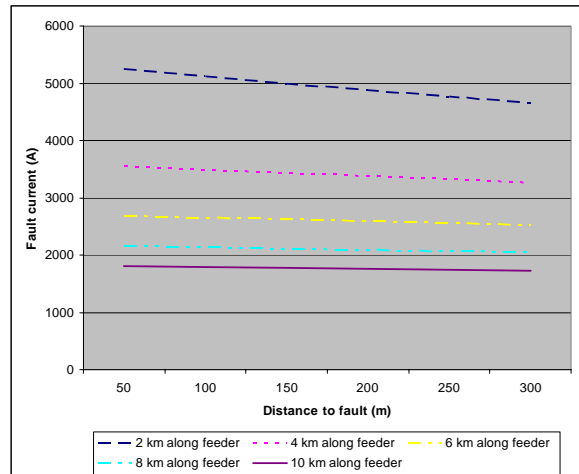


Figure 7: Fault current for downstream faults

Figure 7 indicates that fault current does decrease linearly with the distance to the fault along the overhead mains from the transformer. The rate of decrease is greater the closer the transformer is to the zone substation but the relative changes are not as great as for the voltage at the fault point.

It is obvious that the main factor effecting both fault voltage and current is the distance of the distribution transformer from the zone substation.

3.2.2 Upstream Clash

The network in Figure 5 was also used to examine faults upstream from the transformer towards the zone substation. The results are given in Figures 8 and 9.

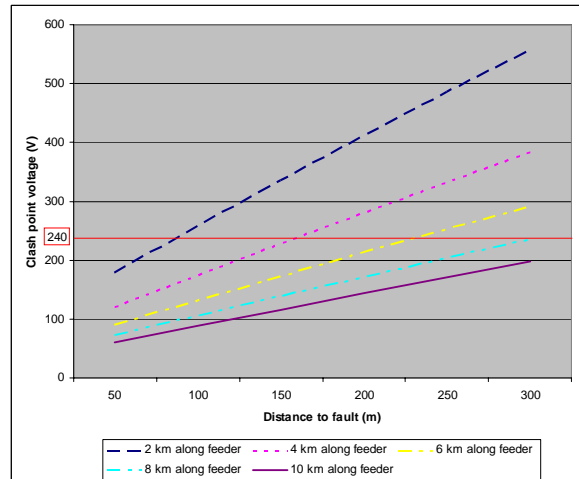


Figure 8: Line-neutral voltage at clash point for upstream faults

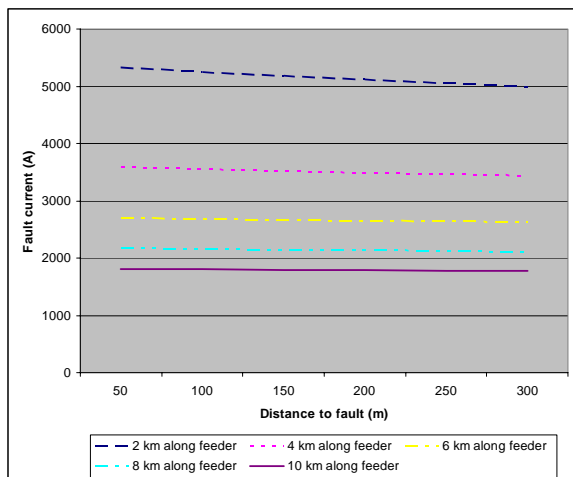


Figure 9: Fault current for downstream faults

Results for fault voltage and current are much the same as for the downstream case again showing the dominant effect of the distance of the distribution transformer from the zone substation.

4. PROTECTION CONSIDERATIONS FOR INTERMIX FAULTS

As can be seen from the case studies, the main result of the clashing of conductors at different voltage levels is to reduce the voltage at the fault to below the nominal lower voltage. However, this will only be the case until the fuses on the transformer secondary operate. At this time the voltage rapidly moves to the higher voltage level possibly resulting in the destruction of customer equipment including any surge arresters on the lower voltage system. Surge arresters are designed to handle the short term transients associated with the initial conductor clashing but are rapidly overheated and destroyed if continuous MV/HV is applied.

This type of fault can only be protected against if the circuit breaker at the zone substation that protects the higher voltage feeder operates before the fuses on the transformer secondary. Intermix faults are not normally considered when grading overcurrent protection systems, and the circuit breaker at the zone substation is relied upon to eventually clear the fault. However, protection engineers should be able to examine a range of intermix faults for typical LV/MV network constructions and at a range of distances from zone substations to assess whether or not the zone circuit breaker will operate quickly enough to prevent high voltage being applied to customers' equipment.

5. CONCLUSIONS

The analysis presented allows straightforward calculation of voltages and currents associated with intermix faults once circuit parameters are known. It was found that the dominant parameter determining both fault voltage and current was the distance of the distribution transformer from the zone substation. During such a fault the voltage on the faulted phase is reduced to below the nominal lower voltage. However, should the lower voltage have fuses which operate to isolate the network from the transformer then the voltage on the network will rapidly rise to the higher voltage possibly damaging connected customer equipment. Such a situation can only be prevented if the zone substation circuit breaker opens the circuit before the lower voltage fuses operate.

6. REFERENCES

- [1] K. Chong and P. S. Bodger, "Accidental contact between distribution lines of dissimilar voltages", AUPEC 2002, Melbourne, Sept. 2002.