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MODELING VOLTAGE SAGS ON UTILITY AND INDUSTRIAL POWER SYSTEMS

by

Kai Yao ©

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Abstract

The voltage sags, one of the most common power quality disturbances, may cause the misoperation of an electric power system's sensitive loads such as computers, power electronic devices and controls, PLCs, etc..

This thesis presents the basic voltage sag analytical techniques based on circuit theory and reliability theory to estimate voltage sag levels and the number of voltages sags at a particular customer location in a distribution system. An expression for distribution feeders' critical distance is developed to identify the voltage sag sensitive areas within a distribution system. Voltage sags caused by utility primary system single line to ground faults are altered by various transformer connections and are examined in detail. In order to reveal the transient features of voltage sags, simulation case studies are conducted on an industrial power system. The simulation results reveal the voltage magnitude and voltage phase angle deviations on all buses within the industrial system.

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Modelling Voltage Sags on Utility and Industrial Power Systems" submitted by Kai Yao in partial fulfillment of the requirements for the degree of Master of Science.

D. O. Koval (Supervisor)

J. C. Salmon

M. Zuo

June 29, 2000

Date Approved

In loving memory of my Grandmother

With all my love to

my dedicated, loving wife, Lan

my happy, shining and creative niece, Judy

Acknowledgment

Words cannot truly express my deepest gratitude and appreciation to Dr. Don Koval, my M.Sc. supervisor, for his guidance, encouragement and support during the preparation of this thesis. He has helped me not to get lost during the development of this thesis by providing a motivating, enthusiastic, and critical atmosphere during my thesis time. Without his lifting me up when this thesis seemed interminable, I doubt it should ever have been completed.

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Chapter 1 Introduction

1.1 Power Quality

Power Quality (PQ) is defined as any power problem manifested in voltage, current or frequency deviation that results in the failure or malfunction of customer equipment [1]. It has been a growing concern for both the utilities and customers over the past two decades. This issue has resulted from the proliferation of power quality sensitive equipment, such as microprocessor-controlled devices, computers, variable speed drives and semiconductor devices. As a consequence, power quality disturbances, which have been considered normal for many years, now may cause disruption to the industrial power system with a resulting loss of production. Power quality disturbances such as momentary under-voltage (sag), over-voltage (swell), surges and harmonics have been identified as the major sources of power quality problems [1].

Power Quality is a whole new area within electrical engineering where fundamental research involves basic concepts and definitions; modeling and analysis; measurement and instrumentation; sources; effects; and mitigation. The ultimate goal of power quality research is to maintain a satisfactory quality of the electric supply. See [2,3,4] for a general review of the subject, research guidelines and new emerging power quality standards and guidelines. Several U.S. and European standard efforts are shown in [5, 6].

Many PQ research activities were aimed at capturing the characteristics of PQ disturbances and identifying the current PQ level in certain areas. Two major projects are CEA National Power Quality Survey [7] and EPRI Power Quality Survey [8]. In 1991, the Canadian Electrical Association (CEA) launched a three year Canadian National Power Quality Survey. Twenty two utilities were involved and 550 sites monitored. Some of the data collected have been analyzed and results, for instance, frequency of sags of industrial and commercial customers have been reported [9]. Between 1990 and 1995, Power Electric Research Institute (EPRI) took a survey on PQ levels across continental United States [10] in which twenty-four utilities participated. In the initial stage of this survey, a new monitoring device known as BMI 8010 was designed. A data management system known as PQview has also been developed which aimed at tackling the enormous amount of data (22GB/per year).

1.2 Power Quality Disturbances

1.2.1 Classification of PQ Disturbances

1) ***Sags***: momentarily short duration (0.5-30 cycles) decrease of the rated voltage (0.1-0.9pu).

2) ***Swells***: momentarily short duration (0.5-30 cycles) increase of the rated voltage (1.1 - 1.8 pu).

3) ***Transients***: high amplitude, short duration (< 0.5 cycle) voltage disturbances.

4) ***Voltage unbalance***: variation of magnitude and/or phase angle from different phase.

5) ***Harmonics***: voltage and/or current deviation from a true sine wave due to unwanted frequencies that are multiples of fundamental wave.

6) ***Frequency deviation***: a variation of frequency from 60Hz (e.g. caused by the starting of heavy loads on weaker generator systems).

7) ***Flicker***: refers to repetitive sags or swells.

8) ***Spikes***: in-phase impulses which increase the instantaneous voltage.

9) ***Voltage deviation***: a long term change above (over-voltage) or below (under-voltage) the prescribed normal voltage range.

10) ***Blackout***: refers to a total loss of input voltage for a few cycles or more.

Table 1-1 Causes and Effects of PQ Disturbances

Disturbances	Typical Causes	Effects
Sags and Swells	Faults, Motor starting, lightning strike	Computer system interruptions, motor stalling
Transients	Load, Lightning, capacitor-bank switching	System overvoltages, insulation failures, malfunction of sensitive electronic devices
Harmonic Distortion	Power Electronics, arcing device, saturable device	Capacitor blowing, transformer heating/failures, breaker nuisance trips, protective relaying errors

Table 1-1 illustrates the origin and impacts of voltage sags, voltage swells and impulse. Their waveforms are shown in Figure 1-1, Figure 1-2, Figure 1-3 and Figure 1-4.

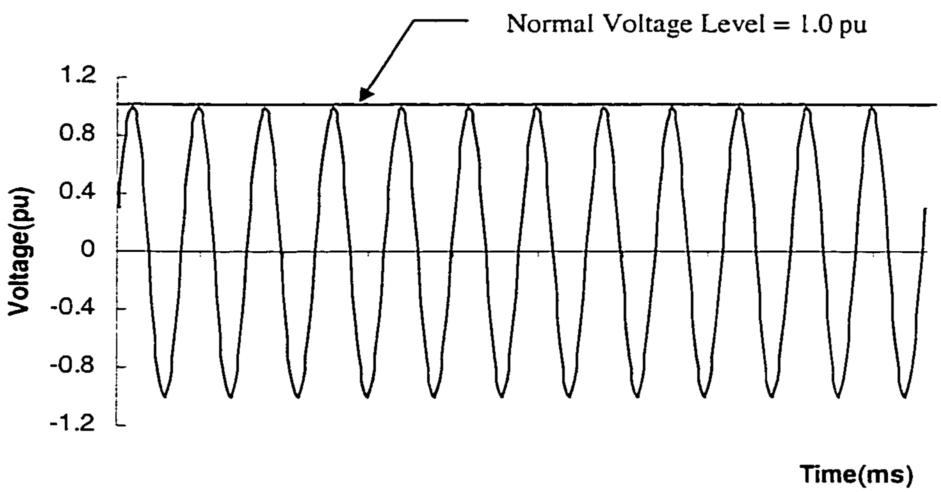


Figure 1-1 Normal Voltage Wave-form

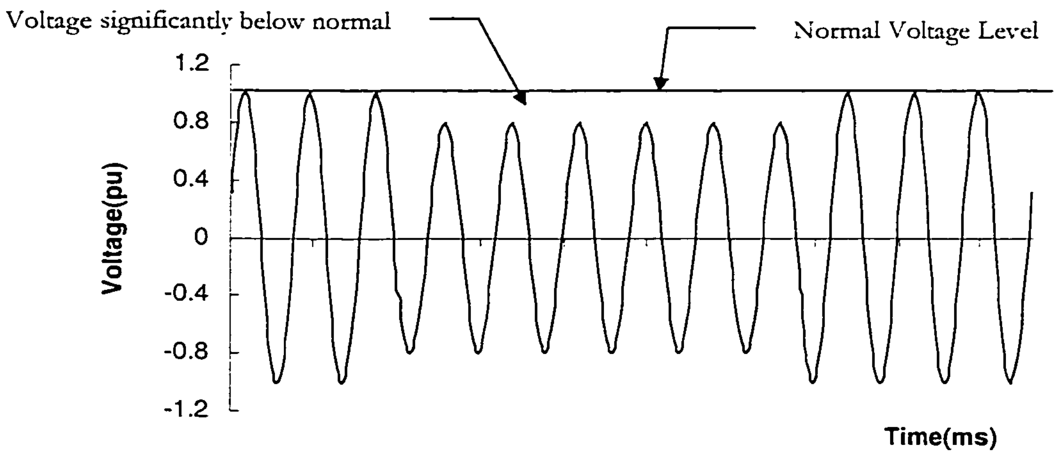


Figure 1-2 Sample Wave-form of a Voltage Sag

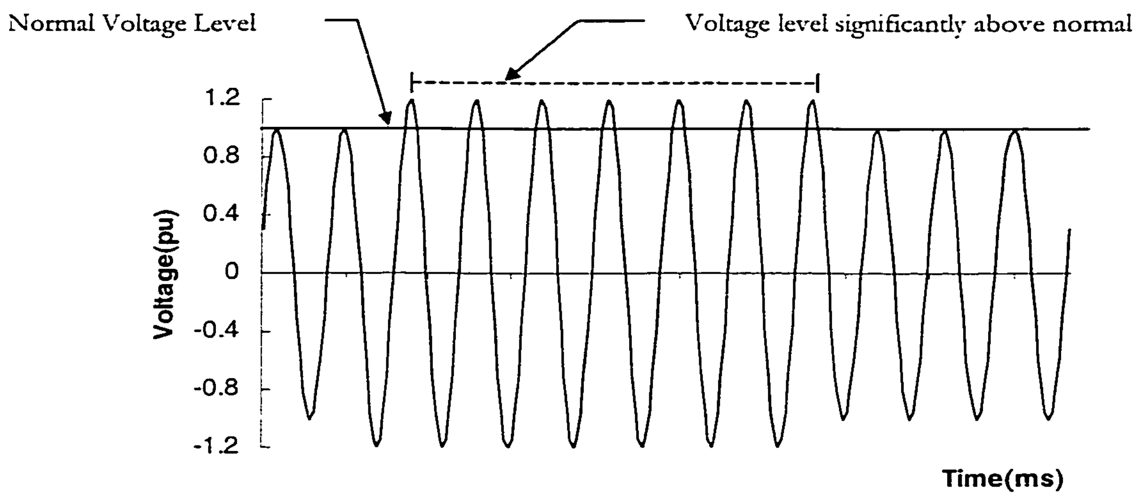


Figure 1-3 Sample Wave-form of a Voltage Swell

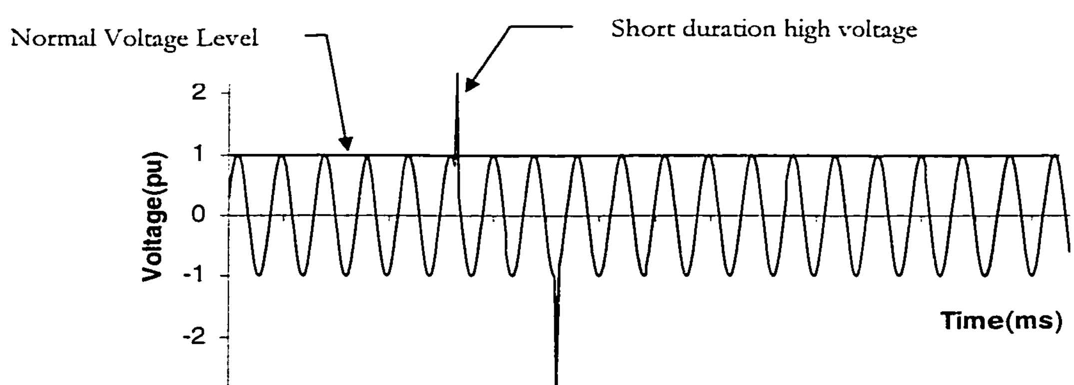


Figure 1-4 Sample Wave-form of a Voltage Surge (Transient)

In addition to PQ surveys, efforts have been made in capturing the characteristics of various PQ disturbances. In the field of modeling and power flow study of harmonics, many studies have been conducted in quite an extensive way [12,13,14,15,16]. A study of transient propagation at a distribution network was presented in [27] in which responses at adjacent feeders due to a fault originating at one feeder have been examined and the theoretical analysis was confirmed by field test. Field measurement results for propagation characteristics of surges in the wiring system of an industrial building are given in [28].

1.2.2 Power Quality Disturbance Mitigation Techniques

PQ disturbances are customarily eliminated or mitigated by power conditioning equipment such as isolation transformers, surge suppressers, UPS and voltage regulators [17,18]. Novel solutions for the mitigation aspects of power quality is a rapid developing area both for research and the mitigation equipment market. Nevertheless, it should be noticed that although power conditioning can deal with the PQ problem to a certain extent, their installation incurs economic losses for the customer in view of up front energy losses ranging from 10-20% [17]. Current PQ disturbance mitigation techniques include provision of a dedicated line, separate regulating transformer for sensitive loads, surge supressors, etc.

1.3 Voltage Sags

Among the above mentioned power quality disturbances, voltage sag was chosen as the subject of this thesis. The short duration sags and swells occur frequently in practice [20, 21]. It is shown that they tend to occur on the order of ten times more often than a complete loss of power. The voltage sags originate from faults either on the utility system or at a customer's facilities. Voltage sags may also occur during the starting of large motors or the switching of large loads. They are also caused by temporary heavy demand for electricity that exceeds the utilities' capability to meet the demand of the system.

1.3.1 Magnitude and Duration of Voltage Sags

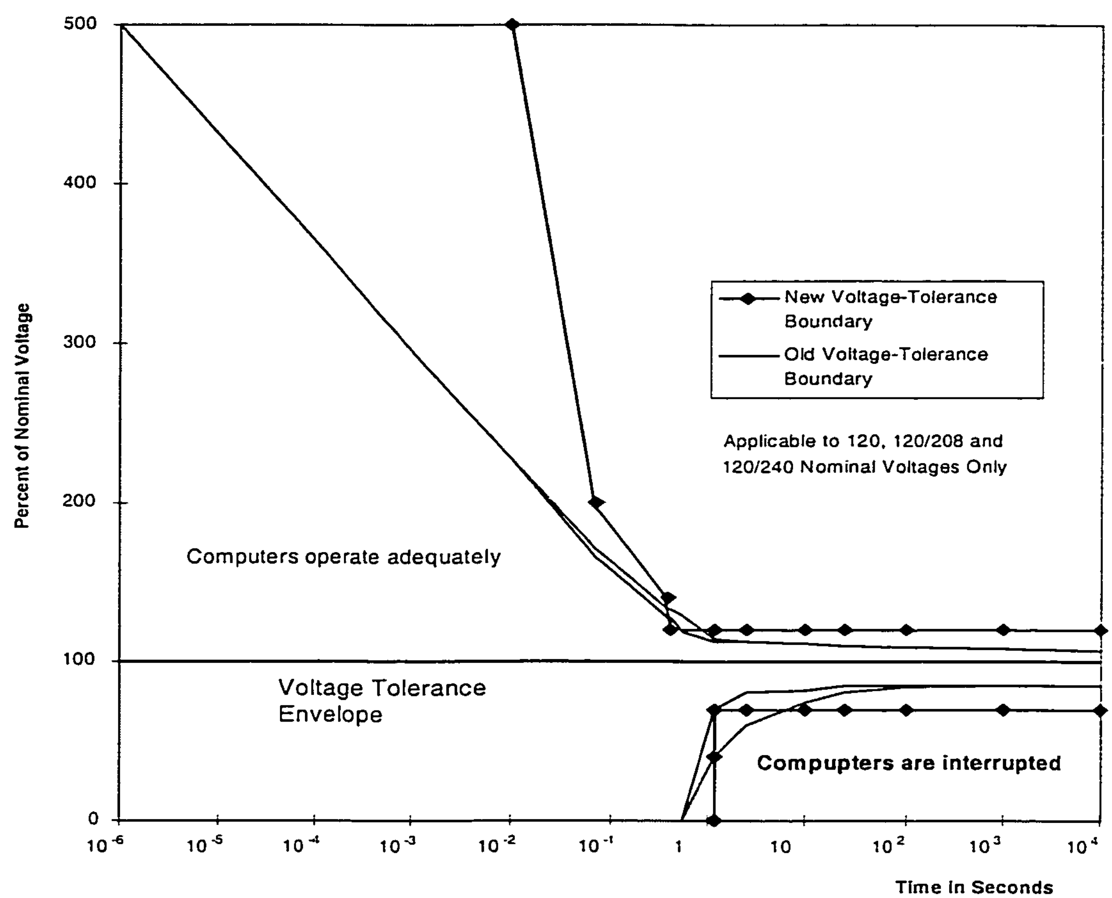


Figure 1-5 CBEMA Curve

The impact of voltage sags on equipment is determined by it's magnitude and duration. For instance, a voltage sag with a drop of 80% in magnitude and 0.4s duration may result in greater damage than one with 85% magnitude decrease and 0.1s duration. Therefore, the effects of voltage sags are often measured by comparison with voltage tolerance curves obtained through field testing. One of the commonly referenced voltage tolerance curves is CBEMA Curve [35] established by the Computer Business and Equipment Manufacturers Association (CBEMA) as shown in Figure 1-5. Reference [22] provides a similar malfunction range for VCRs, microwave ovens and electronic clocks. It is shown in this curve that a 50% voltage sag lasting 5 cycles would affect only the VCR. A comprehensive study with the same nature as CBEMA Curve, e.g. a universally accepted susceptibility curve(s) for sensitive electronic equipment is noted to be necessary to facilitate the voltage sag studies. Currently, such information may be obtained from the equipment manufacturer.

Table 1-2 Duration of Voltage Sags

Statistic	Primary	Secondary
Average Duration (s)	0.8014	0.9221
Standard Deviation(s)	1.2245	1.3659
Minimum Duration(s)	0.1000	0.1000
Maximum Duration(s)	8.8000	9.7

Among others, the magnitude and duration of voltage sags are closely related to the protective relay devices. In case of fault-induced sag, the duration of voltage sag is determined by the fault clearing time that is related to protective relay installed. A field record data [30] shows that if the fault can be cleared in less then 0.2 seconds and the voltage remains above 80% nominal, the load of this particular site will not be affected by the disturbance.

Table 1-2 was constructed from data given in Canadian Power Quality Survey [11] and shows the duration of voltage sags on the primary and secondary sides of customer transformers.

1.3.2 Frequency of Occurrence

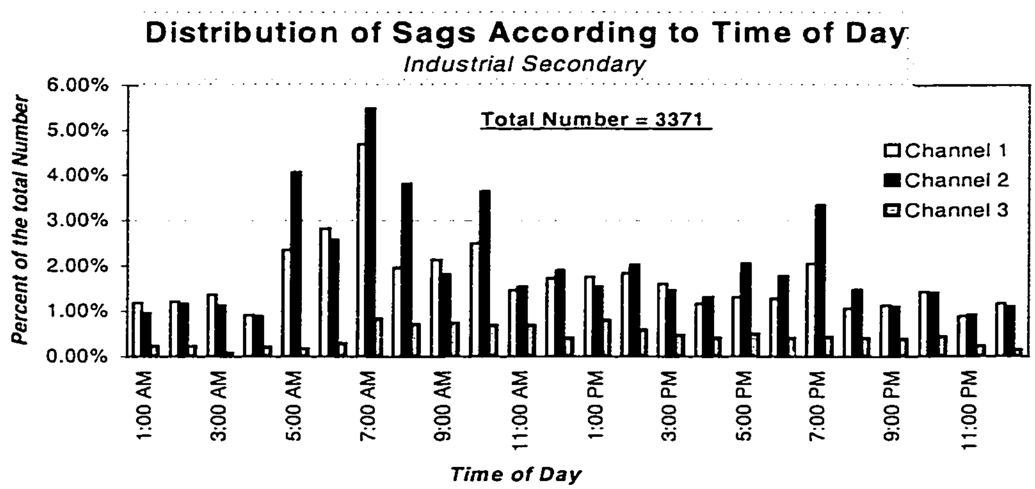


Figure 1-6 Distribution of Voltage Sags

Based on the CEA power quality survey results [11], it is shown that the frequency of voltage sags often follow the loading pattern of the system. Daily voltage sag occurrence at one of the surveyed sites is shown in Figure 1-6.

Theoretical predications of the frequency of voltage sags in a certain industrial system require an accurate network impedance model and reliability data in the electrical neighborhood.

As an alternative to voltage sag monitoring, stochastic predication methods can be used to evaluate the frequency of voltage sags at a specific site [18]. This method is intended to overcome the limitation of power quality monitoring in capturing voltage sags at a specific site of interest.

1.3.3 Sensitivity of Equipment to Voltage Sags

The magnitude and duration of a voltage sag that could disrupt electronic equipment vary from device to device. The following is a summary for some typical equipment.

1) Extreme sags may cause the motor to lose enough rotational inertia to affect its performance or task. If sags happen frequently enough, the motor may draw high inrush currents often enough to trip a breaker. Motor contactor coils will generally drop out for voltages in the range of 50% to 75% for duration of 1-5 cycles [20].

2) AC and DC drives are typically designed for continuous operation with voltage variations of +10% to -5% to -15%. Outside of this range the drive may not be able to maintain speed or other parameters that are critical to the process and may proceed to shut down. In addition, even if the drive were designed to ride through this condition, the product, which is being made in the process, may be damaged or suffer in quality such that it is not acceptable for use. DC drives, compared to AC drives, are more susceptible to voltage sags because they inherently lack the electrical energy storage devices [20].

3) PLCs that are used to control equipment such as AC and DC drives may shut down the devices for voltages on the order of 80% to 85% of nominal. The remote I/O

units, for instance, have been found to trip for voltages as high as 90% for a few cycles [24].

4) In an industrial plant, high-intensity discharge (HID) lighting are often the most sensitive equipment to low voltages. The lamps will typically extinguish for voltages in the range of 85% to 90% of nominal for periods of time as short as 1 cycle and will take several minutes to restart [20]. A common problem associated with HID systems is that the lamps can turn off during a voltage sag. Unlike fluorescent systems that will quickly turn back on, the HID system must wait several minutes before being restarted. This is not only annoying but can be dangerous.

1.4 Scope of the Work

1.4.1 Basic voltage sag analysis in a distribution system

Short circuit faults, especially single line to ground faults, are one of the main sources of voltage sags. Short-circuited fault analysis is mainly used to provide data for system design, protective relay coordination, equipment selection, etc. by obtaining the fault currents. In the meantime, short circuit calculation combined with reliability data can also be used to predicate number of voltage sags and their level of severity as shown in Chapter 2.

1.4.2 Critical distance of voltage sags in a distribution system

The critical distances method [28] is often used to estimate the number of voltage sags due to faults at various voltage levels in a radial system, see Chapter 3. By using this method, the "sphere of influence" can be determined which may facilitate the reliability efforts by confining the study within that susceptible area. Suppose that a piece of equipment trips if the voltage at a certain point of common coupling drops below the critical voltage. In this case, it will trip for all faults within a critical distance from the point of common coupling. The critical distance is given by a complicated expression as shown in [28]. See Chapter 3 for derivation of and discussion about this expression.

1.4.3 Effects of transformer connections on voltage sags

Voltage sags seen by the customer are a function of the connections of the transformer connecting the load to the system. With respect to a single line to ground fault on the primary side of a distribution transformer, the voltage sags on the secondary side with respect to wye-delta connections are examined in Chapter 4 using circuit analysis.

1.4.4 Simulation studies of voltage sags

Simulation studies using the sample system are utilized to access the following sag characteristics:

1) Effects of fault location on voltage sag levels;
2) Nature of sag produced by different types of faults;
3) Transients involved in the sag propagation;

In addition, attempts are made on examining the existence of voltage phase angle jump, see Chapter 5. Recently, some publications have shown that great efforts have been made on revealing phase angle jump and it's impacts [25] ~ [30]. As illustrated in these publications, the phase angle jump exists in the fault period and has an adverse impact on equipment such as variable speed drives [27].

Chapter 2 Basic Voltage Sag Calculations in a Distribution System

Voltage sag characteristics such as the magnitude, duration and frequency of occurrence can be captured using circuit analysis, reliability data and specification of protective relays. This ability to predicate voltage sag profiles within a distribution system offers an opportunity to evaluate alternate plans and prevent voltage sag problems.

2.1 Voltage Sag Analysis

A voltage sag case study is used to illustrate the impact that faults have on a distribution system and the voltage sag experienced by customers in relation to their physical location from the disturbances in the distribution system. For the purpose of illustration, a simplified example of determining the voltage sag at a point of interest is provided and analyzed.

A sample two feeder distribution system with a three-phase fault on Bus 8 is used for this analysis as shown in Figure 2-1. To consider the voltage support which is generated by large motors and other transient components, a motor is added to Bus 7.

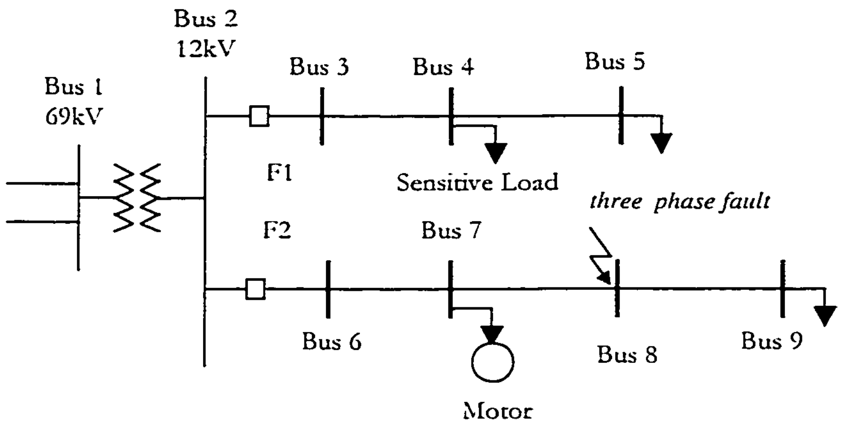


Figure 2-1 Voltage Sags from Fault

By applying circuit analysis at the above equivalent circuit, the voltage sag at the 12kV bus is

$$V_{sag} = \frac{Z_{2-7}Z_{7-8} + Z_s Z_{7-8} + Z_m Z_{2-7} + Z_m Z_{7-8}}{Z_{2-7}Z_{7-8} + Z_m Z_{7-8} + Z_s Z_{2-7} + Z_m Z_{2-7} + Z_m Z_s} \quad \text{......................(2.1)}$$

where:

V_{sag} - voltage sag at 12kV feeder bus in per unit

Z_s - source impedance in per unit seen at 12kV feeder bus (i.e., Bus #2)

Z_m - per unit motor impedance

Z_{2-7} - feeder impedance from Bus 7 to 12kV feeder bus

Z_{7-8} - feeder impedance from fault point Bus 8 to Bus 7

Z_f - per unit feeder impedance per km

If the voltage support provided by the motor connected to the distribution feeder is neglected, e.g. motor is small and Z_m is large, then the voltage sag at the 12kV bus is

$$V_{sag} = \frac{Z_{2-7} + Z_{7-8}}{Z_s + Z_{2-7} + Z_{7-8}} \qquad (2.2)$$

If we define "L" as the distance between the 12kV bus and the fault location on Bus 8, then on 12kV bus, the voltage sag is

$$V_{sag}(12\text{kV bus}) = \frac{LZ_f}{Z_s + LZ_f} \qquad (2.3)$$

Sensitive load on Bus 4 will experience voltage sags due to feeder #2 fault

$$V_{sag}(\text{sensitive load}) = \frac{LZ_f}{Z_s + LZ_f} \qquad (2.4)$$

The voltage sag magnitude at a specific location depends on the system impedance, fault impedance, transformer connection and the pre-sag voltage level. The impact of the voltage sag depends upon equipment sensitivity. It is important to note that the feeder faults closer to 12kV bus (i.e. L is small) result in lower voltage sags seen at sensitive load point. Faults at the remote end of feeder #2 (i.e. L is large) will cause significantly less voltage sags on the 12kV bus.

Voltage will return to normal on feeder F1 once the breaker on F2 interrupts the flow of current. Unfortunately, the sensitive loads on F1 could experience a production outage if the voltage sag magnitude and duration are more severe than the sensitive load capacities.

Voltage sags also occur for single and two-phase faults. The magnitude is often different on each of the three phases.

Faults on industrial and commercial power systems produce the same voltage sag phenomena. A fault on one feeder drops the voltage on all other feeders in the plant. The voltage sag even shows up in the utility system.

2.2 Number of voltage sags in distribution systems

Faults within a distribution system can cause momentary voltage drops that interrupt industrial production of loads on this feeder or neighboring feeders. The voltage sag characteristics associated with a distribution feeder can be predicated by using circuit theory models and available reliability data such as a specific feeder's annul failure rate (number of faults per year per km), etc.. Predication of number of voltage sags seen by a sensitive load requires sag calculation for every possible fault on the distribution system. The overall estimated number of voltage sags then is the sum of the individual instances. The following sample calculation demonstrates how to estimate number of voltage sags seen by a sensitive load in a distribution system.

A simplified distribution system consists of two feeders as shown in Figure 2-2. Points f_1 to f_6 are fault locations on feeder F2 that cause the voltage level on the common bus and hence the sensitive load drops to a certain value. The industrial customer (sensitive load in Figure 2-2) wants to know how many voltage sags can be expected from faults on feeder F2.

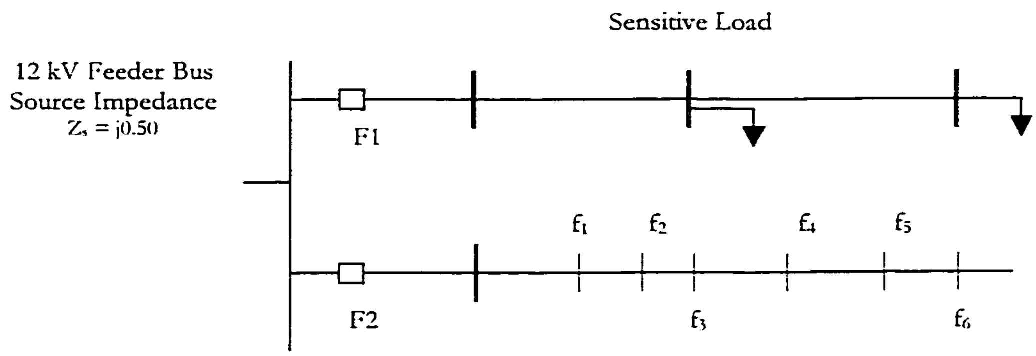


Figure 2-2 Radial Distribution System Single Diagram

For this example, consider all faults to be bolted three-phase. The pre-fault voltage is assumed to be 1.0 per unit. The per unit source reactance to the feeder is j0.50. Feeder F2 is 12km long with a reactance of j0.40 per unit per km. The average number of three phase faults is 0.15 faults per km per year.

For a voltage sag level at the feeder bus, the feeder length of exposure can be determined by Equation (2.4).

$$L = \frac{V_{sag} Z_s}{(1 - V_{sag}) Z_f} \qquad (2.5)$$

Given $V_{sag} = 0.40$, then

$$L = \frac{0.4 \times 0.5}{(1 - 0.4) \times 0.6} = 0.83(km)$$

Hence, the number of voltage sags less than or equal to 0.40 is

$$N = L^{*}\gamma = 0.83^{*}0.15 = 0.13$$

Table 2-1 Radial Distribution System Voltage Sag Calculation

Fault Point	Lowest Phase Sag Voltage Per Unit (V_{sag})	Length(L) km of Line Exposure	Failure Rate Events per km per year(γ)	Number of Sags Less Than or Equal to Sag Voltage (N)
f_1	0.40	0.83	0.15	0.13
f_2	0.50	1.25	0.15	0.19
f_3	0.60	1.88	0.15	0.28
f_4	0.70	2.90	0.15	0.44
f_5	0.80	5.00	0.15	0.75
f_6	0.90	11.25	0.15	1.69

Table 2-1 shows the calculation results for expected number of voltage sags caused by three-phase faults on different fault locations for the sample system. Any fault closer to the feeder bus can cause voltage sags worse than those at the point of interest. For example, three phase faults between the feeder bus and 5km out on feeder F2 will cause at least a voltage sag of 0.8 per unit on the feeder bus. For faults farther than 5km away, it is not possible for a voltage sag on the feeder bus to be lower than 0.8 per unit.

As for the number of voltage sags caused by single line to ground and phase-to-phase faults, it can be calculated following the same procedures, except that the expression of line exposure is different from Equation (2.5). See Chapter 3 for a general expression applicable to all faults. The overall number of voltage sags that may be experienced by the sensitive load can then be calculated by summing up number of voltage sags caused by each individual fault. Furthermore, in a distribution system that has multiple feeders, the number of voltage sags seen by the sensitive load is the sum of the contribution from all folders. For instance, the addition of a second feeder identical to F2 doubles the number of voltage sags as seen by the industrial customer. The complete picture must also include the probability of voltage sags from the industrial distribution system and the transmission system.

Chapter 3 Critical Distance of Voltage Sags in a Distribution System

To develop a voltage sag assessment and prevention plan for a distribution system, it is necessary for utilities, customers and consulting engineers to identify the voltage sag sensitive area within a distribution system of interest. This objective can be achieved by finding the critical distances related to individual feeders within the system of interest. The critical distance of voltage sags in a radial distribution system is defined as the length of the feeder with respect to a point of common coupling (PCC) where all fault will cause the voltage at PCC to drop to a certain value. It is also referred as the "exposure length" [2]. The feeder bus in this case study is the point of common coupling.

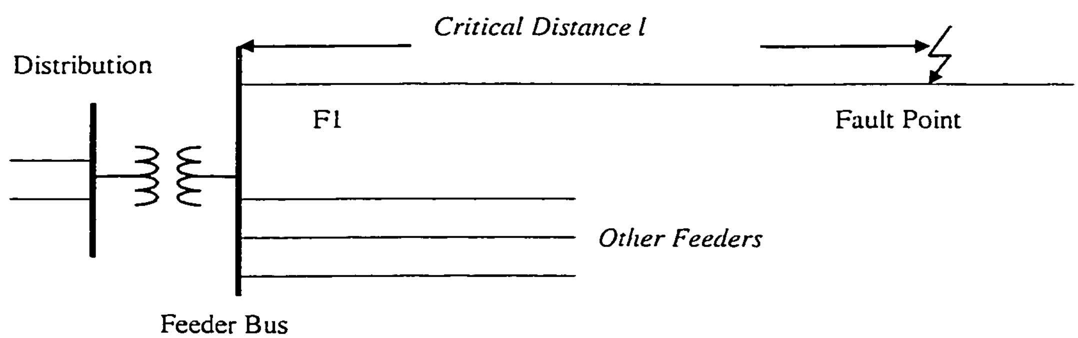


Figure 3-1 A Radial Distribution System

For the industrial distribution radial feeder system as shown in Figure 3-1, the critical distance of feeder F1 is l - the distance between feeder bus and fault location. Specific definition of above parameters and deduction of a general expression l with respect to single phase to ground, phase to phase and three phase faults are shown in the following sections.

3.1 Voltage sags at PCC due to various faults

Figure 3-2 shows a sample source-transformer-distribution-load unit. Circuit analysis is conducted on this sample system to find a generalize expression for the voltage sag levels at Bus 2 corresponding to single phase to ground, phase to phase and three-phase faults at Bus 3.

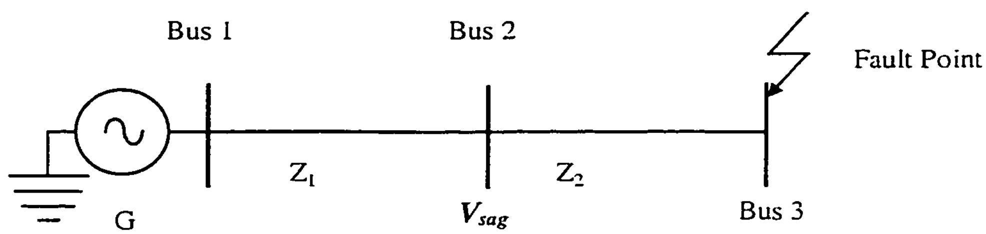


Figure 3-2 Sample Source-transformer-distribution-load Unit

3.1.1 Three-Phase Fault

In the sample system as shown in Figure 3-3, a three-phase fault is placed on the customer bus - Bus 3. The system voltage source is the Thevenin equivalent with respect to Bus 2 which is the PCC in this case. In Figure 3-3, by applying circuit analysis, we have

$$\frac{V}{Z_{2-3}} = \frac{V_s}{Z_{1-2} + Z_{2-3}} \quad (3.1)$$

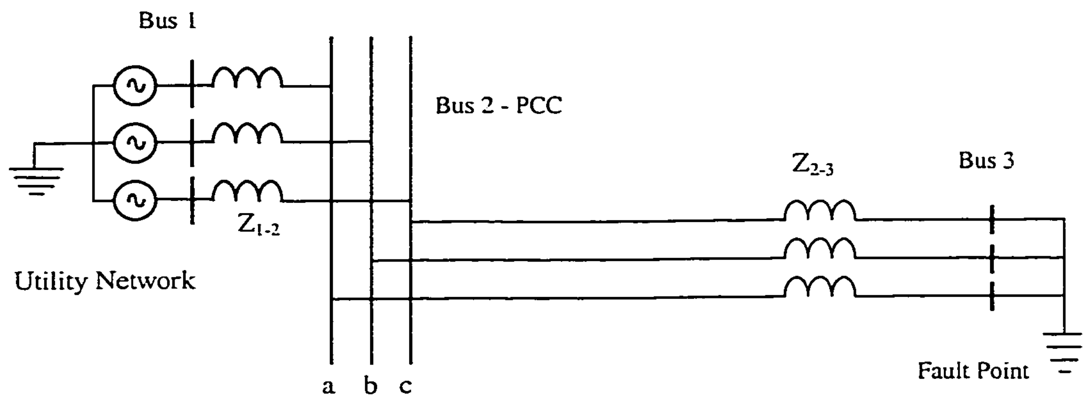


Figure 3-3 Sample System with a Three-phase Fault

where:

V_s - the system source phase voltage with per unit magnitude of 1.0

V - voltage at point of common coupling (PCC)

Z_{1-2} - the positive-sequence impedance from source to PCC

Z_{2-3} - the positive-sequence impedance from PCC to fault point

Let $Z_1 = Z_{1-2}$ and $Z_2 = Z_{2-3}$, the voltage at PCC will be

$$V = \frac{Z_2}{Z_1 + Z_2} \quad (3.2)$$

3.1.2 Single-phase fault

The system diagram with a single line to ground fault on phase a is shown in Figure 3-4. The sequence networks including the Thevenin equivalent circuit are shown in Figure 3-5.

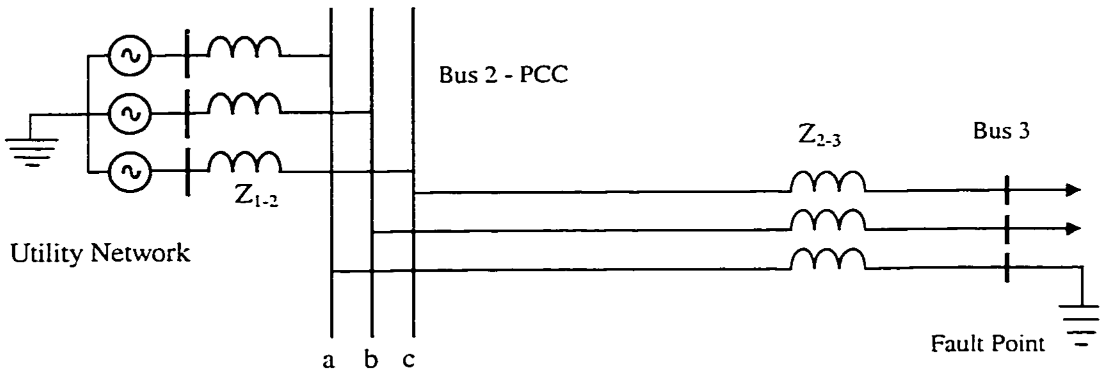


Figure 3-4 Sample System with a Single Phase Fault on phase a

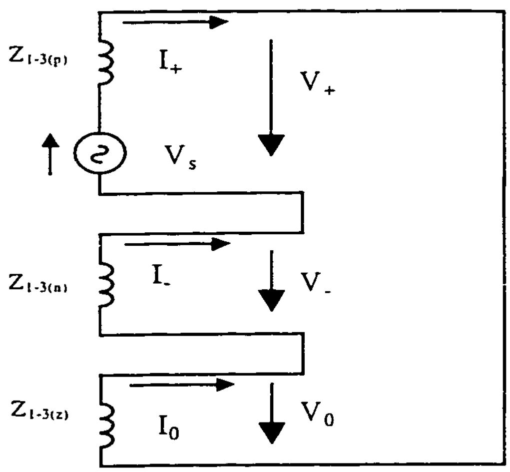


Figure 3-5 Thevenin Equivalent Circuit of Sequence Network

From Figure 3-5, the sequence currents can be obtained as

$$I_+ = I_- = I_0 = \frac{1}{Z_{1-3(p)} + Z_{1-3(n)} + Z_{1-3(z)}} \qquad (3.3)$$

where:

$Z_{1-3(z)} = Z_{1-2(z)} + Z_{2-3(z)}$ - zero-sequence impedance form source to fault point

$Z_{1-2(z)}$ - the zero-sequence impedance from source to PCC

$Z_{2-3(z)}$ - the zero-sequence impedance from PCC to fault point

$Z_{1-3(p)} = Z_{1-2(p)} + Z_{2-3(p)}$ - positive-sequence impedance form source to fault point

$Z_{1-2(p)}$ - the positive-sequence impedance from source to PCC

$Z_{2-3(p)}$ - the positive-sequence impedance from PCC to fault point

$Z_{1-3(n)} = Z_{1-2(n)} + Z_{2-3(n)}$ - negative-sequence impedance form the source to feeder fault point

$Z_{1-2(n)}$ - the negative-sequence impedance from source to PCC

$Z_{2-3(n)}$ - the negative-sequence impedance from PCC to feeder fault point

In Figure 3-4, by using circuit theory in sequence domain, the positive, negative and zero sequence voltages can be obtained as shown below.

$$V_+ = 1 - I_+ Z_{1-2(p)} \qquad (3.4)$$

$$V_- = -I_- Z_{1-2(n)} \qquad (3.5)$$

$$V_0 = -I_0 Z_{1-2(z)} \qquad (3.6)$$

The voltage at PCC is

$$\begin{aligned} V &= V_0 + V_+ + V_- \\ &= 1 - I_+ (Z_{1-2(p)} + Z_{1-2(n)} + Z_{1-2(z)}) \\ &= 1 - \frac{Z_{1-2(p)} + Z_{1-2(n)} + Z_{1-2(z)}}{Z_{1-3(p)} + Z_{1-3(n)} + Z_{1-3(z)}} \qquad (3.7) \end{aligned}$$

Let

$$Z_1 = Z_{1-2(p)} + Z_{1-2(n)} + Z_{1-2(z)}$$

$$Z_2 = Z_{2-3(p)} + Z_{2-3(p)} + Z_{2-3(p)}$$

Equation (3.7) then can be expressed as

$$V = \frac{Z_2}{Z_1 + Z_2} \qquad (3.8)$$

3.1.3 Phase-to-phase fault

The distribution system with a phase-to-phase fault between b and c phases and its sequence networks are shown in Figure 3-6 and Figure 3-7.

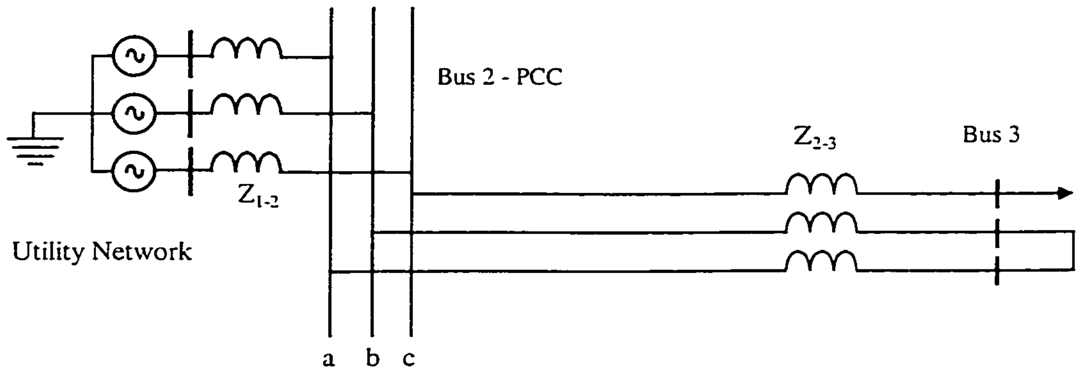


Figure 3-6 Sample System With a Phase-to-Phase Fault Between Phase b and c

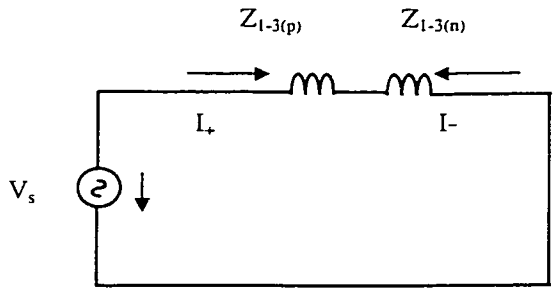


Figure 3-7 Thevenin Equivalent Circuit of Sequence Networks

By inspecting the sequence network, the sequence currents can be found

$$I_+ = I_- = \frac{1}{Z_{1-3(p)} + Z_{1-3(n)}} \quad (3.9)$$

$$I_0 = 0 \quad (3.10)$$

The positive and negative currents on phase b and c are

$$I_{b+} = I_+ e^{-j120} \quad (3.11)$$

$$I_{c+} = I_+ e^{j120^o} \quad (3.12)$$

$$I_{b-} = I_- e^{j120^o} \quad (3.13)$$

$$I_{c-} = I_- e^{-j120^o} \quad (3.14)$$

In Figure 3-6, it could be found that the positive-sequence voltages difference between c and b at the PCC is

$$\begin{aligned} V_+ &= -E_b + I_{b+}Z_{1-2(p)} + E_c - I_{c+}Z_{1-2(p)} \\ &= e^{-j120^o} + I_{b+}Z_{1-2(p)} + e^{j120^o} - I_{c+}Z_{1-2(p)} \\ &= (-e^{j120^o} + e^{j120^o}) - (I_{c+}Z_{1-2(p)} - I_{b+}Z_{1-2(p)}) \\ &= (-e^{j120^o} + e^{j120^o}) - Z_{1-2(p)}(I_+ e^{j120^o} - I_+ e^{-j120^o}) \\ &= \sqrt{3}j - \sqrt{3}jI_+Z_{1-2(p)} \\ &= \sqrt{3}j(1 - I_+Z_{1-2(p)}) \quad (3.15) \end{aligned}$$

Substituting Equation (3.9) into Equation (3.15),

$$V_+ = \sqrt{3}j(1 - \frac{Z_{1-2(p)}}{Z_{1-3(p)} + Z_{1-3(n)}}) \quad (3.16)$$

Similarly, the negative-sequence voltage difference between C and B at the feeder bus is found to be

$$V_- = -\sqrt{3}j(\frac{Z_{1-2(n)}}{Z_{1-3(p)} + Z_{1-3(n)}}) \quad (3.17)$$

From the positive and negative voltage, voltage between phase C and B could be obtained as

$$V'_{cb} = V_{+} + V_{-} = \sqrt{3}j(1 - \frac{Z_{1-2(p)} + Z_{1-2(n)}}{Z_{1-3(p)} + Z_{1-3(n)}}) \qquad (3.18)$$

Let $Z_1 = Z_{1-2(p)} + Z_{1-2(n)}$ and $Z_2 = Z_{2-3(p)} + Z_{2-3(n)}$, the above equation can be represented as

$$V'_{cb} = \sqrt{3}j\frac{Z_2}{Z_1 + Z_2} \qquad (3.19)$$

Note that in Equation (3.19), V'_{cb} is phase to phase voltage, and is assumed to have phase to phase voltage base. For single-phase and three-phase fault analysis, the voltage base is the phase voltage.

It is known that the line and phase base voltage have the following relationship for a balanced phase sequence

$$V_{Line} = j\sqrt{3}V_{Phase}$$

Under line voltage base, the voltage on PCC can be represented as

$$V = \frac{V'_{cb}}{V_{Phase}} = \frac{Z_2}{Z_1 + Z_2} \qquad (3.20)$$

3.2 Critical Distance of Voltage Sag

Based on the analysis presented in section 3.1.1, 3.1.2 and 3.1.3, the voltage at the point of common coupling (PCC) resulting from different types of fault can be expressed as

$$V = \frac{Z_2}{Z_1 + Z_2} \qquad (3.21)$$

Table 3-1 Specifications of Parameters in Equation (3.21)

Type of Fault	Z_1 (Equivalent Source Impedance)	Z_2 (Feeder Impedance Between PCC and feeder fault point)	V (voltage at PCC)
Single-phase	$Z_{1-2(p)} + Z_{1-2(n)} + Z_{1-2(z)}$	$Z_{2-3(p)} + Z_{2-3(n)} + Z_{2-3(z)}$	Faulted phase to ground
Phase-phase	$Z_{1-2(p)} + Z_{1-2(n)}$	$Z_{2-3(p)} + Z_{2-3(n)}$	Voltage between two faulted phases
three phase	$Z_{1-2(p)}$	$Z_{2-3(p)}$	Phase to ground

Note the symbols in the above equation have different definition dependent upon the fault type being considered as specified in Table 3-1. The impedance phasor diagram for the system is shown in Figure 3-8.

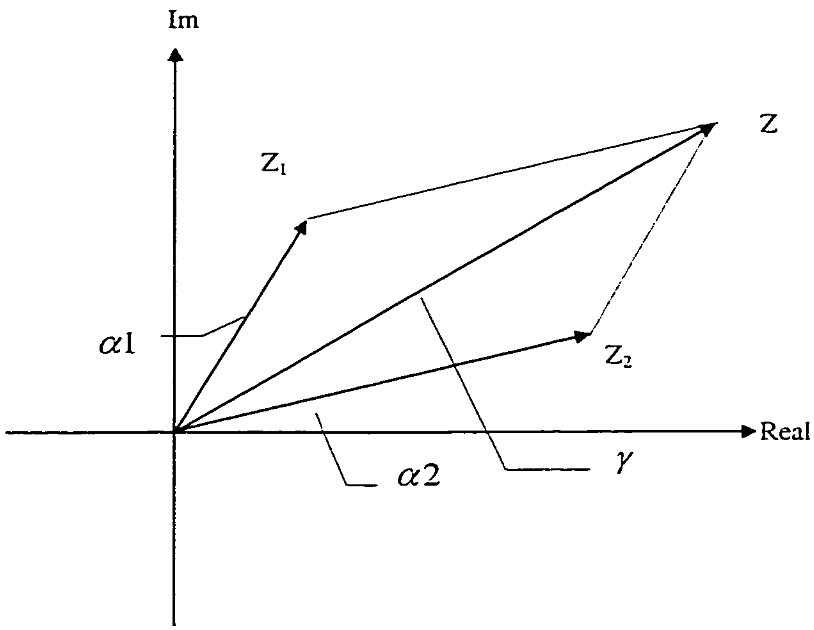


Figure 3-8 Impedance Phasor Diagram

By applying the phasor notation, Equation (3.21) can be rewritten as follows

$$\overline{V} = \frac{\overline{Z}_2}{\overline{Z}_1 + \overline{Z}_2} \qquad (3.22)$$

By inspection of Figure 3-8, the voltage on PCC can be expressed in the following polar form,

$$\begin{aligned} Ve^{jb} &= \frac{Z_2 e^{j\alpha 2}}{Z_1 e^{j\alpha 1} + Z_2 e^{j\alpha 2}} \\ &= \frac{Z_2 e^{j\alpha 2}}{Z\ e^{j\gamma}} \\ &= \frac{Z_2}{Z} e^{j(\alpha 1 - \gamma)} \qquad (3.23) \end{aligned}$$

where $Z = \left|\overline{Z}_1 + \overline{Z}_2\right| = \sqrt{Z_1^2 + Z_2^2 + 2Z_1Z_2\cos\alpha}$

α - the angle between vector $\overline{Z}_1$ and $\overline{Z}_2$ in complex plane

Let $Z_2 = \ell z_2$

where ℓ - the distance between fault point to PCC, namely, the ***"Critical Distance"***

z_2 - the impedance of the faulty feeder per unit length

Taking the magnitude of $\overline{V}$ in Equation (3.23) gives

$$V = \frac{Z_2}{Z} = \frac{\ell z_2}{\sqrt{Z_1^2 + (\ell z_2)^2 + 2Z_1\ell z_2\cos\alpha}} \quad \text{.........(3.24)}$$

and hence

$$V^2 = \frac{(\ell z_2)^2}{Z_1^2 + (\ell z_2)^2 + 2Z_1\ell z_2\cos\alpha} \quad \text{.........(3.25)}$$

Rearranging Equation (3.25) leads to

$$(\ell z_2)^2 = V^2Z_1^2 + V^2\ell^2z_2^2 + 2V^2Z_1\ell z_2\cos\alpha$$

$$(V^2z_2^2 - z_2^2)*\ell^2 + 2V^2Z_1z_2\cos\alpha*\ell + V^2Z_1^2 = 0$$

Solving the above equation for the critical distance ℓ

$$\ell = \frac{-2VZ_1z_2\cos\alpha \pm \sqrt{4V^4Z^2{}_1z_2^2\cos^2\alpha + 4(-V^2+1)z_2^2V^2Z_1^2}}{2z_2^2(V^2-1)}$$

$$= \frac{-VZ_1 z_2 \cos\alpha \pm z_2 VZ_1 \sqrt{V^2\cos^2\alpha + (-V^2+1)}}{z_2^{\,2}(V^2-1)}$$

$$= \frac{-VZ_1 \cos\alpha \pm VZ_1 \sqrt{-V^2\sin^2\alpha + 1)}}{z_2\ (V^2-1)}$$

$$= \frac{Z_1}{z_2}\frac{V}{1-V}\left[\frac{V\cos\alpha \mp \sqrt{1-V^2\sin^2\alpha}}{1+V}\right] \qquad (3.26)$$

In the above expression, comparison between $V\cos\alpha$ and $\sqrt{1-V^2\sin^2\alpha}$ is made through comparing their square.

$$(V\cos\alpha)^2 = V^2(1-\sin^2\alpha) = V^2 - V^2\sin^2\alpha$$

$$(\sqrt{1-V^2\sin^2\alpha})^2 = 1 - V^2\sin^2\alpha$$

Considering the fact that the voltage on PCC under fault condition V<1, therefore

$$V\cos\alpha < \sqrt{1-V^2\sin^2\alpha}$$

On the other hand, since $\ell > 0$, the solution of Equation (3.26) can only be

$$\ell = \frac{Z_1}{z_2}\frac{V}{1-V}\left[\frac{V\cos\alpha + \sqrt{1-V^2\sin^2\alpha}}{1+V}\right] \qquad (3.27)$$

To determine the critical distance, a voltage sag level should be specified which in most cases is 90% of the nominal voltage.

3.3 Consideration on voltage support

Figure 3-9 shows a distribution system with a three-phase fault. A motor is added to node A to represent the voltage support.

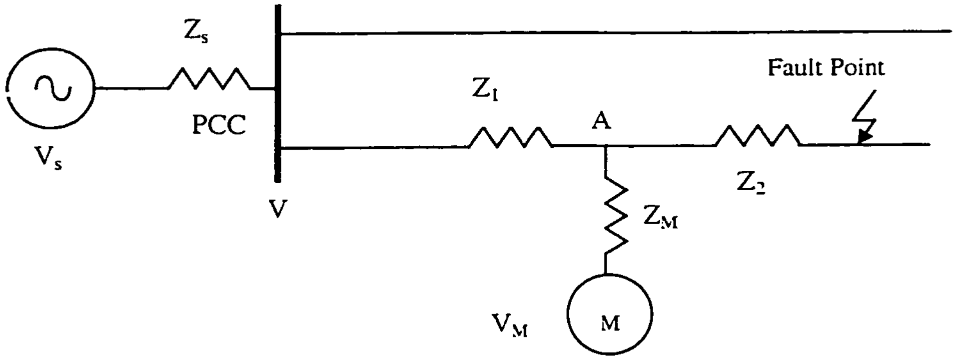


Figure 3-9 An Industrial Distribution System

Applying Nodal Equation to node PCC and A

$$V\left(\frac{1}{Z_s}+\frac{1}{Z_1}\right)-V_M\frac{1}{Z_1}=\frac{V_s}{Z_s} \quad (3.28)$$

$$V_M\left(\frac{1}{Z_1}+\frac{1}{Z_2}+\frac{1}{Z_m}\right)-\frac{1}{Z_1}=\frac{V_m}{Z_m} \quad (3.29)$$

Solving the above two equations for V

$$V=\frac{Z_1Z_2+Z_sZ_1+Z_sZ_2+Z_mZ_1+Z_mZ_2}{Z_1Z_2+Z_sZ_1+Z_sZ_2+Z_mZ_1+Z_mZ_s} \quad (3.40)$$

where:

V - voltage at PCC in per unit

Z_1 - feeder impedance from bus A to feeder bus PCC

Z_2 - feeder impedance from fault point to bus A

Z_m - per unit motor impedance

Z_s - per unit source impedance

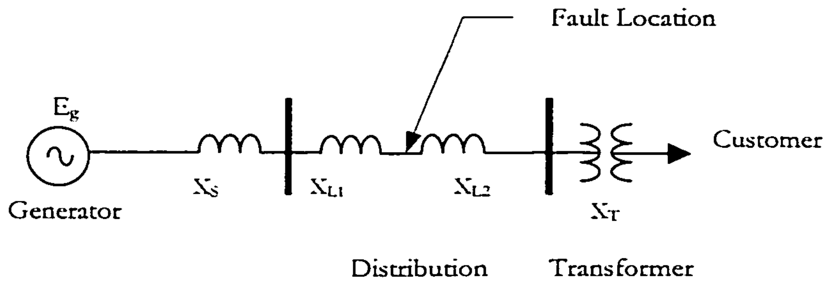
Chapter 4 Effects of Transformer Connections in a Distribution System

Voltage sags seen by the customers are not only influenced by fault locations and fault types, but also by the transformer connections. The decrease of the voltage magnitude and the phase angle deviation are a function of the connection of the transformer between the load and system. This phenomenon is illustrated in this chapter using basic circuit analysis on a simple generator-transformer load unit. Calculations are undertaken on nine different connections. A Y-Delta transformer connection is used in sample calculations.

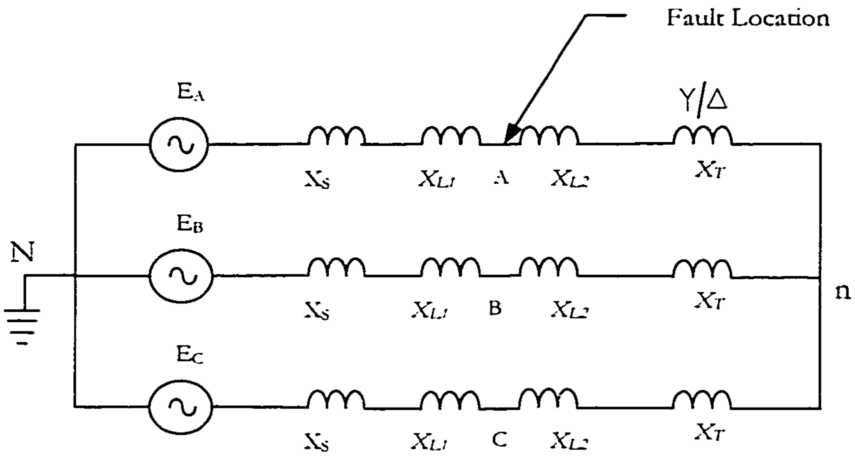
4.1 Voltage sags on the primary side due to a single line to ground fault

A single line to ground fault (SLGF) is placed at A on phase A which divides the line section into two parts as shown in Figure 4-1. The voltage sources for a balanced equivalent Thevenin voltage source are defined as:

$$E_A = 1\angle 0^0$$
$$E_B = 1\angle -120^0$$
$$E_C = 1\angle 120^0$$



(a) Sample system one-line diagram



(b) Equivalent circuit of (a)

Figure 4-1 A Sample Generator-Transformer-Load Unit under Fault Condition

Other symbols in Figure 4-1 and those used in the calculation below include

X_S - source impedance

X_T - transformer impedance

X_{L1} - impedance for line section on the left of the fault point

X_{L2} - impedance for line section to the right of the fault point and

$$X_{SL} = X_S + X_{L1}$$
$$X_{TL} = X_T + X_{L2}$$
$$X = X_{SL} + X_{TL}$$
$$X_L = X_{L1} + X_{L2}$$

Applying Nodal Equation to neutral point of the secondary side of the transformer gives

$$V_n\left(\frac{1}{X} + \frac{1}{X} + \frac{1}{X_{TL}}\right) = E_B * \frac{1}{X} + E_C * \frac{1}{X} \quad \text{..........(4.1)}$$

Let $\alpha = \frac{X_{TL}}{X}$ and solve Equation (4.1) for V_n,

$$V_n = \frac{E_B + E_C}{2 + \frac{1}{\alpha}} = \frac{\alpha(E_B + E_C)}{2\alpha + 1} \quad \text{..........(4.2)}$$

Since $E_A = -(E_B + E_C)$,

$$V_n = -\frac{\alpha}{2\alpha + 1} E_A \quad \text{..........(4.3)}$$

The voltage between the fault point and the neutral point of the transformer is

$$V_{An} = -V_n = \frac{\alpha}{2\alpha + 1} E_A \quad \text{..........(4.4)}$$

$$V_{Bn} = \frac{E_B - V_n}{X} X_{TL}$$

$$= (E_B + \frac{\alpha}{2\alpha + 1} E_A)\alpha \quad \text{..........(4.5)}$$

$$V_{Cn} = \frac{E_C - V_n}{X} X_{TL}$$

$$= (E_C + \frac{\alpha}{2\alpha + 1} E_A)\alpha \quad \text{..........(4.6)}$$

Accordingly, the phase to phase voltages can be obtained as follows:

$$
\begin{aligned}
V_{AB} &= V_{An} - V_{Bn} \\
&= \frac{\alpha}{2\alpha+1}E_A - (E_B + \frac{\alpha}{2\alpha+1}E_A)\alpha \\
&= \frac{\alpha(1-\alpha)}{2\alpha+1}E_A - \alpha E_B \quad \text{.......(4.7)}
\end{aligned}
$$

$$
\begin{aligned}
V_{BC} &= V_{Bn} - V_{Cn} \\
&= (E_B + \frac{\alpha}{2\alpha+1}E_A)\alpha - (E_C + \frac{\alpha}{2\alpha+1}E_A)\alpha \\
&= \alpha(E_B - E_C) \quad \text{.......(4.8)}
\end{aligned}
$$

$$
\begin{aligned}
V_{CA} &= V_{Cn} - V_{An} \\
&= (E_C + \frac{\alpha}{2\alpha+1}E_A)\alpha - \frac{\alpha}{2\alpha+1}E_A \\
&= \frac{\alpha(1-\alpha)}{2\alpha+1}E_A - \alpha E_C \quad \text{.......(4.9)}
\end{aligned}
$$

For a distribution fault, the worst case occurs when the fault is close to the substation bus. This is the same as a fault near the customer primary, which results in $X_{L2} \approx 0$ and V_{AB}, V_{BC} and V_{CA} becoming phase-phase voltages of the transformer primary, respectively. The parameter α can be approximated by:

$$
\begin{aligned}
\alpha &= \frac{X_{TL}}{X} \\
&\approx \frac{X_T}{X_S + X_L + X_T} \\
&= \frac{1}{\frac{X_S + X_L}{X_T} + 1} \quad \text{.......(4.10)}
\end{aligned}
$$

For simplification, the following calculations assume that $X_T >> X_S + X_L$, which is often situation in practice and further leads to α being very close to unity: $\alpha \approx 1$. Accordingly, Equation (4.4), (4.5) and (4.6) can be transformed into

$$V_{An} = \frac{1}{3}E_A = \frac{1}{3}*1*\angle 0^\circ = 0.333333 \qquad (4.11)$$

$$V_{Bn} = \frac{E_A}{3} + E_B = \frac{1}{3}*1*\angle 0^\circ + (-\frac{1}{2} - \frac{\sqrt{3}}{2}j)$$
$$= 0.881917\angle -101^\circ \qquad (4.12)$$

$$V_{Cn} = \frac{E_A}{3} + E_C = \frac{1}{3}*1*\angle 0^\circ + (-\frac{1}{2} + \frac{\sqrt{3}}{2}j)$$
$$= 0.881917\angle 101^\circ \qquad (4.13)$$

$$V_{AB} = V_{An} - V_{Bn} = 1\angle 60^\circ \qquad (4.14)$$

$$V_{CA} = V_{Cn} - V_{An} = 1\angle 120^\circ \qquad (4.15)$$

$$V_{BC} = V_{Bn} - V_{Cn} = \sqrt{3}\angle -90^\circ \qquad (4.16)$$

By expressing V_{AB} , V_{CA} and V_{BC} based on the phase to phase voltage base, they become

$$V_{AB} = \frac{1}{\sqrt{3}}\angle 60^\circ = 0.577350\angle 60^\circ \qquad (4.17)$$

$$V_{BC} = \frac{1}{\sqrt{3}}*\sqrt{3}\angle -90^\circ = 1\angle -90^\circ \qquad (4.18)$$

$$V_{CA} = \frac{1}{\sqrt{3}}\angle 120 = 0.577350\angle 120^\circ \qquad (4.19)$$

The phasor diagram of the phase and phase-phase voltages is shown in Figure 4-2.

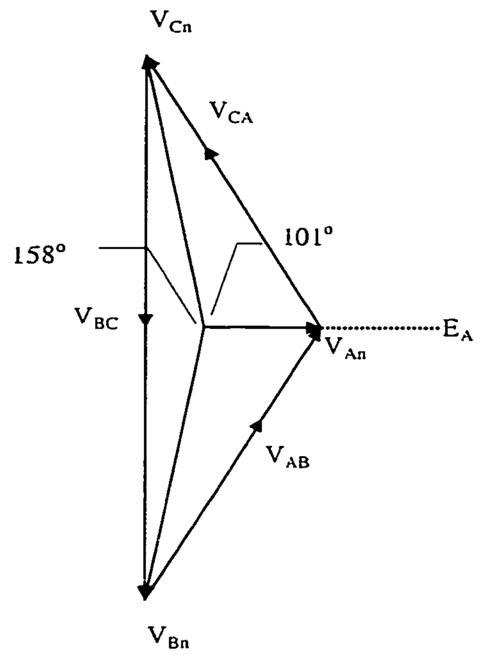


Figure 4-2 Primary Voltages due to a SLGF on Phase A of Transformer Primary

4.2 Voltage sag on the secondary side of the transformer

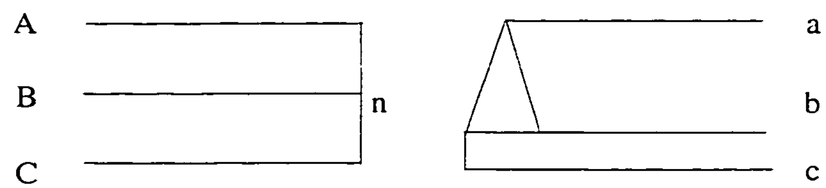


Figure 4-3 A Transformer with Ungrounded Wye-Delta Connection

The voltage across each winding of the secondary side of a transformer is a result of magnetic coupling with its corresponding winding on the primary. For a transformer connection as shown in Figure 4-3, the primary side voltages can be found in Equation (4.11), (4.12) and (4.13). Note that the transformer shown here is an ideal one with unity ratio. Accordingly, the secondary voltages can be found as

$$V_{ab} = V_{An} = 0.333333 \qquad (4.20)$$

$$V_{bc} = V_{Bn} = 0.881917\angle -100.9^{\circ} \qquad (4.21)$$

$$V_{ca} = V_{Cn} = 0.881917\angle 100.9^{\circ} \qquad (4.22)$$

Their phasor diagram for secondary phase-phase voltages is shown in Figure 4-4. Based on the previous, the voltage sags on the secondary side of a distribution transformer with respect to nine combinations of connections can be obtained and are shown in Table 4-1.

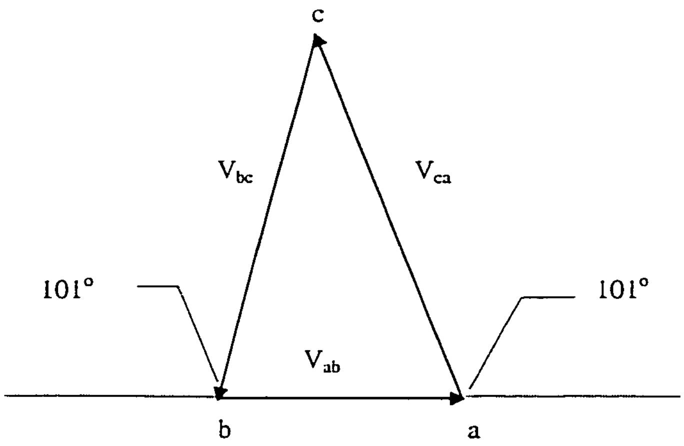
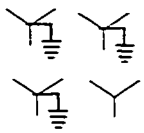
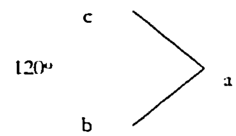
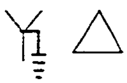
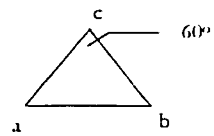
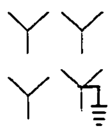
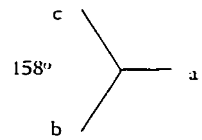
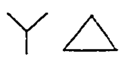
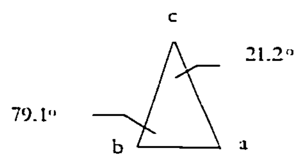
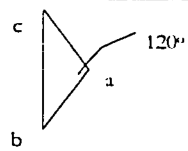
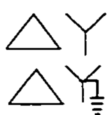
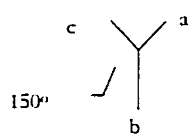


Figure 4-4 Secondary Voltages due to a SLGF on Phase A of Transformer Primary

From Table 4-1, it was found that the lowest voltage magnitude deviation is 33%, the highest is 1. Considering the fact that the secondary side of the transformer is open-circuited, no voltage sags with above 33% of the pre-fault voltage could be expected. The analysis also confirms that the voltage sag seen on the load side is a function of the transformer connection.

Table 4-1 Transfer of Voltage Sag to the Low Voltage Level with a Single-phase to Ground Fault on the Primary

Transformer Connection	Phase-Phase V_{ab}	V_{bc}	V_{ca}	Phase-Neutral V_{an}	V_{bn}	V_{cn}	Phasor Diagram
	0.58	1	0.58	0	1	1	
	0.58	0.58	0.58	----	----	----	
	0.58	1	0.58	0.33	0.88	0.88	
	0.33	0.88	0.88	----	----	---	
	0.58	1	0.58	----	----	----	
	0.88	0.88	0.33	0.58	1	0.58	

Chapter 5 Simulation Study of Voltage Sags in an Industrial Power System

Computer simulation studies can be used to determine voltage levels and propagation characteristics of voltage sags at different locations within an industrial power system when a electrical fault occurs within the system. The results of these calculations can be used to define an "area of vulnerability" [24] for a particular customer's electric and electrical equipment. The probability of a fault within this area of vulnerability can then be determined.

5.1 Electric-Magnetic Transient Program (EMTP)

Currently various simulation packages are available, with each one specializing in one specific area or several areas of power systems. The primary simulation tool used for this thesis is Electric-Magnetic Transient Program (EMTP). Since being developed by Herman Dommel at BPA in 1960's, EMTP has been widely used in transient analysis of power systems. The EMTP is a general-purpose computer program for simulating high-speed transient effects in electrical power system.

5.2 Sample System

The sample system used in this thesis is one of the test systems established by IEEE Harmonics Modeling and Simulation Task Force for harmonics related analysis and simulation studies [30]. It consists of 13 buses and is representative of a small-sized industrial plant. The single line diagram of the test system is shown in Figure 5-1. The utility feeds the system at 115kV. The fault capacity available from utility is 1000MVA, the X/R ratio is 22.2. The in-plant generator operates at 13.8kV. The parameters of line, transformer and load are provided in Table 5-1, 5-2, 5-3 and 5-4.

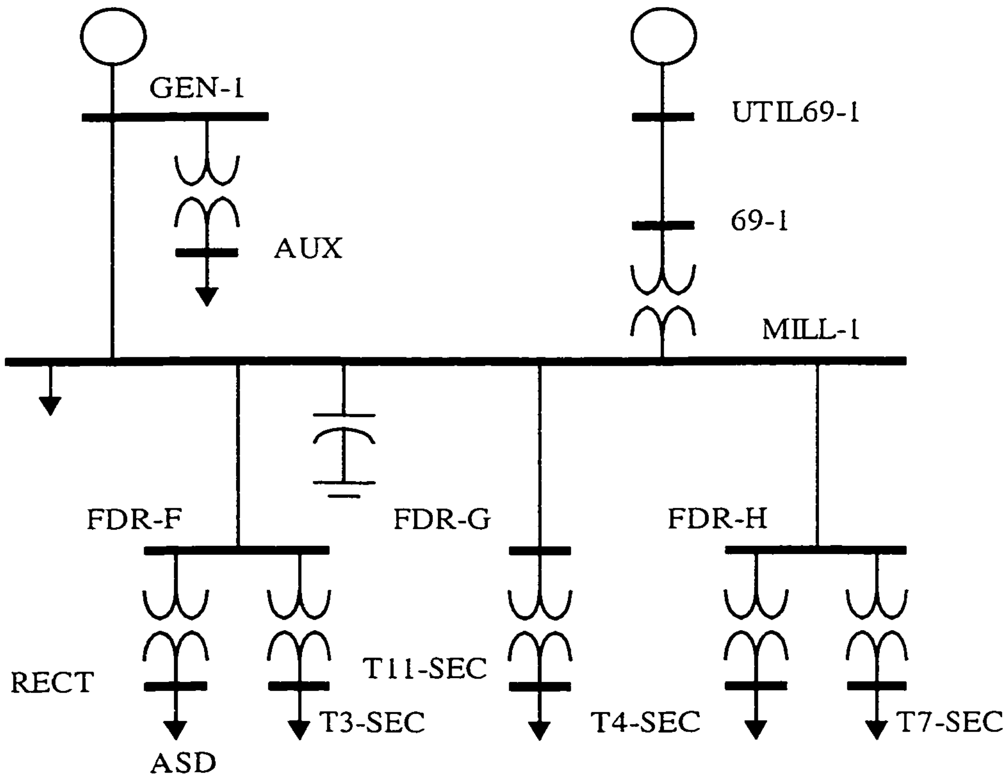


Figure 5-1 A 13-Bus Balanced Industrial Distribution System

Table 5-1 Transformer Data

No	From	To	Connection	Tap	V1 (kV)	V2 (kV)	S (kVA)
1	UTIL69-1	MILL-1	D/Y	69	69	13.8	15000
2	GEN1	AUX	Y/D	13.45	13.8	0.48	1500
3	FDR-F	RECT	Y/D	13.45	13.8	0.48	1250
4	FDR-F	T3-SEC	Y/D	13.11	13.8	4.16	1725
5	FDR-G	T11-SEC	Y/D	13.45	13.8	0.48	1500
6	FDR-H	T4-SEC	Y/D	13.8	13.8	0.48	1500
7	FDR-H	T7-SEC	Y/D	13.11	13.8	2.4	3750

Table 5-2 Distribution Line Parameters

Number	From	To	VOLTAGE (kV)	MVA	Z_{base}	R(pu)	X(Pu)
1	UTIL69-1	69-1	13.8	10	19.044	0.00139	0.002647
2	MILL-1	GEN-1	13.8	10	19.044	0.00122	0.023234
3	MILL-1	FDR-F	13.8	10	19.044	0.00075	0.014288
4	MILL-1	FDR-G	13.8	10	19.044	0.00157	0.029899
5	MILL-1	FDR-H	13.8	10	19.044	0.00109	0.020758

Table 5-3 Distribution Line Parameters

Branch No.	From	To	VOLTAGE (kV)	MVA_{Base}	R(pu)	X(Pu)	R_{Phase}	X_{Phase}
1	UTIL69-1	69-1	13.8	10	0.00139	0.00264	0.00647	0.05637
2	MILL-1	GEN-1	13.8	10	0.00122	0.02323	0.02323	0.04627
3	MILL-1	FDR-F	13.8	10	0.00075	0.01429	0.01428	0.01198
4	MILL-1	FDR-G	13.8	10	0.00157	0.02990	0.02970	0.02494
5	MILL-1	FDR-H	13.8	10	0.00109	0.02076	0.020758	0.01733

Table 5-4 Node Load and Equivalent Impedance

Number	Node	V_{LL} (kV)	V_{ph} (kV)	$P_{3\text{-}ph}$ (kVar)	$Q_{3\text{-}ph}$ (kVar)	R(Ohm)	X(Ohm)
1	MILL-1	13.8	7.967	2240	2000	5.9374	5.3013
2	AUX	0.48	0.277	600	530	0.2157	0.1905
3	RECT	0.48	0.277	1150	290	0.1884	0.04750
4	T3-SEC	4.16	2.402	1310	1130	7.5744	6.5337
5	T11-SEC	0.48	0.277	810	800	0.1440	0.1422
6	T4-SEC	0.48	0.277	370	330	0.3468	0.3093
7	T7-SEC	2.40	1.386	2800	2500	1.1447	1.0220

5.3 Modeling Power System Components

5.3.1 Load

Loads are represented as constant per phase impedance obtained through the following equation

$$R + jX = \frac{V^2}{P - jQ}$$

The equivalent per phase impedance of all the load is shown in Table 5-4.

5.3.2 Overhead Line

For steady state and low frequency studies like voltage sag analysis, an overhead line can be modeled as Π equivalent circuit for long lines. For short lines, the shunt capacitance can be neglected.

Table 5-5 Evqivalent Phase Impedance

Branch No.	Node	V_{LL} (kV)	V_{Ph} (kV)	$Q_{3\text{-phase}}$	$P_{3\text{-phase}}$	R	X
1	MILL-1	13.8	7.967	10	19.044	0.00139	0.002647
2	AUX	0.48	0.277	10	19.044	0.00122	0.023234
3	RECT	0.48	0.277	10	19.044	0.00075	0.014288
4	T3-SEC	4.16	2.402	10	19.044	0.00157	0.029899
5	T11-SEC	0.48	0.277	10	19.044	0.00109	0.020758
6	T4-SEC	0.48	0.277	10	19.044	0.00157	0.029899
7	T7-SEC	2.4	1.386	10	19.044	0.00109	0.020758

5.3.3 Power Transformer

Available transformer models are ideal transformer models, satiable transformer models and models based on mutually coupled coils. In this study, an EMTP built-in simplified T model is chosen.

5.4 Case Studies on Voltage Sag due to Short Circuit Fault

5.4.1 Case 1: Single Line to Ground Fault (SLGF) at Node FDR-H

It is noted more than 85% of faults are induced by single phase to ground fault [15]. The voltage wave-forms on node FDR-F and RECT are shown in Figure 5-2 and Figure 5-3 when a single line to ground fault is applied to node FDR-H.

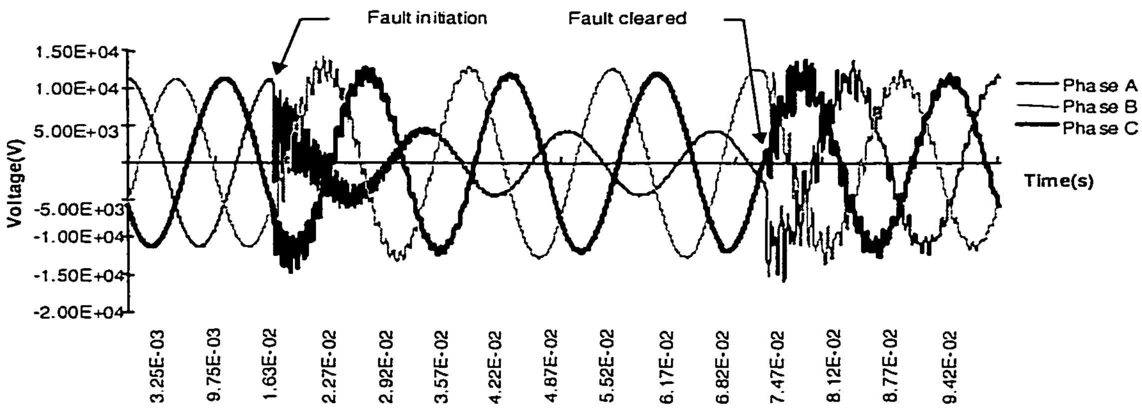


Figure 5-2 Voltage Response on Node FDR-F due to a SLGF on FDR-H

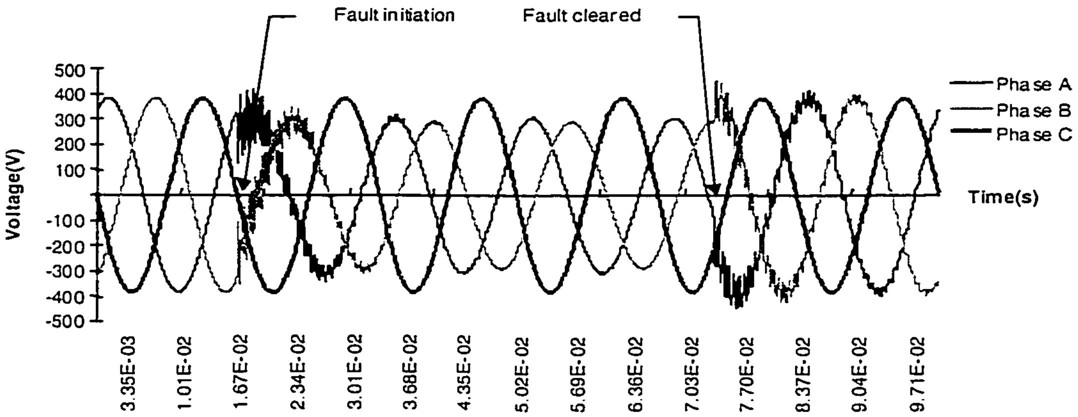


Figure 5-3 Voltage Response on Node RECT due to a SLGF on FDR-H

The transient happens at the instance of the fault and lasts for about 1~2 time periods. The transient phenomenon is influenced by the presence of the power factor correction capacitor on Bus MILL-1. It could be easily explained by the circuit theory that, during a transient process, the voltage across a capacitor can not change instantaneously and significantly affects the transient waveform seen throughout the industrial system.

It is noted for a system that does not have harmonic filters, power factor correction capacitors, the transmission line to ground capacitors or the transformer inter-winding capacitors in the model, the transient period will not appear in the resultant simulation waveforms.

With the capacitor on Bus MILL-1 being removed from the test system, the voltages on RECT show sudden drops as shown in Figure 5-4. This is exactly what is expected in a system without capacitive components while in line and transformer models the capacitive part is also ignored. Under this condition, the definition of phase angle jump [19] can be identified and analysis of effects of phase angle jump on some equipment that are sensitive to this change can be justified.

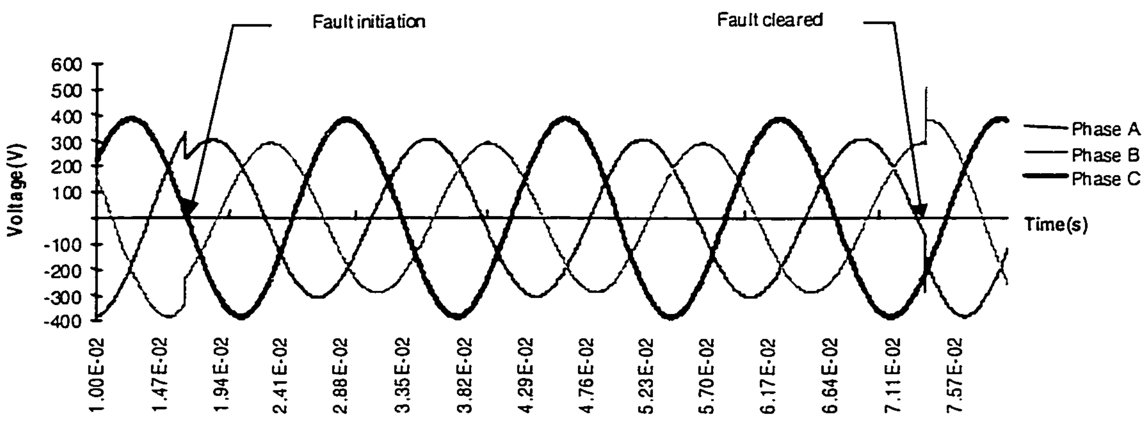


Figure 5-4 Voltage Response on Node RECT due to a SLGF on FDR-H with Capacitor on MILL-1 Being Removed

5.4.1.1 Voltage magnitude deviation

Voltage magnitude deviation $V_s\%$ is defined as

$$\frac{(V_f - V_n) * 100}{V_n}$$

where: V_f - RMS voltage during fault

V_n - voltage before fault

Accordingly, the voltage magnitude deviation for phases A, B and C of node RECT due to a SLGF on node FDR-H are -18.75%, -23.96% and 0.00% respectively, where minus sign indicates a voltage drop.

5.4.1.2 Voltage phase angle deviation

The voltage phase angle deviation (jump) θ_j on phases A, B and C of the feeder bus is defined as

$$\theta_j = \theta_f - \theta_n$$

where: θ_f - phase angle during fault

θ_n - phase angle before fault

The voltage phase angle jump on phase A, B and C of node RECT due to a SLGF on node FDR-H are -20.64°, 7.44° and 13.2°, respectively. It should be noted is these phase angles are picked up in the time period when transient has died down. In the first 1~2 cycle where transient still exists, however, the voltage angle itself is of no significance because the distortion of the sine wave dismisses the foundation on which the phasor representation of the sinusoidal circuit are developed. This situation is easily seen in Figure 5-5 where a zoom-in version of Figure 5-3 is given.

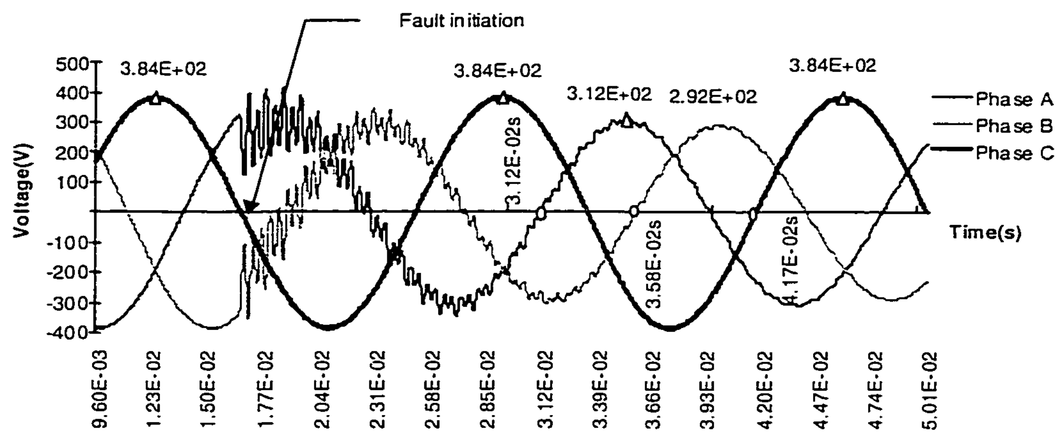


Figure 5-5 Zoom-in of Figure 5-3

The voltage magnitude drop ranges from 0 to 32.45%, the phase angle jump varies from 0.96° to 35.76° as shown in Table 5-6.

Table 5-6 Node Voltage Magnitude and Phase Angle Deviation due to SLGF on FDR-H

Node	Voltage Magnitude Deviation (%)			Phase Angle Jump(°)		
	A	B	C	A-B	B-C	C-A
AUX	0.00%	0.00%	0.00%	0.96	-1.2	0.24
RECT	-18.75%	-23.96%	0.00%	-20.64	7.44	13.2
T3-SEC	-22.53%	-23.15%	0.00%	-22.8	7.44	-15.36
T11-SEC	-22.55%	-23.61%	0.00%	-24.96	11.76	13.2
T4-SEC	-30.91%	-31.43%	0.00%	-35.76	22.56	13.2
T7-SEC	-32.45%	-32.45%	0.00%	-35.76	22.56	13.2

Figure 5-6 demonstrates the relationship between the site distance from the fault point and the severity of voltage drop. It is easily seen that the severity of the voltage drop at a particular site is proportional to its distance from the fault point, which is FDR-H in Figure 5-1. The furthest point is AUX where voltage drop is approximately zero, whereas on T7-SEC voltage dips to 35.75% on Phase A which is the faulty phase.

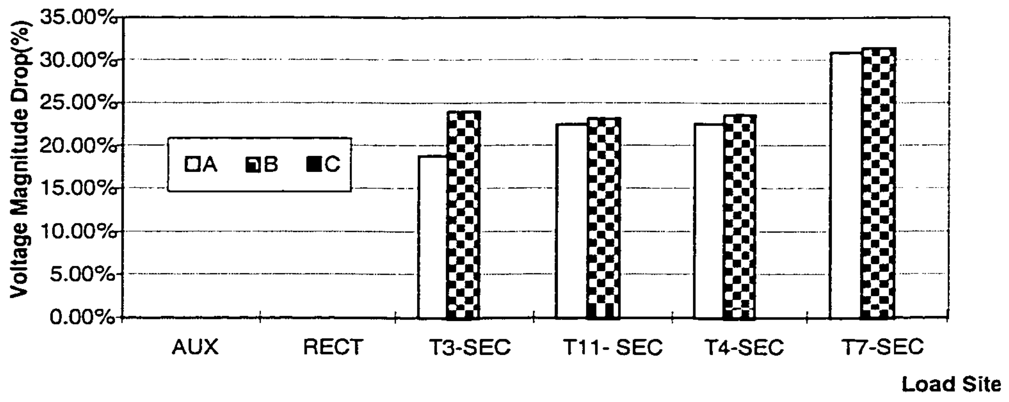


Figure 5-6 Voltage Magnitude Drop on Each Sites

5.4.2 Case 2: Three Phase Fault at Node FDR-H

Figure 5-7 shows the voltages on RECT with a three-phase fault on FDR-H. Distinctions in voltage response on RECT between a single phase to ground and three phase fault are the transient period is longer and voltage drop is greater. The voltage magnitude drops for phases A, B and C are -62.24%, -63.02% and -64.58%, respectively, indicating that three phase fault brings about voltage dip more severe that SLGF. Due to the prolonged transient period, the application of phase angle deviation can only be made in the area where the transient has died down. Nevertheless, the phase angle deviation still exists in the time interval where transient has disappeared. Whether the phase angle deviation in this time period could cause adverse effects on loads needs considerably more research.

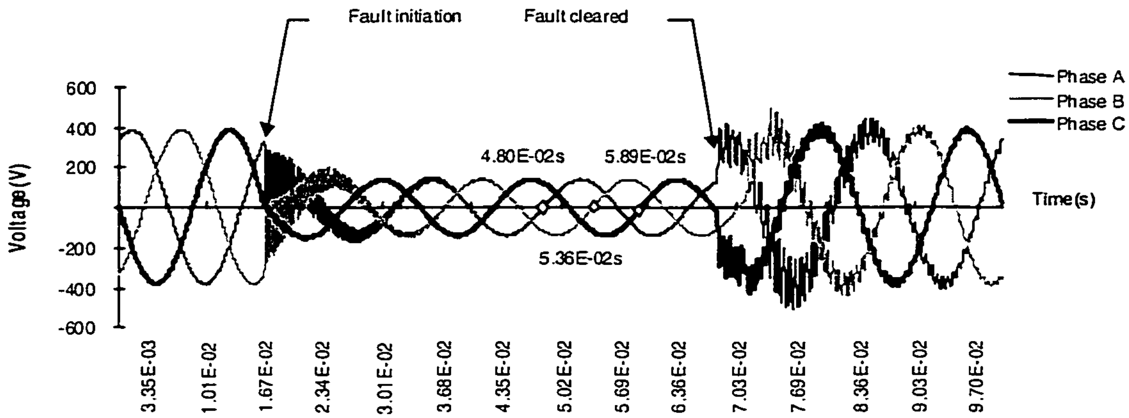


Figure 5-7 Voltages on RECT with a Three-phase Fault on FDR-H

The angle deviation for phase A, B and C are 0.96°, -0.12° and -0.84°, respectively, which is smaller than those in the case with a single phase fault. For comparison, voltage sags for each case study are listed in Table 5-7.

Table 5-7 Node Voltage Deviation due to Three Phase Fault on FDR-H

Node	Voltage Sag(%)			Phase Angle Jump(°)		
	A	B	C	A-B	B-C	C-A
AUX	0.00%	0.00%	0.00%	0	0	0
RECT	-62.24%	-63.02%	-64.58%	0.96	-0.12	-0.84
T3-SEC	-64.51%	-64.51%	-64.51%	0	0	0
T11-SEC	-64.19%	-64.19%	-64.19%	0	0	0
T4-SEC	-100.00%	-100.00%	100.00%	0	0	0
T7-SEC	-100.00%	-100.00%	100.00%	0	0	0

5.4.3 Case 3: Single Phase Fault at Bus Mill-1

Similar to case 1, node RECT is chosen as the node of concern. Figure 5-8 and Figure 5-9 show the voltage wave-form on the primary and secondary side of transformer No.3 which feeds the load on RECT. The voltage magnitude and phase angle deviations are provided in Table 5-8.

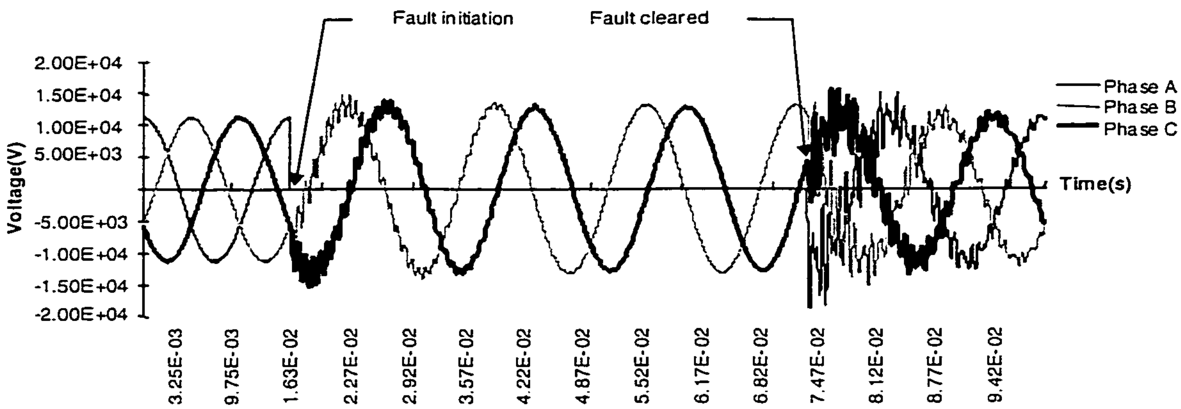


Figure 5-8 Voltage Response on FDR-F to SLGF on MILL-1

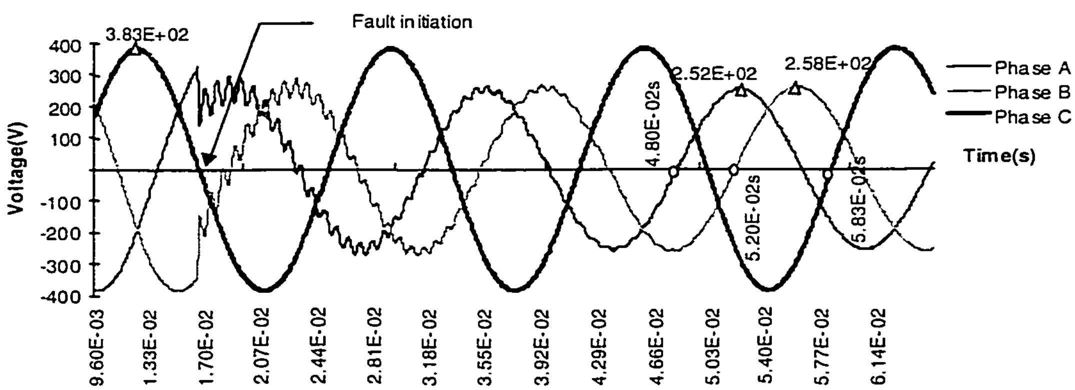


Figure 5-9 Voltage Response on RECT to SLGF on MILL-1(Zoom-in of Figure 5-8)

Table 5-8 Node Voltage Magnitude and Phase Angle Deviation due to SLGF on MILL-1

Node	Voltage Sag(%)			Phase Angle Jump(°)		
	A	B	C	A-B	B-C	C-A
AUX	0.00%	0.00%	0.00%	0	0	0
RECT	-34.20%	-32.38%	0.00%	-33.6	16.08	17.52
T3-SEC	-33.95%	-32.72%	0.00%	-33.6	18.24	15.36
T11-SEC	-33.69%	-32.10%	0.00%	-33.6	16.08	17.52
T4-SEC	-33.07%	-32.55%	0.00%	-33.6	16.08	17.52
T7-SEC	-33.69%	-32.56%	0.00%	-33.6	13.92	19.68

The group of equipment susceptible to phase angle jump is not clearly defined. Also, this parameter is not qualified in any digital monitoring equipment currently available in the market. The consequences of phase angle jump are not well understood and need to be further investigated.

Conclusions

Voltage sags are the most important power quality problem experienced by most industrial customers. Adjustable-speed drive controls, computers, robotics, programmable logic controllers and other control applications are susceptible to interruptions caused by voltage sags.

In this thesis, the basic theoretical models required to evaluate voltage sags in utility and industrial systems are presented. Factors that influence the severity and propagation characteristics of voltage sag, transformer connections and fault location were investigated. It is shown that with respect to a single line to ground fault on the primary side of a transformer, the loads on the secondary side of a transformer with Wye-Delta and Wye-Delta to ground connections can experience voltage sag as low as 33%. To ensure a high quality power supply, transformer connections have to be considered in addition to utilising other voltage sag suppression techniques. The effects of transformer connections can be further examined by applying various modelling methods for three-phase transformer connections such as accurate transformer models provided by EMTP.

The fault location within a distribution system significantly affects the severity of voltage sags experienced by loads on adjacent feeders. The further a susceptible customer load is located from the fault location, the less the chance it will be caught in the low voltage area. Critical distance analysis combining with reliability theory can help to identify vulnerable area within a distribution system and further predict the magnitude, duration and frequency of voltage sags. Such an effort can also be found in reference [27].

A simulation study of an industrial power system revealed some of the transient behaviour and propagation characteristics of voltage sags in the system. In transient period before the fault condition is eliminated, not only does the voltage magnitude drop, but also the phase angle deviates from normal symmetrical conditions. It is noted that in existing references, the group of equipment susceptible to phase angle jump has not been thoroughly investigated and clearly defined. Simulation studies of voltage sags can also be used to demonstrate other features of voltage sag such as non-rectangular waveform and zero-crossing points during fault [21]. Further simulation studies involve selection of accurate component models, such as generator models that consider the effects of generator controllers, speed controllers and excitation systems [27].

To reduce the impact and prevent occurrence of voltage sags, it is necessary for utilities, customers and consulting engineers to develop comprehensive voltage sag mitigating strategies. The analytical methods, derivation results and simulation studies presented in this thesis can be utilized to facilitate the efforts in this area. For instance, the voltage sag profile of a power system can be captured by predicating the number of voltage sags and area of vulnerability at any customer location. By considering the affects of transformer connections, the severity of voltage sags seen by the customer can be mitigated using alternative transformer connections. Simulation studies using various simulation tools can be used to find the transient features of voltage sags, hence, identify the possible operational problems with adjustable speed drive controls and other electronically controlled equipment.

Further voltage sag research on power systems is required in the areas of equipment ride-through capabilities, effects of voltage sags on motor load, and power quality standard.

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