# Voltage Recovery After Unbalanced and Balanced Voltage Dips in Three-Phase Systems

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***Abstract*—This paper studies the recovery of the voltage after a voltage dip due to a fault in a three-phase system. The instant of voltage recovery corresponds to the instant of fault clearing. For single-phase and phase-to-phase faults, a single point-on-wave of voltage recovery can be defined. For two-phase-to-ground and three-phase faults, the recovery takes place in two or three steps. The voltage recovery is described in a systematic way by using a classification of three-phase unbalanced voltage dips. The voltage recovery needs to be modeled correctly for studies of equipment immunity against voltage dips.**

***Index Terms*—Equipment immunity, power quality, power transmission and distribution, voltage dips (sags).**

## I. Introduction

A voltage dip is a short-duration reduction in rms voltage. A three-phase unbalanced voltage dip is a short-duration reduction in rms voltage in at least one of the three phase or line voltages [1], [2]. Voltage dips are due to short-duration increases in current elsewhere in the power system. The main causes of voltage dips are faults, motor starting, and transformer energizing. A voltage dip at the terminals of equipment may lead to maloperation of the equipment. Most maloperations are associated with voltage dips due to faults. One of the causes of maloperation is the sudden increase in voltage upon fault clearing [1]: the voltage recovery leads to high inrush current for rectifiers [5], current, and torque peaks for motor load [6]–[8] and possible saturation of transformers [9]. The details of the voltage recovery are likely to affect the operation of the equipment. In this paper, the voltage recovery is studied in more detail for three-phase unbalanced voltage dips (i.e., for voltage dips in three-phase systems).

When using a power-system analysis package that calculates voltage and current waveforms in time domain, the fault clearing at current zero is modeled correctly and the resulting voltage dip waveforms will represent the voltage recovery as accurately as the system model. The aim of the study presented in this paper is twofold. The results will give a better insight in the voltage recovery process without the need for doing a large number of simulations. That enables a quicker choice of simulation parameters when testing equipment performance.

The results presented in this paper will also enable the testing of end-user equipment like power-electronic converters, without the need to model the power system in detail. The results presented in this paper form part of the model of the interface between a three-phase power system and end-user equipment.

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TABLE I
THREE-PHASE UNBALANCED DIPS DUE TO DIFFERENT FAULT TYPES AND TRANSFORMER CONNECTIONS

| Fault type | location of dip | | |
|---|---|---|---|
| | I | II | III |
| Three-phase | A | A | A |
| Three-phase-to-ground | A | A | A |
| Two-phase-to-ground | E | F | G |
| Two-phase | C | D | C |
| Single-phase-to-ground | B | C | D |

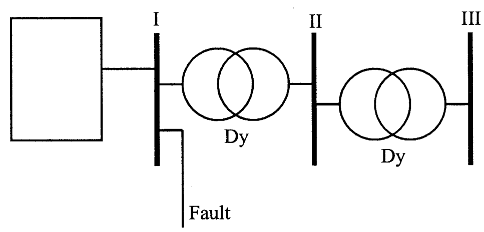


Fig. 1. System with three voltage levels for definition of types of three-phase unbalanced voltage dips.

## II. Three-Phase Unbalanced Voltage Dips

A three-phase fault leads to an equal drop in voltage in all three phases. Nonsymmetrical faults lead to drops in one, two, or three phases, with not all phases having the same drop. The resulting voltage drops and phase-angle shifts depend on a number of factors. A classification into four types is proposed in [3] and extended to seven types in [1] and [5]. The mathematical basis of the classification and a method for extracting the dip type from measured voltage wave shapes is given in [4]. For this paper, the classification into seven types is used, according to Table I and Fig. 1. A fault occurs at the indicated location in Fig. 1. This leads to voltage dips at the locations I, II, and III. The resulting dip types for these three locations, for the five different fault types, are given in Table I. For the purpose of this paper, Table I may be considered as the definition of dip types A through G. Other transformer types are considered in [3] but this does not result in new dip types.

The phasor expressions for the voltages during these seven types of three-phase unbalanced voltage dips are given in Table II under the assumption that positive, negative, and zero-sequence source impedance are equal.

The classification holds in general, not just for the assumptions made in the table, are described in [4]. The study of voltage

TABLE II
PHASOR EXPRESSIONS FOR THREE-PHASE UNBALANCED VOLTAGE DIPS FOR EQUAL POSITIVE, NEGATIVE, AND ZERO-SEQUENCE SOURCE IMPEDANCE

| | |
|---|---|
| Type A<br>$\overline{V}_a = V$<br>$\overline{V}_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$ | Type B<br>$\overline{V}_a = V$<br>$\overline{V}_b = -\frac{1}{2} - \frac{1}{2}j\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2} + \frac{1}{2}j\sqrt{3}$ |
| Type C<br>$\overline{V}_a = 1$<br>$\overline{V}_b = -\frac{1}{2} - \frac{1}{2}jV\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2} + \frac{1}{2}jV\sqrt{3}$ | Type D<br>$\overline{V}_a = V$<br>$\overline{V}_b = -\frac{1}{2}V - \frac{1}{2}j\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2}V + \frac{1}{2}j\sqrt{3}$ |
| Type E<br>$\overline{V}_a = 1$<br>$\overline{V}_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$ | Type F<br>$\overline{V}_a = V$<br>$\overline{V}_b = -\frac{1}{2}V - \frac{1}{2}j\left(\frac{2}{3} + \frac{1}{3}V\right)\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2}V + \frac{1}{2}j\left(\frac{2}{3} + \frac{1}{3}V\right)\sqrt{3}$ |
| Type G<br>$\overline{V}_a = \frac{2}{3} + \frac{1}{3}V$<br>$\overline{V}_b = -\frac{1}{2}\left(\frac{2}{3} + \frac{1}{3}V\right) - \frac{1}{2}jV\sqrt{3}$<br>$\overline{V}_c = -\frac{1}{2}\left(\frac{2}{3} + \frac{1}{3}V\right) + \frac{1}{2}jV\sqrt{3}$ | |

recovery, as described in this paper, holds for the general case but where needed, reference will be made to the expressions in Table II.

For the unbalanced dip types, a symmetrical phase can be defined. The expressions in Table II are for symmetrical phase a, indicated as $\mathrm{B_a}$, $\mathrm{C_a}$, etc. A type D dip with its largest drop in phase c is referred to as a $\mathrm{D_c}$ dip; a type C dip with large drops in phases a and c is referred to as a $\mathrm{C_b}$ dip; etc. In the remainder of this report, the a phase will be taken as symmetrical phase in most cases.

## III. VOLTAGE RECOVERY BASICS

Voltage recovery after a dip due to a fault takes place when the circuit breaker clears the fault. Circuit breakers clear a fault when the fault current has a zero crossing. Let $\cos\psi$ be the power factor of the fault current then the current zero crossing takes place at an angle $\psi$ for the prefault voltage or 180° later. The point-on-wave of voltage recovery after a dip due to a fault is thus $\psi$ or $\psi + 180°$ with reference to the upward zero-crossing of the pre-event voltage. In the remainder of this paper, only the first value will be considered, knowing that there are always two possible points of recovery per cycle, half a cycle apart.

The voltage after recovery can be written as

$$v(t) = \sin(\omega_0 t + \psi) \tag{1}$$

with $t = 0$ the recovery instant. Fault clearing not always takes place at the same instant for the three phases. The angle of the fault current will be different for different types of faults but generally speaking they are found in the same range of values: 45 through 60° for faults in distribution systems; 75 through 85° for faults in transmission systems.

In this paper, only solidly-grounded systems are considered. For high-impedance grounded systems, the angle is different for single-phase-to-ground faults. Also, single-phase-to-ground faults do not cause any significant dip, and two-phase-to-ground faults cause the same dip as phase-to-phase faults.

## IV. SINGLE-PHASE AND PHASE-TO-PHASE FAULTS

### A. Voltage Dips of Type B

Voltage dips of type B are due to single-phase faults. Let $\cos\psi_1$ be the power factor of the fault current for a single-phase fault, then the voltage after recovery is in the three phases

$$\begin{aligned} v_a &= \sin(\omega_0 t + \psi_1) \\ v_b &= \sin(\omega_0 t + \psi_1 - 120°) \\ v_c &= \sin(\omega_0 t + \psi_1 + 120°). \end{aligned} \tag{2}$$

The voltage recovers in the three phases at the same instant, with the point-on-wave in the faulted phase equal to the angle between source voltage and fault current $(\psi_1)$. When the non-faulted phases show a swell, this also recovers together at the same instant as the dip in the faulted phase.

### B. Voltage Dips of Type C

Voltage dips of type C are due to single-phase-to-ground or phase-to-phase faults. Consider a phase-to-phase fault between phases b and c. The fault current is driven by the voltage difference between phases b and c and has a zero crossing at an angle $\psi_2$ compared to the prefault voltage, with $\cos\psi_2$ the power factor of the fault current for a phase-to-phase fault. An angle $\psi_2$ for the bc voltage corresponds to an angle $\psi_2 + 90°$ for the voltage in phase a. The voltages after recovery can be written as

$$\begin{aligned} v_a &= \sin(\omega_0 t + \psi_2 + 90°) \\ v_b &= \sin(\omega_0 t + \psi_2 - 30°) \\ v_c &= \sin(\omega_0 t + \psi_2 - 150°). \end{aligned} \tag{3}$$

Like with type B, the voltage recovery takes place in both phases at the same time. The point-on-wave of recovery is equal to $\psi_2$ for the voltage difference between the faulted phases.

For a voltage dip of type C due to a single-phase fault, the expressions in (2) have to be transformed according to the Dy transformer. This results in the following expressions:

$$\begin{aligned} v_a &= \sin(\omega_0 t + \psi_1 + 90°) \\ v_b &= \sin(\omega_0 t + \psi_1 - 30°) \\ v_c &= \sin(\omega_0 t + \psi_1 - 150°). \end{aligned} \tag{4}$$

The only difference with (3) is in the angle $\psi$. But as this angle is similar for single-phase-to-ground and phase-to-phase faults, the recovery after a type C dip will be the same for a single-phase-to-ground and for a phase-to-phase fault.

### C. Voltage Dips of Type D

Voltage dips of type D are due to a single-phase-to-ground fault after two Dy transformers or due to a phase-to-phase fault

TABLE III
VOLTAGE RECOVERY FOR VOLTAGE DIPS DUE TO SINGLE-PHASE AND PHASE-TO-PHASE FAULTS

| Dip Type | Point-on-wave of voltage recovery | |
|---|---|---|
| | phase voltages | line voltages |
| Type $B_a$ | $\phi_a = \psi_1$<br>$\phi_b = \psi_1 - 120°$<br>$\phi_c = \psi_1 + 120°$ | |
| Type $C_a$ | $\phi_a = \psi_k + 90°$<br>$\phi_b = \psi_k - 30°$<br>$\phi_c = \psi_k - 150°$ | $\phi_{bc} = \psi_k$<br>$\phi_{ca} = \psi_k - 120°$<br>$\phi_{bc} = \psi_k + 120°$ |
| Type $D_a$ | $\phi_a = \psi_k$<br>$\phi_b = \psi_k - 120°$<br>$\phi_c = \psi_k + 120°$ | |

after one Dy transformer. The voltage after recovery is the same as (2)

$$\begin{aligned} v_a &= \sin(\omega_0 t + \psi_k) \\ v_b &= \sin(\omega_0 t + \psi_k - 120°) \\ v_c &= \sin(\omega_0 t + \psi_k + 120°) \end{aligned} \tag{5}$$

with $k = 1$ for single-phase-to-ground faults and $k = 2$ for phase-to-phase faults. Recovery takes again place in the three phases at the same time, with the point-on-wave of recovery equal to $\psi$ in the phase with the lowest voltage (the "faulted phase").

### D. Summary

The results for single-phase and phase-to-phase faults are summarized in Table III. For these two fault types, it is possible to define a point-on-wave of voltage recovery, but the definition is different for the different fault types. For types B and D, it is the angle of the lowest phase voltage, for type C it is the angle of the lowest line voltage.

## V. Two-Phase-to-Ground Faults

### A. Fault Clearing

The clearing of a two-phase-to-ground fault takes place in two steps. After the clearing of the first phase of the fault current, the two-phase-to-ground fault develops into a single-phase-to-ground fault and the amplitude and phase angle of the fault current will typically be different.

Consider a fault between phases b c and ground. Let 0° be an upward zero crossing in the phase b fault current, then there are four occasions per cycle in which a circuit breaker may clear the fault current in one phase: 0 and 180° in phase b; 120 and 300° in phase c. After the clearing of the first phase, the second phase will clear when the current in that phase gets through zero. If we neglect the difference in phase angle for single-phase-to-ground and two-phase-to-ground fault current, this results in four possible clearing sequences

- phase b at 0°, phase c at 120°;
- phase c at 120°, phase b at 180°;
- phase b at 180°, phase c at 300°;
- phase c at 300°, phase b at 360°.

The second clearing takes place 120° after the first clearing when the first clearing is in phase b, and 60° later when the first clearing is in phase c. This implies that there will be two different recovery sequences after voltage dips due to two-phase-to-ground faults.

Taking into account the difference in phase angle of the fault current for different fault types, the duration of the intermediate stage is $120° + \psi_1 - \psi_3$ when the first clearing takes place in phase b and $60° + \psi_1 - \psi_3$ when the first clearing takes place in phase c, with $\cos\psi_3$ the power factor of the current for a two-phase-to-ground fault, and $\cos\psi_1$ for a single-phase-to-ground fault.

Note that it is assumed here that the second clearing takes place at the first occasion after the first clearing. This is not necessarily the case. Statistical analysis of voltage dip and/or fault current recordings is needed to decide how often the first occasion is missed by the circuit breaker.

### B. Voltage Recovery

The resulting voltage dip and recovery sequence depend on the location of the voltage dip measurement compared to the fault location. With reference to Fig. 1, the dip type before the first clearing is E, F, and G at locations I, II, and III, respectively.

The two fault-clearing sequences for a two-phase-to-ground fault are

- bcn → cn → normal in 120°;
- bcn → bn → normal in 60°.

This translates, with help of Table in the following voltage recovery sequences at location I:

- $\mathrm{E_a} \rightarrow \mathrm{B_c} \rightarrow$ normal in 120°, first recovery at angle $\psi_3$ in phase b;
- $\mathrm{E_a} \rightarrow \mathrm{B_b} \rightarrow$ normal in 60°, first recovery at angle $\psi_3$ in phase c.

After one Dy transformer, that is, at location II, the voltage recovery sequences are

- $\mathrm{F_a} \rightarrow \mathrm{C_c} \rightarrow$ normal in 120°, first recovery at angle $\psi_3$ for phase difference ac;
- $\mathrm{F_a} \rightarrow \mathrm{C_b} \rightarrow$ normal in 60°, first recovery at angle $\psi_3$ for phase difference ab.

And after two Dy transformers (location III)

- $\mathrm{G_a} \rightarrow \mathrm{D_c} \rightarrow$ normal in 120°, first recovery at angle $\psi_3$ in phase b;
- $\mathrm{G_a} \rightarrow \mathrm{D_b} \rightarrow$ normal in 60°, first recovery at angle $\psi_3$ in phase c.

The results for two-phase-to-ground faults are summarized in Table IV.

## VI. Balanced Voltage Dips

Balanced dips (type A) are due to three- phase and three-phase-to-ground faults. As shown in Table I, the dip before fault clearing is the same for all locations. The voltage recovery however depends on the presence of an earth connection with the fault and on the presence of transformers between the fault location and the place where the dip is measured.

### A. Three-Phase Faults

The clearing of a three-phase fault (without earth connection) takes place in two stages. After the clearing in the first phase,

TABLE IV
VOLTAGE RECOVERY FOR VOLTAGE DIPS DUE TO TWO-PHASE-TO-GROUND FAULTS

| Dip Type | point-on-wave of first recovery | intermediate stage and duration | | point-on-wave of second recovery |
|---|---|---|---|---|
| $E_a$ | $\phi_a=\psi_3+120°$<br>$\phi_b=\psi_3$<br>$\phi_c=\psi_3-120$ | $B_c$ | $120°+\psi_1-\psi_3$ | $\phi_a=\psi_1-120°$<br>$\phi_b=\psi_1+120°$<br>$\phi_c=\psi_1$ |
| $E_a$ | $\phi_a=\psi_3-120°$<br>$\phi_b=\psi_3+120°$<br>$\phi_c=\psi_3$ | $B_b$ | $60°+\psi_1-\psi_3$ | $\phi_a=\psi_1-60°$<br>$\phi_b=\psi_1+180°$<br>$\phi_c=\psi_1+60°$ |
| $F_a$ | $\phi_a=\psi_3-150°$<br>$\phi_b=\psi_3+90°$<br>$\phi_c=\psi_3-30°$ | $C_c$ | $120°+\psi_1-\psi_3$ | $\phi_a=\psi_1-30°$<br>$\phi_b=\psi_1-150°$<br>$\phi_c=\psi_1+90°$ |
| $F_a$ | $\phi_a=\psi_3+150°$<br>$\phi_b=\psi_3+30°$<br>$\phi_c=\psi_3-90°$ | $C_b$ | $60°+\psi_1-\psi_3$ | $\phi_a=\psi_1-150°$<br>$\phi_b=\psi_1+90°$<br>$\phi_c=\psi_1-30°$ |
| $G_a$ | $\phi_a=\psi_3+120°$<br>$\phi_b=\psi_3$<br>$\phi_c=\psi_3-120$ | $D_c$ | $120°+\psi_1-\psi_3$ | $\phi_a=\psi_1-120°$<br>$\phi_b=\psi_1+120°$<br>$\phi_c=\psi_1$ |
| $G_a$ | $\phi_a=\psi_3-120°$<br>$\phi_b=\psi_3+120°$<br>$\phi_c=\psi_3$ | $D_b$ | $60°+\psi_1-\psi_3$ | $\phi_a=\psi_1-60°$<br>$\phi_b=\psi_1+180°$<br>$\phi_c=\psi_1+60°$ |

a phase-to-phase fault results. This one is cleared in the two remaining phases at the same time, about 90° after the first fault clearing. The recovery of the voltage dip depends on the presence of transformers between the fault and the dip.

The fault-clearing sequence is

- abc → bc → normal in 90°.

For location I in Fig. 1, this results in the following voltage recovery sequence:

- $\mathrm{A} \to \mathrm{C_a} \to \mathrm{normal\ in}\ 90°$, first recovery at angle $\psi_4$ in phase a.

At location II, the recovery sequence is

- $\mathrm{A} \to \mathrm{D_a} \to \mathrm{normal\ in}\ 90°$, first recovery at angle $\psi_4$ for the phase difference bc.

At location III, the recovery sequence is the same as at location I. As there can be no zero-sequence component present, the recovery behind two Dy transformers is the same as at the fault location.

### *B. Three-Phase-to-Ground Faults*

For a three-phase-to-ground fault, the fault clearing takes place in three stages: from three-phase-to-ground to two-phase-to-ground to single-phase-to-ground to full recovery. The duration of each of the two intermediate stages is 60°. Assume that phase a is the first to clear, then phase c will recover 60° later and phase b another 60° later.

The fault-clearing sequence is

- abcn → bcn → bn → normal in two times 60°.

This results in the following voltage-recovery sequences, with reference to Fig. 1:

- $\mathrm{A} \to \mathrm{E_a} \to \mathrm{B_b} \to \mathrm{normal}$ at location I;
- $\mathrm{A} \to \mathrm{F_a} \to \mathrm{C_b} \to \mathrm{normal}$ at location II;
- $\mathrm{A} \to \mathrm{G_a} \to \mathrm{D_b} \to \mathrm{normal}$ at location III.

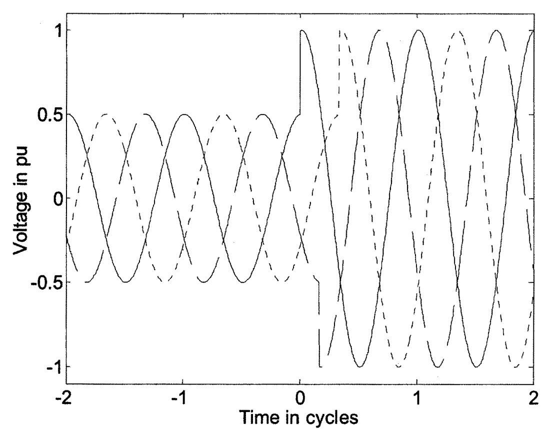


Fig. 2. Voltage recovery for a dip due to a three-phase-to-ground fault at transmission level: solid line: a phase; dotted line: b phase; dashed line: c phase.

The results for three-phase and three-phase-to-ground faults are summarized in Table V. All dips are of type A, but the recovery can take place in five different ways depending on the location of the fault and the presence of an earth connection with the fault.

## VII. EXAMPLE

As an example, the voltage recovery is studied for a voltage dip due to a three-phase-to-ground fault. The first case to be studied is a three-phase-to-ground fault in the transmission system. The fault-clearing angle $\psi$ is 85° for all fault types and there is no phase shift during the dip. Fig. 2 shows the voltage recovery measured at location I in Fig. 1 (no transformer). The dip develops from type A to type $\mathrm{E_a}$ to type $\mathrm{B_b}$ as the voltage recovers in phases a, c, and b. The expressions in the Table have been used to calculate the complex voltages, with $V = 0.50$.

The voltage recovery after a Dy transformer is shown in Fig. 3. The dip develops in this case from type A to type $\mathrm{F_a}$ to

TABLE V
VOLTAGE RECOVERY FOR DIPS DUE TO THREE-PHASE AND THREE-PHASE-TO-GROUND FAULTS

| Type | First recovery | Stage 1 and duration | | second recovery | Stage 2 and duration | | Third recovery |
|---|---|---|---|---|---|---|---|
| A | $\phi_a = \psi_4$<br>$\phi_b = \psi_4 - 120°$<br>$\phi_c = \psi_4 + 120°$ | $C_a$ | $60° + \psi_2 - \psi_4$ | $\phi_a = \psi_2 + 90°$<br>$\phi_b = \psi_2 - 30°$<br>$\phi_c = \psi_2 - 150°$ | n.a | n.a. | n.a. |
| A | $\phi_a = \psi_4 + 90°$<br>$\phi_b = \psi_4 - 30°$<br>$\phi_c = \psi_4 - 150°$ | $D_a$ | $60° + \psi_2 - \psi_4$ | $\phi_a = \psi_2 + 180°$<br>$\phi_b = \psi_2 + 60°$<br>$\phi_c = \psi_2 - 60°$ | n.a | n.a. | n.a. |
| A | $\phi_a = \psi_4$<br>$\phi_b = \psi_4 - 120°$<br>$\phi_c = \psi_4 + 120°$ | $E_a$ | $60° + \psi_3 - \psi_4$ | $\phi_a = \psi_3 + 60°$<br>$\phi_b = \psi_3 - 60°$<br>$\phi_c = \psi_3 + 180°$ | $B_b$ | $60° + \psi_1 - \psi_3$ | $\phi_a = \psi_1 + 120°$<br>$\phi_b = \psi_1$<br>$\phi_c = \psi_1 - 120°$ |
| A | $\phi_a = \psi_4 + 90°$<br>$\phi_b = \psi_4 - 30°$<br>$\phi_c = \psi_4 - 150°$ | $F_a$ | $60° + \psi_3 - \psi_4$ | $\phi_a = \psi_3 + 150°$<br>$\phi_b = \psi_3 + 30°$<br>$\phi_c = \psi_3 - 90°$ | $C_b$ | $60° + \psi_1 - \psi_3$ | $\phi_a = \psi_1 - 150°$<br>$\phi_b = \psi_1 + 90°$<br>$\phi_c = \psi_1 - 30°$ |
| A | $\phi_a = \psi_4$<br>$\phi_b = \psi_4 - 120°$<br>$\phi_c = \psi_4 + 120°$ | $G_a$ | $60° + \psi_3 - \psi_4$ | $\phi_a = \psi_3 + 60°$<br>$\phi_b = \psi_3 - 60°$<br>$\phi_c = \psi_3 + 180°$ | $D_b$ | $60° + \psi_1 - \psi_3$ | $\phi_a = \psi_1 + 120°$<br>$\phi_b = \psi_1$<br>$\phi_c = \psi_1 - 120°$ |

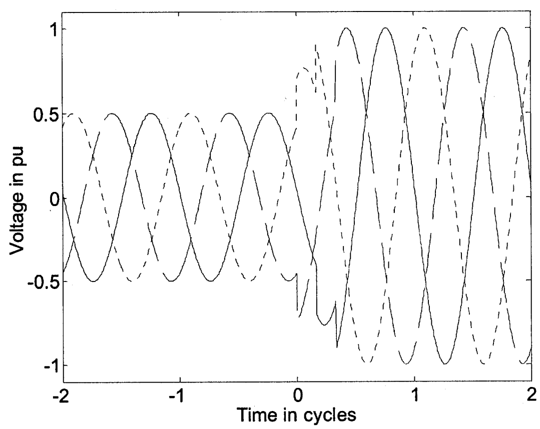


Fig. 3. Voltage recovery for a dip due to a three-phase-to-ground fault at transmission level, measured behind a Dy transformer.

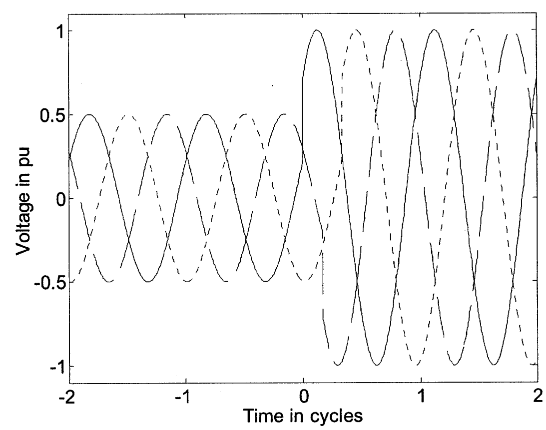


Fig. 4. Voltage recovery for a dip due to a three-phase-to-ground fault at distribution level.

type $C_b$. For type C dips due to single-phase-to-ground faults, the characteristic voltage ($V$ in Table II) is obtained from

$$V_1 = \frac{1}{3} + \frac{2}{3}V_3 \quad (6)$$

with $V_1$ the characteristic voltage for a single-phase-to-ground fault and $V_3$ for a three-phase fault at the same location [3]. Note that (6) holds for equal positive, negative, and zero-sequence impedances. Similar expressions can be derived for the more general case of unequal impedances [1].

As shown in Fig. 3, phase a (solid line) recovers in two stages 60° apart, phase b (dashed line) recovers in two stages 120° apart, and phase c (dotted line) recovers in two stages 60° apart. The last recovery of phase c corresponds to the first one in phase a.

The calculations have been repeated for a three-phase-to-ground fault at distribution level. The fault-clearing angle is taken as 45° and there is a phase shift of −20° during the dip. The results are shown in Figs. 4 and 5. Note that in all cases, the first fault clearing takes place at time zero. This partly explains the change in phase angle for the pre-recovery voltages. Also, the difference in phase-angle jump contributes to this.

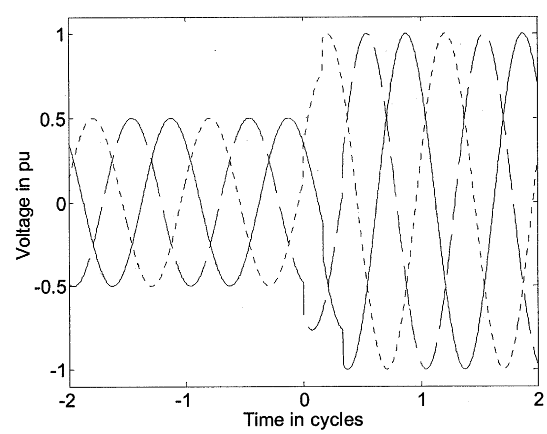


Fig. 5. Voltage recovery for a dip due to a three-phase-to-ground fault at distribution level, measured behind a Dy transformer.

Even though the voltage dip before fault clearing is the same for these four cases, the wave shapes during fault clearing are significantly different. Equipment that is sensitive to the voltage recovery after a dip may show completely different behavior for the different recovery sequences.

## VIII. Conclusions

Based on a classification of three-phase unbalanced voltage dips in seven types, the voltage recovery after voltage dips in three-phase systems has been studied. The recovery is different for different types of faults. For dips due to single-phase and phase-to-phase faults, the recovery takes place in only one step, so that a point-on-wave of voltage recovery can be defined. For dips due to two-phase-to-ground and three-phase faults, the recovery takes place in two steps, for dips due to three-phase-to-ground faults in three steps.

It is shown that the classification of three-phase unbalanced dips into seven types can be used to describe the voltage recovery after two-phase-to-ground, three-phase, and three-phase-to-ground faults.

The results obtained from this study are of importance for the assessment of equipment immunity to voltage dips. For equipment sensitive to the voltage recovery, this part of the dip needs to be modeled in sufficient detail. A single-stage recovery will give incorrect results for two-phase-to-ground, three-phase, and three-phase-to-ground faults. It is also important that realistic values of the fault-clearing angle are used in the study. The behavior of equipment may be different for dips due to faults at distribution level than for dips due to faults at transmission level due to the difference in fault-clearing angle. For equipment testing, it may also be important to consider the relation between the fault clearing angle and the phase-angle jump during the dip. Distribution system faults lead to a smaller fault clearing angle and a larger phase-angle jump than transmission system faults.

Further work consists among others, of obtaining statistics on the different recovery sequences, and of testing generic equipment for dips with different recovery sequences and fault-clearing angles.

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