ABOUT THE QUASISTATIONARY BEHAVIOUR DURING A SHORT CIRCUIT BETWEEN DIFFERENT VOLTAGE LEVELS

Dr. Giovanni CASTELLI
AEW Energie AG - Switzerland
giovanni.castelli@aew.ch

INTRODUCTION

Understanding the systems behaviour during a short circuit between different voltage levels is essential to design a protection system capable to clear also these faults efficiently. With a power systems calculation program it is possible to study such cases, if its algorithm allows the input of these special fault types, if the power system is modelled accordingly and if all required data are available.

The first two parts of this paper are based on the corresponding dissertation [1] presented by the author at the Swiss Federal Institute of Technology Zurich.

METHOD TO MODEL ANY FAULT IN SHORT CIRCUIT PROGRAMS

A widely used method for short-circuit analysis is described in most standard books like [2] or [3]. The power system is modeled as a Y-matrix. Out of this matrix one receives the reduced impedance matrix \( Z_{NF} \) representing the system at the fault location (1). \( I_F \) is the current- and \( U_F \) is the voltage vector describing the system state, \( U_0 \) defines the pre fault condition of the power system at the fault location. The fault is modeled using the fault equation system (2), Equation (1) and (2) are combined to the equation (3). The solutions of this equation are the currents at the fault location.

\[
\begin{align*}
U_F &= U_0 - Z_{NF} I_F \\
F_U I_F &= F_U U_F \\
0 &= F_U U_0 - (F_U Z_{NF} + F_U) I_F
\end{align*}
\]

(1) (2) (3)

Usually all parameters are given in the component system and in p.u. based on the nominal system voltage. The fault equation matrices are predefined for standard fault types at a single fault location.

Problems with fault equations for short-circuits between different voltage levels

For a fault between different voltage levels, the same procedure can be used, if the fault equation system is known. Unfortunately it is not possible to predefine the equation system for all possibilities. For a very simple fault from phase L1 of the first to phase L2 of a second voltage level, the equation system can be set up as shown in the equations (4) and (5). But it must be noted, that these equations are only valid if the first and the second voltage level are transformed to the same p.u. base voltage or if the power system model is given in its physical units. For the general case when all phases of all voltage levels are involved and the fault resistance can not be neglected, it is quite impossible to find a proper fault equation system manually.

\[
\begin{align*}
U_{(2\text{Sys}1)} &= U_{(2\text{Sys}2)} \\
I_{(2\text{Sys}1)} &= -I_{(2\text{Sys}2)} \\
I_{(2\text{Sys}1)} &= 0
\end{align*}
\]

(4)

To solve this problem, an algorithm was developed, that allows generating the fault equations out of a simple description of the fault like “From bus 1, phase L2 to bus 2, phase L3, impedance \( Z_F \)” (Fig. 1).

\[
\begin{align*}
F_U &= \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{align*}
\]

(5)

Fig. 1: Simple description of a complex fault

The algorithm must be able to formulate the equations system in both the phase and component system. No restrictions with respect to the selected p.u. base of the power system model are accepted and also zero fault impedances must be allowed.

**Basic idea for generating the fault equation**

The algorithm is based on the fact, that the fault equation system is similar to a Y-matrix of an electrical element like a line or transformer (Fig. 2). When \( F_U \) is the unit-matrix, \( F_U \) is identical to the Y-matrix containing \( y = 1/Z_F \). Unfortunately for impedance \( Z_F \) going to zero, the elements of the matrix \( F_U \) will become infinite and the equation system can not be solved. There are two methods to avoid such infinite matrix
The combination of these two methods leads to a fault equation by the sum of two lines containing the critical element \( y = 1/Z \).

\[
F_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad F_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}
\]

The fault matrices \( F_1 \) and \( F_2 \) are now formulated in the phase system and for physical units. It is easy to convert them to the component system or to transform them to any p.u. system. It should be noted that Bus 1 and 2 may have different base voltages; therefore the base impedance is not the same for all elements of the matrix (6).

### Algorithm to generate the fault equation system

The algorithm is subdivided into five basic steps to generate the fault equation system. First all connections to a grounded phase are changed to a direct grounding. Then all connections to ground with zero impedance are included in the matrix \( F_1 \) and \( F_2 \) of (6). Next, all buses which are interconnected with a zero impedance path are reduced to a single bus. One matrix line of these reduced buses is selected as “sum-line” and the elements of the equation system are inserted directly in equation (6). At last the connections with non-zero impedance are included at all required places (Fig. 4).

1. **Build the power system model**
2. **Standard short-circuit program**
3. **Algorithm to generate a fault equation**
   - **Read the fault description**
   - **Modify topology of faulted connections to grounded phases**
   - **Include direct connections to ground with zero impedance**
   - **Build a reduced bus for all phases interconnected with zero impedance**
   - **Include the equations of the reduced buses to the matrices**
   - **Include connections with non-zero impedances where applicable**
   - **Normalize the equation system**
   - **Convert the equations to the p.u. base used for the power system model**
   - **Convert the equations to the component system if required**
   - **Combine the fault equation with the reduced power system**
   - **Solve the system and calculate all results**

![Fig. 4: Algorithm for the generation of a fault equation system.](image)

A detailed description of all steps is available in [1]. The algorithm is implemented in some commercially available power system programs like NEPLAN. Up to now the algorithm has been working robust and without problems.

### GENERAL BEHAVIOUR DURING A SHORT CIRCUIT BETWEEN DIFFERENT VOLTAGE LEVELS

The above method was used to simulate a simple fault from one phase of a first (primary) to another phase of a second (secondary) power system (Fig. 5). In the following description the primary is assumed to be a high voltage (HV) and the secondary to be a medium voltage distribution system (MV). Fig. 6 shows the equivalent circuit for this fault type. The dominant parameters are the zero sequence systems of

\[ U_{F,Li(LxSynt)} = 0 \]
\[ I_{F,Li(LxSynt)} + I_{F,Li(LxSynt)} = 1/Z_{F2}(U_{F,Li(LxSynt)} - U_{F,Li(LxSynt)}) \]
\[ I_{F,Li(LxSynt)} = 0 \]
\[ I_{F,Li(LxSynt)} = 0 \]
\[ U_{F,Li(LxSynt)} = 0 \]
\[ U_{F,Li(LxSynt)} = U_{F,Li(LxSynt)} \]

---

1. NEPLAN Power System Analysis Program by BCPBusarello + Cott + Partner AG, Bahnhofstrasse 40, CH-8703 Erlenbach
Fig. 5: Simple short-circuit between two different voltage levels.

Fig. 6: Model of the simple short-circuit in the component sequence system

both involved voltage levels, especially the neutral grounding impedances $Z_{EMV}$ and $Z_{EHV}$ as well as the voltage and phase angle of the two sources. So it is very important to model the neutral grounding and the vector groups of all transformers in the primary and secondary system in detail. Also other parameters like the zero sequence system capacitance must not be neglected.

**Isolated neutral in one power system**

If the MV-system has an isolated neutral, the impedance $Z_{EMV}$ corresponds to its zero sequence system capacitance. The short circuit current is restricted and the voltage triangle in the isolated MV-system will shift in a way that both voltages of the faulted buses become identical (Fig. 7).

The zero-system voltage will increase extraordinarily. The capacitive current is higher than for a single-phase-to-ground fault (SPGF) in the MV-System (Fig. 8) and can have any angel. A simple ground fault protection in the MV-substation might not work.

**Grounded neutral in both power systems**

High currents appear, when the neutrals of both systems are grounded, i.e. $Z_{EMV}$ and $Z_{EHV}$ in Fig. 6 are zero. This is shown in an example of a short-circuit between two HV-systems. In the simple case of two independent systems, the short circuit current flows from the source at the primary voltage level to the fault location, then to the secondary voltage level (Fig. 9).

Fig. 7: Voltages in the isolated system dependent on the vector group of the interconnecting transformer

Fig. 8: Short-circuit currents for an MV-System with isolated neutral

Fig. 9: Simple short-circuit between two independent systems

With a transformer connecting the two systems (Fig. 10), the current flows to the transformers secondary winding and

Fig. 10: Short-circuit between two systems connected with a Yy0 transformer
neutral grounding back to the source. In the primary transformer winding a second current is induced. In our example this current is half of the short-circuit current. This circuit closes through the source, therefore the current of the reduced power system is smaller than the short-circuit current.

With an Yyd-transformer, the delta winding induces additional currents in all windings of the primary side. Fig. 11 shows the current flow for a short circuit between the transformer and the source from phase L1 of the primary to L3 of the secondary system.

![Fig. 11: Short-circuit between two systems connected with a Yyd transformer](image)

It can be seen that an exact modelling of the transformer and the zero sequence system is essential for this type of calculation. Phase shift angles between the different voltage levels must not be neglected as it is often done for load flow and simple short-circuit calculations. Correct results can be received using the superposition method [4] which includes a load flow calculation to determine the pre-fault condition.

A further question was about saturation effects in the core of the interconnecting transformer during the fault between two voltage levels. The above studies did not indicate saturation effects. For an MV-System with isolated neutral, the phase-to-phase voltages will not change; therefore no saturation will occur. For two HV systems with grounded neutrals, the short-circuit current is high enough to cause a break down of the voltages; no saturation effects have been found.

PARAMETERS TO CALCULATE SIMULTANEOUS FAULTS AT DIFFERENT LOCATIONS

The method to model any fault in the short circuit program can also be used to calculate simultaneous faults at different locations. This feature was used to study the case of phase grounding of the faulted phase in the substation, when a SPGF\(^2\) occurs in the power system, a procedure that has been used in some countries to reduce the short circuit current at the fault location [5].

An isolated 16-kV-system (Fig. 12) has been prepared for experiments with a SPGF: using a circuit-breaker, one phase of an overhead line has been grounded rigidly. A few seconds later the same phase was grounded in the substation.

Together with FKH\(^3\) currents and voltages at the fault location and in the substation have been measured [6]. The same power system has been modelled and the calculation results have been compared with the measurements [7].

![Fig. 12: 16-kV-System prepared for short circuit tests](image)

All tests have been performed with and without load. The algorithm of the program has been working fine. Measurements and calculation have shown the same basic behaviour: the capacitive current splits between the short-circuit location and the ground connection in the substation. The load current will split between the phase conductor and ground (Fig. 13).

![Fig. 13: Current flow after grounding the faulted phase in the substation](image)

However the numerical results did not match very well in the first approach. The reason was that the used zero sequence system data of the connecting cable have been taken from theoretical calculations and assumptions. After replacing the cable data with measured impedances, the calculation and measurements became comparable (Fig. 14).

Both, calculation and measurements are very sensitive on the zero sequence system data. To show this, all measurements have been done for two basic configurations with respect to the grounding of the shield of the interconnecting cable. In the case of Fig. 14 the shields have been grounded on one side only giving a high zero sequence system impedance.

Fig. 15 shows the case with the shields grounded on both ends. The zero sequence system impedance of the cable is lower and as consequence, more load current will flow

---

2 SPGF=Single Phase to Ground Fault

3 Fachkommission für Hochspannungsfragen, Voltastrasse 9, CH-8044 Zürich
Impedances have also a dominant influence on the current system. Similar to the zero sequence system, these distribution.

Another influence that may not be neglected in this type of substation.

Even increase after closing the ground connection in the grounding through the ground path. The current at the fault location can even increase after closing the ground connection in the substation.

Another influence that may not be neglected in this type of study is the fault impedance and resistances of the grounding systems. Similar to the zero sequence system, these impedances have also a dominant influence on the current distribution.

**SUMMARY OF MAIN RESULTS**

As main results of the above studies it can be stated that

- A method is available that can easily be implemented in many standard short-circuit programs making it capable to calculate faults between different voltage levels.
- The quasi-stationary behaviour of a power system for the case of a short-circuit between two voltage levels and of simultaneous faults at different locations is described. To study such fault types take care on the following:
  - The zero sequence system has an important influence on the results.
  - The transformers have to be modelled in detail. The vector group must not be neglected.
  - The short-circuit calculation shall be done with the superposition method. This includes a load flow calculation to determine the pre-fault condition.
  - Dependent on the study type the results are very sensitive on the used data (be careful with estimated or with standard data).
  - Fault impedances and resistances of grounding systems shall be taken into account.

**REFERENCES**


