VOLTAGE DIPS ANALYSIS BY MONTE CARLO APPROACH

N BOMBIERI, C. BOVO, M. DELFANTI, M. S. PASQUADIBISCEGLIE, M. POZZI
Politecnico di Milano
Italy
marco.pasquadibisceglie@polimi.it

ABSTRACT

Limiting the presence of voltage dips is becoming a key issue while managing distribution networks. In order to face this problem different technical solutions may be adopted. According to the Italian regulatory framework, the protection of customer plants can be achieved by both circuit breakers and fuses. A comparison between the two possibilities is performed: the task is to estimate number, depth and duration of voltage dips by the mean of a Monte Carlo indirect approach able to simulate the grid behaviour, coupled with a short circuit computation tool. The numerical results on a simple radial network are provided. The benefits associated to the fuses limiting capability are highlighted.

INTRODUCTION

In the recent years a large interest has been dedicated to the quality of supply, with particular reference to the problems caused by voltage dips both in industrial and in domestic applications. For example a supply voltage reduction may interrupt production processes or may induce undesired reset in personal computer and other electronic devices. Since customers are becoming more and more sensible to these and other similar problems, the evaluation of the expected number, depth and duration of voltage dips is turning out to be a key issue for a Distribution System Operator (DSO), especially in order to increase the overall performances of its electrical network.

Focusing the attention on the Italian environment, in the recent years a great interest has been put on different aspects regarding quality of supply and regarding the access conditions to the distribution grid. In particular in December 2006, the Italian Regulator (RAEG) and the Italian Electrotechnical Committee (CEI) issued a public consultation [1] regarding the electrical schemes to be adopted by DSO to connect users to the distribution grid. For the final customers connected in MV two possible protection devices are allowed: a traditional circuit breaker equipped with an overcurrent relay or a switcher coupled with fuses. This paper tries to quantify the differences of the above mentioned solutions in term of depth and duration of voltage dips: the sags expected in a distribution network with customers protected by circuit breaker or by fuses are counted. A Monte Carlo indirect algorithm is used to simulate the system behaviour: whenever a fault occurs, the short circuit current is computed and used to evaluate depth and duration of voltage dips for each final customer.

The model is applied to a simple radial MV distribution system.

INDIRECT MONTE CARLO APPROACH

Being a complex system, the behaviour of an electrical network is subject to many different factors and therefore can not be studied by means of a deterministic tool. For this reason a Monte Carlo algorithm is widely used in the international literature [2] [3] [4] [5]. At each time t_i a component is in one of its possible functional states; according to the “transport of system states” theory, the combination of the states assumed by all the electrical devices gives the system global condition at time t_i. The transition between a situation and another may be simulated by adopting two different approaches: a direct method and an indirect method. The latter is adopted in this paper: given the global system condition at time t_i and the distribution of probability of each possible transition, the transiting component, its new state and the transition time are randomly generated. The process is repeated until the mission time T_M, representing the time horizon of the simulation, is got.

Further details of the proposed approach can be found in [6] and [7].

FUNCTIONAL STATES AND SHORT CIRCUIT EVALUATION

The system state is defined on the basis of the different functional conditions of each device. In [6] and in [7] each electrical device is characterized by both faulty and operational states and all the components may be subject to a transition. In this paper a different choice is made: the main target being the analysis of voltage dips, the attention is focused only on those transitions effectively causing a supply voltage reduction. As a consequence, all the logical components (circuit breakers and switchers) are simulated to be fully reliable and only lines and transformers are allowed to transit to a faulty state.

Regarding faults, only three-phase short circuits are taken into account. In fact, in the Italian MV distribution network the neutral grounding scheme usually limits the single phase short circuit current, and these type of fault does not affect the customers’ supply voltage.

In conclusion only the following states are introduced for each component:

- normal operating state (NOS), i.e. the component is normally working;
- standby state (SBS), i.e. the component is inactive but can be switched on if required (it is the case of an open circuit breaker)
- permanent three-phase fault (P3F), i.e. a permanent 3 phase fault occurs and the component has to be isolated immediately from the system;
- temporary three-phase fault (T3F), i.e. a temporary 3 phase fault occurs.

Whenever a fault occurs, different procedures have to be put in operation in order to evaluate the depth and duration of the voltage dip at each customer. Firstly, since the depth is strongly dependent on the fault position, it is necessary to identify the effective point (within the damaged line or transformer) where the short circuit occurs: this is achieved through a random selection.

Given the fault position, the short circuit tool is started: it consists of a steady state computation based on nodal impedance matrix. Since the chosen approach allows to calculate short circuit only in busses (not along branches), it is necessary to introduce the auxiliary bus AUX coincident with the fault position. The series impedance of the faulty component is therefore divided in two sections, one before and one after the fault, as represented in Fig. 1.

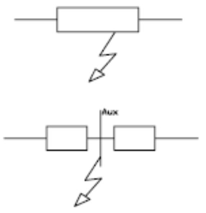

Fig 1 Series impedance management after fault

With the modified network a load flow is used to compute the vector $\mathbf{V_{pf}}$ of the voltage at each node in the pre-fault situation. Let $\overline{V_{aux}}$ be the voltage at the bus AUX in that situation; the 3 phase symmetrical component $\overline{I_{3f}}$ of short circuit current can be computed as follows

$$\overline{I_{3f}} = \frac{\overline{V_{aux}}}{\overline{Z_{aux}} + \overline{Z_f}}$$

where

- $\overline{Z_{aux}}$ is the nodal impedance seen from the bus AUX
- $\overline{Z_f}$ is the randomly generated fault impedance.

$\overline{Z_{aux}}$ is the diagonal element of the nodal impedance matrix **Z** associated to the bus AUX. The matrix **Z** is computed by inverting the modified admittance matrix $\mathbf{Y_{cc}}$, appositely build from the network nodal admittance matrix **Y** through the following procedure:

a) each diagonal element $\overline{Y_{ii}}$ is substituted by $\overline{Y_{ii}} + \overline{Y_{iadd}}$ being $\overline{Y_{iadd}}$ the sum of the admittances of generators and loads connected to the bus *i*;

Given the current $\overline{I_{3f}}$, the vector **V** of the voltage at each bus is computed as

$$\mathbf{V} = \mathbf{V_{pf}} + \mathbf{Z} \cdot \mathbf{I_{cc}} \qquad (1)$$

where $\mathbf{I_{cc}}$ is the vector of the current injection due to the fault: all the element are equal to zero, but the one associated to the bus AUX is equal to $-\overline{I_{3f}}$.

It is worth noticing that the vector **V** contains the symmetrical component of the voltage at each node; these values represent the steady state situation of the network after the transient consequent to the fault. They can be used to compute the symmetrical component of the current circulating in each branch.

PROTECTION DEVICES INTERVENTION

Among the output data, the short circuit tool provides the current circulating in each branch after the fault. These values can be used to verify the intervention of the protection devices installed on lines and at the point of common coupling (PCC).

Let I_b be the symmetrical component of the current circulating in the branch *b* and let this branch be protected by a circuit breaker, equipped with an overcurrent relay. This protection device is simulated with a two step intervention curve:

- if $I_b \geq I_{ist}$ the relay trips immediately with the circuit breaker and the fault is cleared in a very short time (usually 120 ms, associated to the breaking time of the circuit breaker itself);
- if $I_{temp} \leq I_b < I_{ist}$ an intentional delay t_d is introduced;
- if $I_b < I_{temp}$ no intervention occurs.

In case branch *b* is protected with a fuse, the situation is quite different: with respect to the prospective wave associated to the fundamental current I_b, the current actually circulating in the branch is limited, as depicted in Fig. 2.

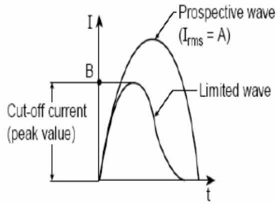

Fig 2 Fuse limiting capability

As a result, all the currents circulating in the network due to the fault are reduced, thus resulting a in reduced dip depth. In particular, given the peak value I_{pc} of the cut-off current, it is possible to evaluate the fundamental component associated to the limited current wave, from which the currents circulating in the other branches and the voltages at each node can be easily computed by means of the matrix **Z**.

The intervention time t_c can be assumed equal to $t_a + t_f$ where t_a is the pre-arching time (after which the interruption is initiated) and t_c is the fusion time (time took up to open the circuit after the interruption is initiated).

Both I_{pc} and t_c are dependent on the prospective fundamental current I_b: the relevant curves are annexed to the documentation accompanying the device.

VOLTAGE DIPS EVALUATION

At each customer node, the dip depth (in term of supply voltage magnitude in the steady state situation after a fault) is computed by applying the short circuit tool described in the above sections (as suitably modified to take into account to the fuse limiting capacity). The dips usually last until the fault is cleared by the intervention of a protection device. After this event two different situations may occur:

a) the customer is connected to the faulty line of the network: the dip evolves in a permanent interruption;
b) the customer is not connected to the faulty line of the network: the dip ends and the supply voltage is fully recovered within its operating limits.

Many different Monte Carlo histories are simulated in order to provide an exhaustive sample of the possible network behaviour. During each history the dips are counted and recorded in different classes on the basis of their depth and duration. The classification illustrated in Table I, derived from the well known UNIPEDE table, is adopted. No class with duration higher than 1 s is considered since all the simulated protection devices are able to act within 1 s.

TABLE I – UNIPEDE voltage dips classification

	Duration				
Residual Voltage	**< 20 ms**	**20-100 ms**	**100-150 ms**	**150-500 ms**	**0.5-1 s**
85-90%					
70-85%					
40-70%					
10-40%					
<10%					

At the end of the computation process, Table I contains the total number of dips belonging to each class that occurred in the distribution network during all the histories. The mean number D_c of dips belonging to class c that may be expected at each bus is computed as follows:

$$D_c = \frac{\sum_{k=1}^{s}\sum_{i=1}^{n} n_{ick}}{n}$$

where

- n_{ick} is the total number of dips of class c which happened at node i in history k;
- n is the total number of nodes in the considered network.

SIMULATION DETAILS

The procedure presented in this paper is applied to the simple radial distribution scheme represented in Fig. 3: a HV/MV station is connected to four distribution cables, each of which feeds a final customer. B indicates the interface devices between the DSO and the customer (owner of the MV/LV transformer), while A designates the protection devices installed by the DSO to protect the feeders.

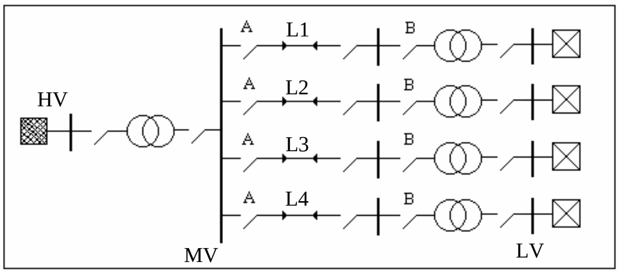

Fig 3 Radial distribution scheme

According to [1] two different configurations are taken into account.

1) all the protection devices are circuit breakers equipped with current relays (I_{ist}=650 A; I_{temp}=250 A, t_d=500 ms; A further delayed to achieve time selectivity);
2) Protection devices in the PCC (B) are switchers equipped with fuses whose limiting and pre-arching time curves are respectively reported in Fig 4 and 5.

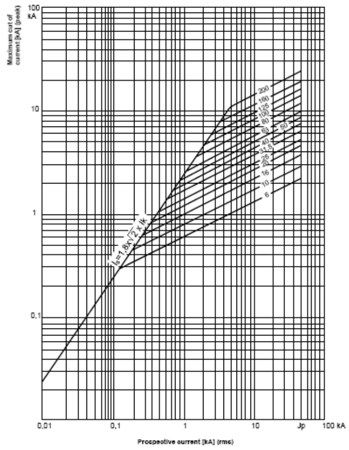

Fig 4 Fuse limiting characteristic

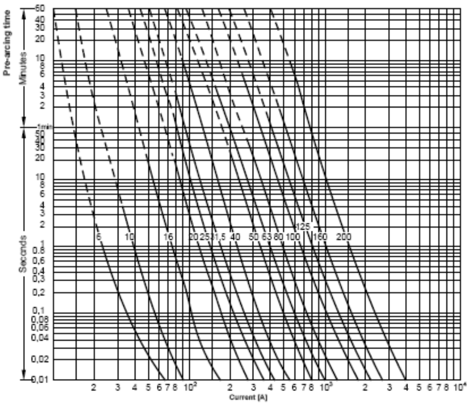

Fig 5 Fuse pre-arching curve.

The HV network has a short circuit power equal to 2500 MVA; all the lines are characterized by resistance $r = 0.25\,\Omega/km$ and reactance $x = 0.2\,\Omega/km$

The other relevant data are summarized in Table II, while Table III reports the transition rates adopted in the simulation.

TABLE II – Relevant data

	A [MVA]	SHCV [%]
Transformer HV/MV	25	10
Transformer MV/LV	0.5	5

Line	Length (km)
L1	5
L2	10
L3	15
L4	20

	A [MVA]	PF
Load	0.5	0.9 ind

TABLE III – Transition rates

From	to	Trans.[h^{-1}]	Line [km/h]
NOS	P3F	5.70e-5	6.14e-6
P3F	NOS	8.33e-3	1.39e-2

For the sake of simplicity only three-phase permanent faults are considered. This choice is quite reasonable since on customers networks and on distribution cables a temporary fault seldom happen.

NUMERICAL RESULTS

Table IV and fig. 6 report the values of D_C for each class: only dips occurring in the customers MV busses are taken into account. The white cells are related to case 1 while the grey cells are related to case 2.

TABLE IV – Mean expected dips

	Duration				
Residual Voltage	**< 20 ms**	**20-100 ms**	**100-150 ms**	**150-500 ms**	**0.5-1 s**
85-90%	0	0	0.076	0	0.052
	0.037	0.003	0.015	0	0
70-85%	0	0	0.091	0	0.16
	0.098	0.024	0.040	0	0
40-70%	0	0	0.11	0	0.074
	0.028	0	0.048	0	0
10-40%	0	0	0.036	0	0
	0	0	0.019	0	0
<10%	0	0	0.054	0	0.0080
	0.011	0.001	0.051	0	0

When circuit breakers are installed, only two duration times occurs, associated to the two intervention steps simulated in the current relays: faults ion customer transformers are usually cleared in the longest time (sixth column) while cables faults, giving origin to higher currents, cause a faster intervention (fourth column). With fuses, the dip duration is significantly reduced: customer fault that in case 1 are cleared in a long time, are now solved by fuses within 100 ms (second and third columns). Besides the short circuit current is limited, hence the voltage drops are contained and many faults does not cause any sag: this results in less dips than in case 1. The fourth column, associated to the longest duration in this case, is still related to cables faults that continue to be cleared by the circuit breakers.

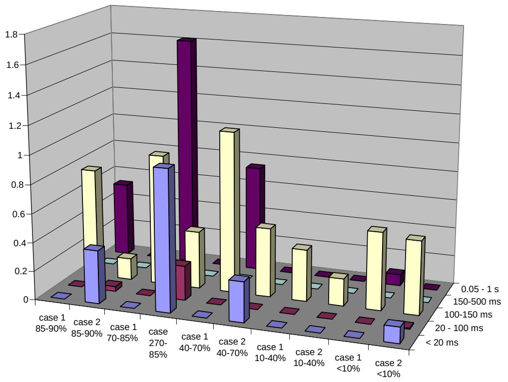

Fig 6. Mean expected dips

CONCLUSIONS

A Monte Carlo indirect approach, coupled with a short circuit computation tool, is used to estimate expected number, depth and duration of voltage dips in a radial distribution network.

According to regulatory framework currently applied in Italy, a comparison between the adoption of circuit breakers and fuses to protect final customers is performed. The numerical results confirms the potential benefits of the fuses in terms of voltage dips: their number, depth and duration may be sensibly reduced, thus advising a larger use of these devices in order to enhance the overall performances of a distribution network with reference to the supply voltage quality.

REFERENCES

[1] AEEG, CEI, 2006, *Regole tecniche per la connessione alle reti di distribuzione dell'energia elettrica in alta e media tensione*, Atto 34/06, available on http://www.autorita.energia.it.

[2] C.M. Rocco, J.A. Moreno, 2003, "System Reliability Evaluation Using Monte Carlo & Support Vector Machine", *Proceedings Annual Reliability and Maintainability Symposium*

[3] M. Marseguerra, E.Zio, 2002, *Basics of Monte Carlo Method with Application to System Reliability*, LiLoLe-Verlag GmbH, Hagen, Germany

[4] A. Dubi, 2000, *Monte Carlo applications in system engineering*, Wiley &Sons., USA

[5] R.Billinton, P. Wang, 1999, "Teaching Distribution System Reliability Evaluation Using Monte Carlo Simulation", *IEEE Trans, on Power Systems*, Vol.14, Issue 2.

[6] C. Bovo, M. Delfanti, M. S. Pasquadibisceglie, M. Pozzi, E. Zio, 2005, "Indirect Monte Carlo approach to evaluate reliability and availability indices of distribution networks", *Proceedings of Cired*, Turin

[7] C. Bovo, M. Delfanti, M. S. Pasquadibisceglie, M. Pozzi, E. Zio, 2006, "Indirect Monte Carlo approach to test the distribution supply quality", *Proceedings of Cidel*, Buenos Aires