EXTENDING SWITCHING RECLOSING TIME TO REDUCE INTERRUPTIONS IN DISTRIBUTION NETWORKS

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ABSTRACT

In the paper the authors evaluate the possible benefits of extending the switching reclosing time to reduce transient interruptions in distribution networks. A probabilistic fault arc reignition model for MV distribution networks developed with a simulation tool, permits investigating on the possible benefits of the extension of the switching reclosing time delay before the first fast reclosure.
The application of the model in simulating realistic MV, shows that an enlarged reclosing time may result in a reduction of the probability of fault reignition and, thus, a significant impact in increasing the number of self-extinguish faults and decreasing the number of sustained interruptions.

INTRODUCTION

Performance-based rates (PBRs) are regulatory orders that reward utilities for good reliability and penalize them for poor reliability. Subsequently to PBRs directives, usually based on incentives and penalties to promote a continuous reliability improvement in power distribution systems, a large deployment of network automation with reclosing practices has been the usual solution adopted by distributors to achieve the goal of providing a distribution network with high performances in terms of number and duration of interruptions. For instance, in Italy, the Italian Regulator for Electric Energy and Gas (AEEG) introduced important innovations in the regulation of continuity of supply for the period 2007-2011 [1]. In particular, regulatory Order 333/07 provides for a payment to each MV customer which suffers a number of long unplanned interruptions per year higher than a threshold. For the years 2010 and 2011 the guaranteed standard is 2, 3, and 4 interruptions/year for each MV customer depending on the territorial characteristics (respectively for high, medium and low density areas). Each interruption beyond the mentioned threshold (till a pre-defined maximum number) determines a penalty paid by the local distribution system operator (DSO). Conversely, if the DSO improves better than the standard, it receives a reward. The reward and penalty mechanism was initially focused only on the SAIDI indicator for long unplanned interruptions; with Order 333/07 it was extended to the System Average Interruption Frequency Index (SAIFI) and Momentary Interruption Frequency Index (MAIFI) indicators, calculated respectively on unplanned long and short interruptions. The interruptions counted in the calculation of the MAIFI indicator are those longer than one second and shorter than three minutes. The mentioned regulation makes pressure on DSOs, which are forced to improve their network performances. In particular, for improving the MV distribution system reliability, distributors adopt in their MV substations circuit breakers able to perform multiple auto reclose operation in order to reduce the number of short and long interruptions due to transient faults. In the paper the authors evaluate the possible benefits of adding an external time delay to the circuit breaker reclosing procedure. The goal of this additional delay is to be reasonably sure that the arc at the fault location will not reignite at the reclosing instant creating a second fault, and, then, obtain significant benefits on continuity of service. In order to provide a quantitative measure of the mentioned approach, in the paper a probabilistic fault arc reignition model has been incorporated in a MV distribution network and the dynamic interaction of the arc with the electric circuit is investigated. A Monte Carlo simulation tool is used to simulate the highly random behaviour of the technical and environmental parameters involved in the problem.

FAULT ARC AND REIGNITION MODEL

In order to reproduce the complete fault phenomena in distribution networks considering the auto-reclosing of a line breaker the fault arc model and the recovery model of the dielectric medium in the fault area have to be developed. The arc mathematical model used by the authors for describing the electrical behaviour of the arc subsequent to a fault on a distribution network, is the classical Cassie and Mayr model (1):

$$\frac{dg(t)}{dt} = \frac{1}{\tau} \cdot \left[G - g(t) \right] \quad (1)$$

where *g(t)* represents the time dependent arc conductance, *G(t)* is the stationary arc conductance, and τ is the arc thermal time constant. By solving eq. (1) it is possible finding the arc voltage and current. The arc model is in relationship with a model for the arc reignition after the zero-crossing of the arc current. Parameters that are involved in the solution of the eq.(1) can be obtained from arc measurements and validated for MV distribution networks [3, 4].
In [2] this model has been applied to the determination of the self-extinguish conditions of the secondary arc in the

transmission lines, and it has been developed by estimating with (2) the reignition voltage v_d:

$$v_d(t) = \left[5 + \frac{1650 \cdot T_e}{2.15 + I_{RMS}}\right] \cdot (t - T_e) \cdot l_a \cdot 10^5 \; [\mathrm{V}] \quad (2)$$

where T_e is the extinction time of the secondary arc (zero crossing) measured from the transition between the primary and the secondary arc, t is the time elapsed from the secondary arc comparison, and I_{RMS} is the RMS value of the secondary arc current. If the arc voltage is lower than the reignition voltage, the arc will be self extinguished. The current range of the single-phase-to-ground faults in MV networks, with isolated or resonant grounding, is comparable to the secondary arc current in the Transmission systems. Equation (2) cannot be used in case of delayed autoreclosing procedures in distribution networks because it is valid only immediately after the arc interruption. For this reason, in the paper the insulation recovery characteristics has been correlated with the temperature variation in the zone surrounding the fault for arcs in order to take into account the flashover probability variation. A thermal model has been implemented with the EMTP program that allows representing the temperature rise in the surroundings of the fault arc and the subsequent cooling when the arc is interrupted in over-head lines (outside) as well as for arcs within MV cells. A detailed description of the whole probabilistic model is presented in [5]

When the fault arc is definitely interrupted opening the line breaker, the auto-reclosing dead time should be sufficiently long to avoid the fault reignition when the switching overvoltage, caused by the auto-reclosing, is applied to the fault point. The minimum deionization time depends on the rated voltage of the power system, the involved air gap, the fault current amplitude and the weather conditions (humidity, velocity of wind, air pressure, air temperature, etc.). Some results have been collected in the past, based on laboratory and field tests and on operating experience [6]. From these results and with reference to 20 kV distribution overhead lines, the minimum dead time should last from 12 t 15 cycles (around 240÷300 ms). However, some reignition events may still occur due to adverse environmental conditions (e.g. when the fault occurs inside a metal enclosed electrical installation).

Therefore, it could be useful to extend the auto-reclosing dead time, Δt_{DT}, in order to leave additional time for a better recovery of the dielectric strength and reduce the risk of flashover, R_{FO} that can be calculated with (3):

$$R_{FO}(\Delta t_{DT}) = \int_{V_{min}}^{V_{max}} G(V) \cdot F(V, \Delta t_{DT}) \cdot dV \quad (3)$$

where $G(V)$ is the switching surge frequency distribution, $F(V, \Delta t_{DT})$ is the transient flashover probability at different auto-reclosing dead times, V_{min} and V_{max} are the minimum and maximum switching overvoltages (fig. 1).

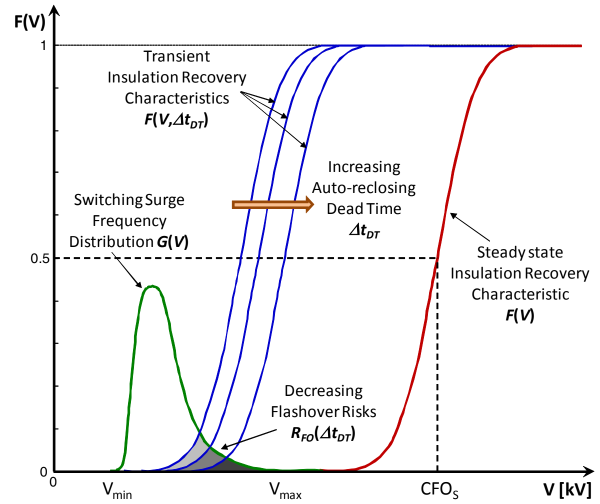

Fig. 1: Effect of flashover risk decrement with increasing auto-reclosing delay.

CASE STUDY

The probabilistic arc model described in the previous section and more in detail in [5] has been successfully implemented with the commercial package EMTP-RV for the electromagnetic transient analysis and applied to the MV distribution system depicted in Fig. 2. The test network is a 20 kV distribution system supplied by a 132 kV grid with a 40 MVA transformer. The 20 kV system consists of several overhead lines and cables with radial arrangement.

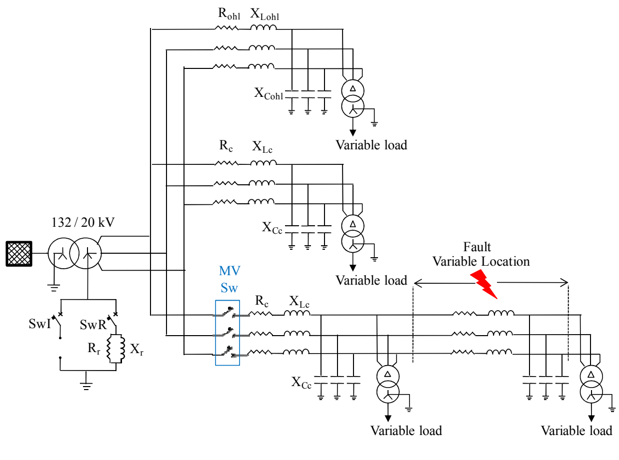

Fig. 2: MV test Network.

The feeder subject to faults is constituted by 1 km of 185 mm2 cable line (Rc = 0.164 Ω/km, XLc = 0.115 Ω/km, Cc = 0.47 µF/km) and by 40 km of copper over-head line with 70 mm2 cross section (R_{ohl} = 0.270 Ω/km, X_{ohl} = 0.4 Ω/km, C_{ohl} = 0.01 µF/km). Faults may appear along the feeder randomly. The load across the feeder is roughly 4 MW.

The reclosing delay is subject to minimum reclosing time that is, for modern equipment, about 300ms. This is the shortest permissible time in which the circuit breaker is required to reclose, considering rated control voltage and

rated pressure. This minimum dead time is needed, firstly, to be reasonably sure that the arc at the fault location, along the distribution lines, will not re-ignite and thus create a second fault (deionization time), and, secondly, to allow the mechanical linkages and latches of the circuit breakers to achieve a stable reset position before a closing operation is started.
The reclosing delay is also subject to a maximum value, due to regulator's directives. For example, the Italian regulator starts counting the short interruptions from 1 second up to 3 minutes. Consequently, the DSO has to limit the maximum dead time under 1 second in order to avoid a worsening of its power quality indices.
Numerous simulations have been performed by modifying the neutral connection and arrangement of the network. Generally no reignitions have been found with reclosing times higher than 400 ms, as Italian DSOs use to set their line circuit breakers.

Effects on transient faults reduction

In order to provide a measure of the effects of enlargement of the dead time during reclosing a Monte Carlo simulation has been performed. The sampling procedures is used to estimate the probability of arc reignition after a reclosing of variable time delay duration. The position of fault is sampled along the feeder and also the fault resistance, variable between 0 and 1000Ω, has been randomly chosen as well as, several parameters like the environmental conditions (humidity, pressure, temperature) in the zone surrounding the fault and the instant of the first circuit opening.
The convergence of the Monte Carlo method is measured by the coefficient of variation that has been set to 5%.
Arcs of single-line-to-earth faults in overhead lines and double-phase faults in MV switchboards have been simulated considering isolated and resonant earthed neutral. Simulation results are synthesized in Table I.

TABLE I
REDUCTION OF TRANSIENT FAULTS WITH ENLARGEMENT OF RECLOSING TIME DELAY

	% of reignitions Single Phase fault		% of reignitions Double Phase Fault
Reclosing Time delay	Fault in free air Isolated Neutral	Fault inside of MV cell	Fault inside of MV cell
0.4s Ref. case	0.03%	33.5%	83.75%
0.5 s	0.01%	9.56%	63.76%
0.6 s	-	1.40%	56.71%
0.7 s	-	0.12%	43.60%
0.8 s	-	0.08%	42.45%

The percentage of fault reignitions in the reference case, represented by of the typical time delay used by the Italian Distributors (e.g. 400ms), is very high in case of single or double phase fault inside electrical installations, while for single phase in free air, 400ms it is a time sufficient to guarantee the quenching of the majority of transient faults. In order to reduce reignitions of single and double phase faults within MV cells it is necessary increasing the reclosing dead time. It is possible to observe that there is a high reduction of reignitions enlarging the dead time, but, the cases of double phase fault reignitions, within MV cells, still remain high and greater than 40% also for a dead time of 0.8s. Extending the dead time more than 0.8s it is not achievable because there is the risk that the circuit breaker does not fully close within 1 second, that is the limit for short interruption, and then this may cause a worsening of power quality indices for the DSO.
Finally, some considerations need to be done about the possibility that customers can suffer more for the increment of temporary interruption duration due this enlargement of the time delay in circuit reclosing. In fact, with the increased usage of sensitive electronic equipments in various industries, offices and household appliances, it is important to diminish the power quality disturbances. In [7] the effects of voltage dips on domestic and office equipment were studied, and a project investigates the behaviour of domestic and office appliances for different magnitude, duration and angle of incidence of voltage dip. From the analysis of experimental results presented in [7] it is possible to observe that industrial, office and home appliances have a different behavior in respect to power quality disturbances.

Effects on reliability indices

As aforementioned, the proposed dead time enlargement of the fast auto-reclosing may affect mainly the number of momentary interruptions.
Performance is usually based on average customer interruption measures: in Italy the indices used are SAIDI, SAIFI and MAIFI (Momentary Average Interruption Frequency Index).
Just to give an idea of this effect, a simple and raw example has been included. An ideal overhead feeder of 20 km has been considered, characterised by the same fault occurrence probability along its path. This feeder supplies 10000 customers, uniformly distributed on the line. Consequently, for the reliability assessment, each fault can be assumed located in the middle of the feeder and it affects half of the total customers (5000). The fault rates used are typical for a MV distribution network, and have been summarized in tab. II. In particular, these values have been referred to the usual dead time of 0.4 s.

TABLE II
TYPICAL FAULT RATES FOR MV DISTRIBUTION NETWORKS.

Fault type	Fault rate [occ./(year·100 km)]	
	Overhead lines	Buried cables
Three-phase permanent	6.0	1.5
Bi-phase permanent	3.6	0.9
Three-phase momentary	8.0	–
Bi-phase momentary	24.0	–
Single-phase momentary	45.0	–

Finally, it has been supposed that no more than one fault per hour occurs, in order to avoid the application of the fault unification procedure provided by the Italian Regulator.
Considering the feeder length, the momentary fault rates become 1.6 (three-phase), 4.8 (bi-phase), and 9.0 (single-phase to ground). It has been assumed that all the three-phase faults are still present after the fast auto-reclosing, and, therefore, they cause always a momentary interruption. Instead, for the bi-phase faults it has been hypothesised that half of them are extinguished with the fast auto-reclosing (transient interruptions) and other half give a momentary interruption. A similar behaviour has been considered for the single-phase faults with a division between transient and momentary interruptions of 80% and 20%.
With these assumptions, the frequency of momentary interruptions suffered by the average customer in a year is:

$$MAIFI_{(0.4s)} = \frac{\left[1.6 + (0.5 \cdot 4.8) + (0.2 \cdot 9)\right] \cdot 5000}{10000} = 2.9$$

By supposing to delay the fast auto-reclosing up to 0.8 s, and by referring to the previous results, it can be assumed roughly that the momentary interruptions due to bi-phase faults are halved. Instead, it is reasonable to consider that the number of single-phase faults that still produce momentary interruptions do not change, because mainly originated from a persistent external cause (an animal or a broken branch of a tree). For simplicity the same assumption has been adopted for the three-phase faults. With these hypotheses, the MAIFI becomes:

$$MAIFI_{(0.8s)} = \frac{\left[1.6 + (0.5 \cdot 0.5 \cdot 4.8) + (0.2 \cdot 9)\right] \cdot 5000}{10000} = 2.3$$

Nevertheless the simplicity of the example, it appears evident the effectiveness of the proposed action on the network performance, especially taking into account that it can be made with no additional costs for distributors but only by changing the settings of their circuit breakers.

CONCLUSIONS

In the paper a model for simulating the reclosing operation in MV distribution networks, which permits varying the reclosing time, has been implemented by using the EMTP-RV program. The software developed includes a Monte Carlo simulation that allows varying randomly several parameters that may influence the quenching phenomena during transient faults in distribution networks.
The studies performed show that an increased reclosing time may have a significant effect in increasing the number of self-extinguish faults, especially in transient double-phase faults in metal enclosed electrical installations. Consequently, DSOs may have significant advantages, on reduction of interruptions due to transient faults, in delaying, as long as possible, the reclosing time in their distribution networks.
With reference to voltage dips following to auto reclose operation in distribution networks, it is possible to state that the enlargement of the reclosing time does not produce any further increment to the negative effects on appliances and components, because they are already susceptible for voltage dips of only tens of milliseconds and they do not get damaged due to voltage interruptions of longer duration.

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