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Power quality enhancing in distribution utilities

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Abstract. One of the most concerning disturbances affecting power quality are voltage sags. Their major source are short-circuits on the utility lines. Faults many kilometres from the disturbed process will generate a momentary voltage sag in the electrical environment to the end user. A reduction of the short-circuit current magnitude may lead to a substantial power quality improvement because the majority of sensitive industrial processes (including computer system, power electronics and variable speed drives) are capable of riding through a sag of a very limited amplitude. Several solutions for Fault Current Limiters (FCLs) design have been described in the recent scientific literature. Nevertheless, the so far proposed FCLs are complex, expensive and may lead to additional operation problems decreasing the distribution reliability. The paper analyses and discusses a possibility of fault current reduction by means of simple permanent reactors and no control circuits, so as to intrinsically overcome most of the above cons.

Key words: power quality, fault current limiter, voltage sags

Povečanje kvalitete električne energije v distribucijskih omrežjih

Povzetek. Ene najpogostejših motenj, ki vplivajo na kvaliteto električne energije so udori napetosti, katerih poglavitni vzrok so kratki stiki v distribucijskem omrežju. Napake, oddaljene več kilometrov od motenega porabnika, povzročijo trenuten udor napetosti v njegovi električni okolici. Zmanjšanje vrednosti kratkostičnega toka lahko vodi k znatnemu izboljšanju kvalitete električne energije, kajti večina občutljivih industrijskih porabnikov (vključujoč računalniške sisteme, močnostno elektroniko in regulirane motorne pogone) je zmožna brez posledic prestati napetostni udor omejene amplitude. V znanstvenih publikacijah je bilo opisano več rešitev za konstrukcijo omejevalcev kratkostičnega toka (FLC). Vendar so omenjene naprave FLC kompleksne in drage ter lahko povzročijo probleme v obratovanju, kar zmanjša zanesljivost dobave električne energije.

Prispevek analizira in razpravlja o močnosti omejevanja kratkostičnih tokov z enostavnimi, stalno priključenimi dušilkami brez regulacijskih vezij, s čimer se izognemo omenjenim slabostim.

Ključne besede: kvaliteta električne energije, omejevalec kratkostičnega toka, udori napetosti

1 Introduction

Voltage sags are important to industrial reliability. Modern process controls are often sensitive to voltage sags, which may cause significant production outages. The world-wide experience proves that the main origin of voltage sags affecting customers are short circuits on utility's lines, with special reference to the overhead distribution ones. Since the voltage sag during a fault is proportional to the short-circuit current, an effective fault-current limitation by means of a device connected at the beginning of the most exposed radial feeders will limit the expected voltage sag amplitude and improve the system power quality.

Several solutions for FCLs design have been proposed in the scientific literature. A common principle consists in a series impedance capable of changing its value very quickly, from a very low to a very high value.

Most of the FCLs based on this principle use a more or less complex passive circuit in series with the line and changing theirs configuration according to a proper signal input control.

This property is usually obtained by means of resonant circuits, transparent at the net frequency, but de-tuned by the intervention of proper power electronic devices. Examples of such FCLs type are reported in References [1,2,3,4].

Series resonant FCLs on a power distribution system have anyhow some drawbacks, they are:

- net frequency resonant circuit requires large series capacitors and inductors (to be placed at each distribution line beginning);
- presence of series capacitors may lead to ferro-resonance and/or customer's motor starting sub-synchronous resonance, phenomena that are hard to be predicted and faced;

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- impedance change requires power electronic devices and related control circuits.

Proposals to overcome at least some of the above drawbacks have been done in the literature. Examples are reported in references [5] (no need for permanent series capacitors) and [6] (no need for power electronic components).

Nevertheless, all the FCLs till now proposed, even if able to mitigate the voltage sag problem, still have a significant medal back, which can be summarised in one sentence: they are complex, expensive and may lead to additional operation problems decreasing the distribution system reliability.

The paper analyses and discusses a feasibility of a fault current limitation by means of simple permanent reactors without control circuits, so as to intrinsically overcome most of the above cons.

2 Possibilities and limitations offered by a simple reactor arrangement

Let us consider for instance a medium voltage - 20 kV - radial distribution system like the one depicted in Fig. 1, typical for Italy, fed by a 132/20 kV transformer.

In principle, a voltage sag may be generated by faults on both the 132 and the 20 kV sides. Anyhow, the worldwide experience proves that the majority of the sags affecting the customers connected to the medium voltage generic line "i", are caused by faults on one of the remaining lines departing from the 20 kV common bus (whereas a fault on line "i" itself will originate an interruption). The voltage sag at the common bus lasts as long as the protection equipment allows the current to flow and has an amplitude proportional to the magnitude of the fault current itself.

Of course, a reactor X, of a proper value of inductance L, placed at the beginning of each line can limit the fault current magnitude and consequently the voltage sag amplitude.

The main drawback of such a trivial arrangement is the voltage drop introduced by the reactor, which must be consistent with the system steady-state correct operation.

The minimum value of X is governed by the maximally allowed sag, or, in other words, the maximally allowed voltage drop δ (p.u.) during a fault. The last is a function of the source impedance.

Assuming that the resistive part of the network impedance is negligible, the simplified equivalent circuit during a symmetrical fault is the one reported in Fig. 2.

The source reactance X_S includes the net reactance X_N and the transformer reactance X_T. The line reactance X_a up to the fault depends on the fault location; considering the worst situation of a fault at the line beginning, we can assume $X_a = 0$. Therefore we have

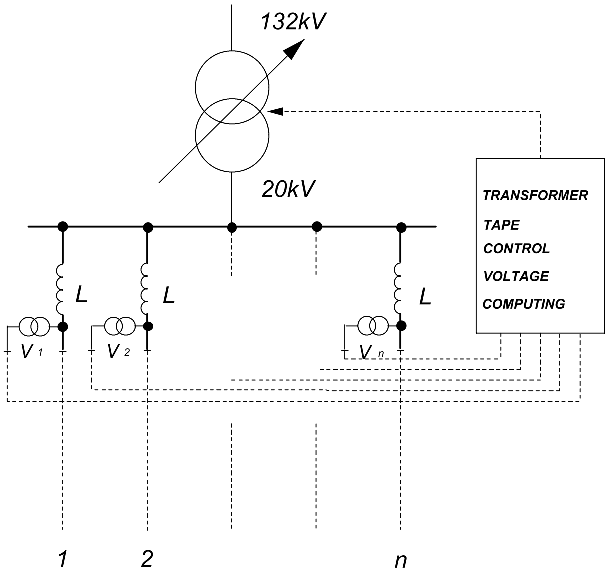

Figure 1. Medium voltage typical radial distribution system

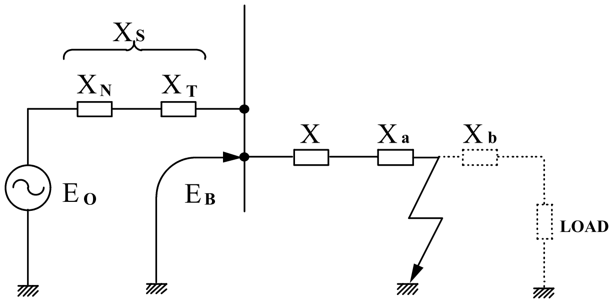

Figure 2. Net equivalent circuit during a fault

$$E_B = (1 - \delta) * E_O \tag{1}$$

$$\frac{E_B}{E_O} = \frac{1}{1 + \frac{X_S}{X}} \tag{2}$$

It follows

$$X = \omega L = X_S \frac{1 - \delta}{\delta} \tag{3}$$

Let us consider for instance a typical Italian situation. The standard transformer station 132/20 kV may have one or two transformers of rated power 25 or 40 MVA.

To limit the voltage sag δ at 0.1 p.u. during faults, the values for the limiting reactor inductance L, can easily be computed for each individual transformer arrangement having a different reactance X_S, by the former Equation (3). The results, assuming for the remaining net electric parameters the values reported in the Appendix, are summarised in Table 1 (all values are referred to 20 kV).

In a typical situation considered, the required fault current limiting inductance shall range from (rounded extreme cases) 25 to 65 mH, according to the number and nominal power of the transformers.

The resistive component of the reactor may be assumed 1% of its reactance, that is 0.08 and 0.2 ohm, respectively.

TRANSF. NOMINAL POWER [MVA]	R_T [ohm]	X_T [ohm]	X_N [ohm]	X_S [ohm]	L [mH]
25	0.096	2.08	0.167	2.247	64.4
2×25	0.048	1.04	0.167	1.207	34.6
40	0.060	1.30	0.167	1.467	42.0
2×40	0.030	0.65	0.167	0.817	24.4

Table 1. Typical values of R_T, X_T, X_N, X_S and L, with different transformer arrangements

The per cent voltage drop introduced by the reactor components X and R is a function of the line load, according to the well known equation

$$\Delta V\% \cong \frac{\sqrt{3}(RI * \cos\varphi + XI * \sin\varphi)}{V} * 100 \qquad (4)$$

The voltage drop, computed as per Equation (4), introduced by the limiting reactor (as a function of the line current and power factor) for the two extreme cases considered, L=25 mH and L=65 mH, is depicted in Fig. 3.

From an inspection of the plotting, it appears, as expected, that an excessive voltage drop ($> 8-10\%$) is possible with the larger inductor, when the load power factor is below 0.95 and the line current is close to its maximum of 150 A.

Two actions are possible to compensate for the above excessive voltage drop.

The first is in principle already depicted in Fig. 1 and consists of a proper transformer on-load tap control. As input control voltage V_c, instead of the usual main busbar, the average value of the voltages V_i, downstream the "n" limiting reactors can be used, that is

$$V_c = \frac{1}{n}\sum_{1}^{n} V_i \qquad (5)$$

The above simple action will improve the situation, roughly compensating the introduced voltage drop by increasing the main bus voltage. The limit in this "average" control is that a perfect compensation is not granted in case of a very different load (and consequently different voltage drops) on each line.

Nevertheless the voltage drop introduced by the limiting reactors becomes negligible, even at the largest line currents, providing that the load power factor is high enough.

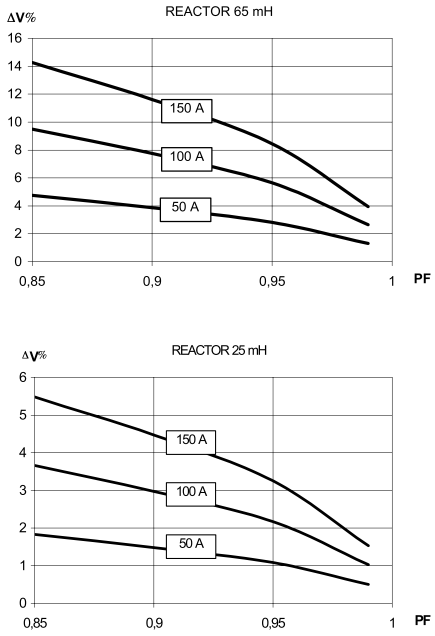

Figure 3. Percent voltage drops introduced by the limiting reactors as a function of the line current and load power factor

A second possible action is then the downstream power factor improving.

For instance, according to the available statistical data, the typical load power factor on a 20 kV distribution line in Italy is: 0.87 during the day (peak) hours and 0.9 during the night (empty) hours.

If a utility encourages its customers to improve their power factor to some 0.95, according to the Fig.3 plotting, the voltage drop becomes tolerable under all the operative circumstances.

The above PF improvement requires some extra investment cost. It can easily be computed for instance that if a load of a given active power P, with a natural PF=0.7, requires a reactive power Q to reach PF=0.88, the additional reactive power to reach PF=0.95 is about 0,5$*Q$. In other words a typical customer to satisfy the above constraint shall increase its standard investment in capacitors by about 50%.

We can thus conclude that by means of the combined two actions, i.e. proper use of the on-load tape control and power factor improvement, the steady-state voltage drop can easily be kept within operative acceptable limits at a very reasonable cost.

Of course, the above means that the goal of power quality improvement requires efforts, or - in other words - investment costs, by both involved partners, i.e. the utility, that has to install reactors and modify the on-load tap control, and the customers, who have to further improve the load power factor. Both actions are rather simple and the related costs reasonable compared to the benefit obtained; the solution looks very appropriate.

It has to be mentioned there exists also another possibility. Namely instead of forcing the customers to improve the power factor, capacitor banks may be installed on the utility premises, directly downstream the limiting reactors. This solution was tested by simulations. The details are not reported in the paper, but some pro and con aspects of such an arrangement are here shortly listed.

In principle the capacitors may either be fixed or step-modulated. As the last option imposes certain complications and extra costs, let us focus on the fixed banks solution.

A fixed capacitor bank downstream the reactor will lead to an over voltage during the line reduced load (night) periods, when the capacitors themselves remain the major load. An average control of this overvoltage acting on the on-load tape control it is still possible, as formerly discussed (now with an opposite sign, that is lowering the voltage during the empty periods). The con is again that a perfect compensation is not ensured in case of a very different residual load on individual lines.

A pro, which partially compensates the above con, is that the installation of the usual station capacitor bank, which is hand operated via a breaker directly connected to the main bus bar, will no longer be necessary (as can be proved by simple computing).

Considering the above pro and con, we feel that an individual customer's power factor improvement still remains to be the most simple and suitable way of reaching the goal.

A further aspect to be addressed is related to the fault detection and line protection. Whenever a FCL device is installed in a power plant (not only in this particular case), the traditional overcurrent protection is no longer suitable for the downstream fault detection and alternative fault detection strategies have to be implemented. In other words, a no-traditional fault depending signal is required as line protection input.

In the present application when a line fault occurs, even if it takes place at the line end, the voltage immediately downstream the reactor drops close to zero, whereas the bus voltage still remains close to the nominal value.

For instance, a logic that detects the above difference in the voltages, while the line breaker is still in a closed position, is a possible candidate as a line fault signal and is suitable to command the line protections to open.

3 Simulation results

To vindicate the proposed solution, several simulations were performed. Some of them are here reported and discussed.

A case study was considered for modelling and simulation of a distribution station 132/20 kV, with one 40 MVA transformer and eight departing lines of ten kilometres each. The net electrical parameters are reported in Appendix.

The lines were assumed to be all running at the nominal power, with the load power factor corrected up to 0.95, and the on-load tap control effect being neglected.

A three-phase (symmetrical) fault was generated on line $n^{\circ}1$ at the distance of one kilometre from the bus feeder.

The voltage sag generated by the fault without limiting reactors was simulated first. The result is reported in Fig. 4.

A severe voltage sag appeared at the common bus and it propagated to the remaining (not faulted) lines (see line $n^{\circ}2$ load voltage). The sag was very deep because the fault location in the given example was assumed very close to the bus. The line $n^{\circ}1$ breaker opened about five cycles after the fault occurrence.

Limiting reactors were then installed at the starting section of each line. Their value, computed according to Equation (3), with δ=0.1 p.u., was 42 mH inductance (with 0.13 ohm resistance).

The simulation was repeated with the reactors.

The relevant results are depicted in Fig. 5. The benefit on the line $n^{\circ}2$ load voltage (as well as on the bus voltage) becomes evident after a simple comparison of the actual result with the former one.

The consequence of the reactors installation is that both the steady-state voltage drop and the sag amplitude during a fault transient still remain within acceptable limits.

Variations in the time of the fault occurrence and its location along the line where also tested: they do not change significantly the final result.

As far as the additional losses introduced by the reactors are concerned, they are minimal, because each individual reactor's resistance corresponds to the natural resistance given by 0.5-1.0 kilometre of the line.

The conclusion is that if the system is equipped with reactors and operated as formerly described, a short-circuit on one of the lines will no longer disturb the load operation on none of the remaining lines in both steady-state and transient conditions.

4 Conclusions

Today, the problem of power quality is very real. One possible way for power quality improvement is the fault current limitation. Several more or less sophisticated FCLs have been proposed till now.

As far as distribution systems are concerned, the use of simple reactors, together with the load PF improvement and a proper use of the on-load tape control, can reach the goal with a solution that does not require res-

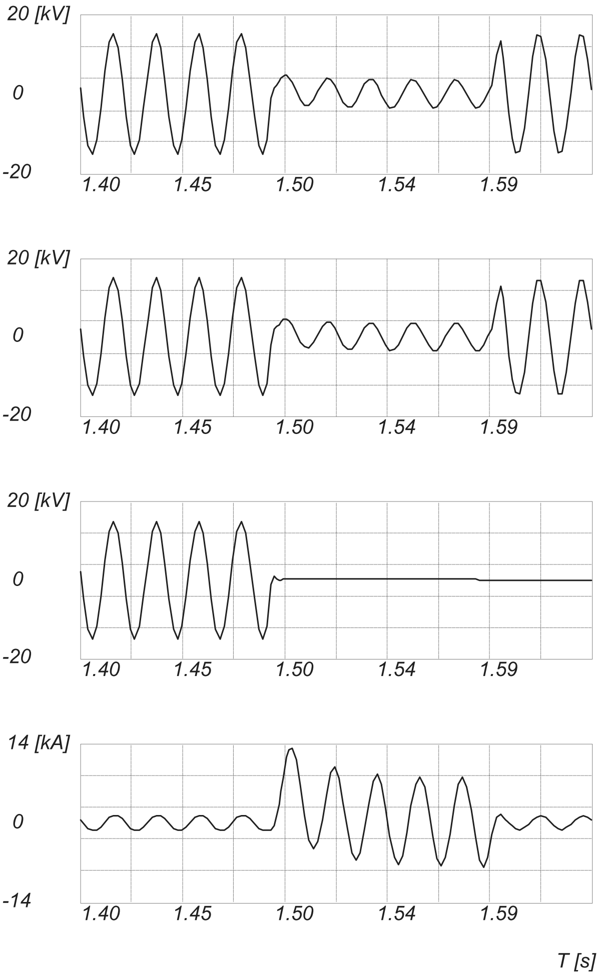

Figure 4. Voltage sag without limiting reactors, originated by a fault on line $n^o 1$ at a distance of one kilometre from the bus. From the top downwards: main bus voltage, line $n^o 2$ load voltage, line $n^o 1$ load voltage and supply transformer feeder current

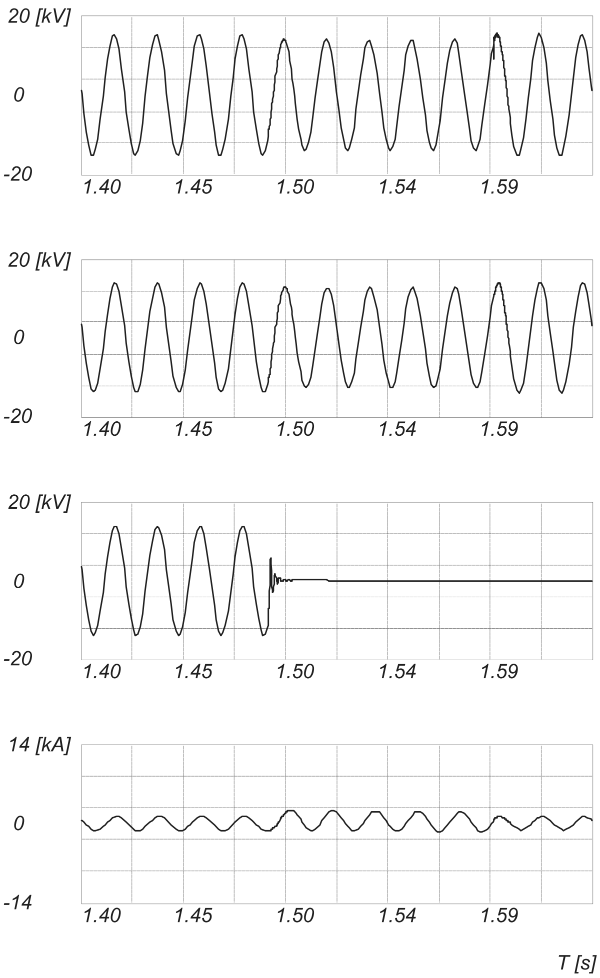

Figure 5. Voltage sag with limiting reactors, originated by a fault on line $n^o 1$ at a distance of one kilometre from the bus. From the top downwards: main bus voltage, line $n^o 2$ load voltage, line $n^o 1$ load voltage and supply transformer feeder current

onating circuits and power electronics. A reasonable compromise is possible in the reactor value selection, so as to satisfy both steady-state and transient requirements. The simulations performed prove the method effectiveness.

This solution requires joint efforts by both partners involved, the utility and the customer, but appears practicable because of its simplicity and moderate cost.

Appendix

The case study considered for modelling and simulation refers to a typical Italian plant. It consists of a station with one transformer and eight radial departing overhead lines. The following main parameters were assumed:

(i) network primary voltage (HV side) 132 kV - 50Hz, with a short-circuit power of 2400 MVA, secondary voltage (MV side) 20 kV, insulated (ungrounded) neutral;

(ii) main transformer 132/20 kV, 40 MVA, short-circuit voltage V_{cc}=13%, copper losses 0.6%;

(iii) eight departing lines of rated power 5 MVA and 10 km length each (line's parameters: series resistance 0.226 (Ω/km, series inductance 1.13 mH/km, capacity 10.3 nF/km);

(iv) line actual load 4.4 MW and 2.3 MVAR (PF 0.88) each.

(v) each load PF improved to 0.95, with local capacitors

(vi) symmetrical short-circuit on the line $n^o 1$, at one km distance from the bus.

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