Introduction

Dispersed generation connected to distribution system can supply unintentional system islands, isolated from the remainder of the network. Since these events pose an actual risk to safety and equipment they must be quickly detected and eliminated. Unfortunately, passive protections based on traditional measures (under/over-voltage, frequency) demonstrate, in particular system operating condition, the possibility of failing the island detection (non-detection zones) [1]. In this paper the feasibility of a relay protection based on Distribution Line Carrier (in the following DLC) signal is investigated for MV distribution systems. The proposal consists in the continuous injection, through a suitable coupling device, of a phase-to-phase superimposed carrier high frequency (a kind of guard signal) at the busbar of HV/MV substation. In this way the signal can be transmitted at any section of the feeder so that any line tripping event will thus be immediately detected by each dispersed generator at the common coupled point, independently of the actual power flowing in the feeder before the loss of main supply. It has been implemented the high frequency models for overhead lines with ground return and cable lines (Carson’s and Wedepohl’s theories) and has been simulated the transmission signal in different system configurations. It has been studied the dependence of signal attenuation on the type of line, the number of lines entering a substation and on the presence of compensation capacitor banks installed at the primary substation bus. Simulations allow us to predict standing wave patterns and the possibility of assessing, with the presence of more receivers, an “optimal mismatching” for the high frequency transmission. Moreover two measurement campaigns have been performed on real MV networks in order to validate the theoretical results.

DLC-based protection for islanding detection

The scheme of fig.1 represents the general idea of using the DLC for preventing DG islanding. The superimposed signal is injected at MV busbar (e.g. 20 kV) by a signal generator (a transmitter T) through a suitable coupling device (CD). The signal propagates all over the MV network and can be usefully received at receiver location (R) through a coupling device. The coupling device has a bandwidth tuned on transmitter frequency. The presence of HV/MV and MV/LV transformers has a blocking effect of DLC signal (they act as a low-pass filter): the DLC propagation will be confined to the MV section. The transformer impedance as seen at MV bus slightly depends upon load variations and always remains very high [2] (between 4 and 50 kHz it is namely greater than 10 kΩ). Consequently the transformers determine a kind of "unbundling" between MV and HV-LV networks. It is thus possible to consider only the presence of MV overhead and cable lines in computing the DLC propagation being the transmitter and receiver located at MV circuit.

Fig. 1. DLC-based protection scheme

Procedure for DLC Propagation Analysis

With reference to the comprehensive modelling of multiconductor systems using elementary matrix cascades at rated frequency (50 or 60 Hz) [3], in this paper the procedure has been suitably generalised at DLC frequency. Let us consider a multiconductor system composed of n conductors. It may be represented as a cascade of m elementary cells of length ∆L (ranging between 1 to 10 m), modelled by a lumped π-circuit (see fig. 2) where the voltage column vectors uS, uR and the current column vectors iS, iSL, iST, iR, iRL, iRT may be considered.
the separate study of longitudinal elements (block L, where \( i_{RL} = \bar{i}_{SL} \)). Self and mutual longitudinal impedances, which account for the earth return currents, can be obtained applying the Carson’s theory [4] for overhead lines and Wedepohl’s theory [5] for cable line and form the matrix \( Z_l (n \times n) \) which characterises the block L:

\[
\begin{align*}
\begin{bmatrix}
\bar{i}_S & \bar{i}_R
\end{bmatrix} &= \begin{bmatrix}
Z_{1} & Z_{1} & \ldots & Z_{1} & -Z_{L} & -Z_{L} & \ldots & -Z_{L}
\end{bmatrix}
\begin{bmatrix}
\bar{u}_S \\
\bar{u}_R
\end{bmatrix}.
\end{align*}
\]

from which, considering that \( i_{RL} = \bar{i}_{SL} \), and being \( Z_l \) non-singular

\[
\begin{align*}
Z_l^{-1} \begin{bmatrix}
\bar{i}_S \\
\bar{i}_R
\end{bmatrix} &= \begin{bmatrix}
1 & \ldots & 1 & -Z_l^{-1} & -Z_l^{-1} & \ldots & -Z_l^{-1}
\end{bmatrix} \begin{bmatrix}
\bar{u}_S \\
\bar{u}_R
\end{bmatrix} = \bar{i}_{SL}.
\end{align*}
\]

The two above algebraic equations can be synthesised in the following matrix relation:

\[
\begin{align*}
\begin{bmatrix}
\bar{i}_S \\
\bar{i}_L
\end{bmatrix} &= \begin{bmatrix}
Z_{1} & Z_{1} & \ldots & Z_{1} & Z_{1} & \ldots & Z_{1}
\end{bmatrix}
\begin{bmatrix}
\bar{u}_S \\
\bar{u}_L
\end{bmatrix}.
\end{align*}
\]

The shunt vector at sending-end \( \bar{i}_{ST} \) and at receiving-end \( \bar{i}_{RT} \) are

\[
\begin{align*}
\begin{bmatrix}
\bar{i}_S \\
\bar{i}_L
\end{bmatrix} &= \begin{bmatrix}
Z_{1} & Z_{1} & \ldots & Z_{1} & -Z_{L} & -Z_{L} & \ldots & -Z_{L}
\end{bmatrix}
\begin{bmatrix}
\bar{u}_S \\
\bar{u}_L
\end{bmatrix} + \begin{bmatrix}
\bar{u}_S \\
\bar{u}_L
\end{bmatrix} \begin{bmatrix}
1 & \ldots & 1 & -Z_l^{-1} & -Z_l^{-1} & \ldots & -Z_l^{-1}
\end{bmatrix}
\begin{bmatrix}
\bar{i}_S \\
\bar{i}_R
\end{bmatrix}.
\end{align*}
\]

An adequate computation of \( Y_{TS} \) and \( Y_{TR} (n \times n) \) depends on the self and mutual shunt capacitive admittances of \( n \) conductors and is differently derived for the overhead and cable lines. The superimposition of (2) and (3) yields:

\[
\begin{align*}
\begin{bmatrix}
\bar{i}_S \\
\bar{i}_R
\end{bmatrix} &= \begin{bmatrix}
Z_{1} & -Z_{L} & \ldots & -Z_{L} & Z_{1} & \ldots & Z_{1}
\end{bmatrix}
\begin{bmatrix}
\bar{u}_S \\
\bar{u}_R
\end{bmatrix} + \begin{bmatrix}
\bar{u}_S \\
\bar{u}_R
\end{bmatrix} \begin{bmatrix}
1 & \ldots & 1 & -Z_l^{-1} & -Z_l^{-1} & \ldots & -Z_l^{-1}
\end{bmatrix}
\begin{bmatrix}
\bar{i}_S \\
\bar{i}_R
\end{bmatrix}.
\end{align*}
\]

which completely represents the steady-state regime of the elementary cell (of length \( \Delta l \)).

**Elementary cell cascades and line matrix \( Y \).** Once \( Y \) is computed, the line matrix \( Y \) must be derived by means of cell cascades. If the line is rather long, the number of cells could be very high: the cell cascades could give computation drawbacks. The problem has been cleverly overcome using binary code. If each cell is represented by the same \( Y_1 \), it is possible to compute the whole matrix \( Y \) with a very low number of operations even if the cell number \( m \) is very high. For instance, if \( m = 1000 \), the “cascade procedure” [3] yields at first \( Y_{12} \), \( Y_{44} \), \( Y_{64} \), \( Y_{124} \), \( Y_{256} \), \( Y_{128} \), \( Y_{512} \). The representation of \( m \) in binary code shows that \( Y \) might be evaluated as a cascade of

\[
Y_{512} = Y_{256} Y_{128} Y_{64} Y_{32} Y_{8}.
\]

totally 14 “cascade operations” are needed. \( Y \) matrix synthesises the multiconductor line behaviour as seen at end-sections, and might be introduced in a matrix modelling of any interconnected systems. Alternatively the elementary cell cascades have been compared with modal analysis i.e. using eigenvalues and eigenvectors [6] giving a really good concordance.

**The bus admittance matrix \( Y \).** Once each line has been represented by its own line matrix \( Y \), the bus admittance matrix \( Y \) is achieved by means of the generalised primitive \( Y_{prim} \) and connection \( C \) matrices:

\[
Y = C^T Y_{prim} C.
\]

**Capacitor bank and Receivers.** The presence of shunt components such as capacitor banks (at MV busbar) or signal receivers can be inserted in the bus admittance matrix \( Y \) in the suitable position. Once the shunt components has been represented by its admittance matrix \( Y_{CB} \) or \( Y_{REC} (3 \times 3) \), the block-diagonal highly sparse matrix \( Y_S \) (of the same order of \( Y \) and with non-zeros only in the blocks where the shunt components are located) can be summed to \( Y \) giving:

\[
Y_{TOT} = Y + Y_S.
\]

**High frequency regime.** The situation for a phase-to-phase transmitter is shown in fig. 3. Section 1 is the transmitter location whereas \( u_1^* \) is the high frequency voltage signal between phase 1 and 2; \( Z_T \) is the impedance matching coupling device. The bus impedance matrix \( Z_{TOT} \) can be obtained by inversion of \( Y_{TOT} \).
where $Z_{aa}$ is the partitioned matrix deriving from $Z_{11}$.

So the bus current vector $i$ is obtained and, by means of $u = Z_{\text{TOT}}i$, the bus voltages can be derived.

**FEASIBILITY OF AN ANTI-ISLANDING DLC PROTECTION**

The possibility of applying the proposed protection depends on the strength of signal at the receivers. A similar idea has been presented [7] using sub-harmonic signal on LV systems for PV power generation. The effectiveness of signal level is strictly linked to the media attenuation. The distribution system has many components and therefore is rather complex. Nevertheless, a general view of DLC problems is possible.

The attenuation in MV networks is due to:
- overhead and cable line attenuation;
- capacitor banks;
- different line segments;
- branching;
- mismatching and standing wave patterns;

**Types of line: overhead and cable lines at high frequency.**

Typical kinds of MV overhead and cable lines are shown in fig. 7 which also reports their main characteristics.

![Fig. 7 Typical MV overhead and cable lines](image)

In order to highlight the different attenuation of overhead and cable lines, it is important to state beforehand some considerations on matching. For phase-to-phase transmission, the matching is done by adding the $Z_M$ impedance between the two phases.

By considering a 3 km length EPR-insulated cable line (fig.8) and by changing the location of the receiver, fig. 9 shows the attenuation with two different values of matching impedance namely $Z_M=3000 \ \Omega$ and $Z_M=100 \ \Omega$. When the line is terminated in a very high ($3000 \ \Omega$) impedance a severe standing wave conditions results.

![Fig. 8 Cable line Configuration](image)

![Fig. 9 Attenuation as a function of receiver location](image)

![Fig. 10 MV line configuration](image)

![Fig. 11 Attenuation as a function of receiver impedance $Z_M$](image)

By observing the fig. 11 the following qualitative
considerations can be drown:
- a MV overhead line gives an attenuation less than 0.5 [dB/km]: (changing in the section, in the kind of conductor in the height of the tower has a slight influence on the attenuation).
- the ACSR (Aluminium Conductors Steel Reinforced) provoke an higher attenuation but always very small;
- a cable line gives an attenuation of about 1.5-4 [dB/km].

The least attenuation is due to polymeric insulated cable (EPR, HEPR) whereas the paper impregnated cables give higher attenuation owing to the higher dielectric constant.
An analogue behaviour can be observed by increasing of the cross-section S: 240 mm² cables give rise to higher attenuation even if the phenomena is less marked with respect to that of dielectric constant.
- Each kind of line shows a minimum of attenuation when the receiver transfers an impedance value next to characteristic impedance (not equal because of phase-to-phase transmission): it should be noted that, even in the presence of slight mismatching, the attenuation is not so great.

When more receivers are present in MV network (e.g. a widespread DG), the optimal matching for a receiver could be a lack of signal strength for the others.
So the concept of an optimal mismatching zone (OMZ) can be considered: fig. 12 shows a clarifying example.
The matching impedance of R2 remains constant (Z_{M R2}=460Ω) whereas Z_{M R1} changes its magnitude.

![Fig. 12 Single line diagram of two cable lines with two receivers](image)

Fig. 12 shows that the optimal matching for R1 causes an high attenuation in R2 (about 15 dB), being the major level signal derived by R1. It is possible however to single out an optimal mismatching zone ranging between 300Ω and 600Ω.

If the same case is tackled for overhead lines, the OMZ ranges between 2500Ω and 3500Ω.

If, as in real MV networks, there is a number of combinations of overhead and cable lines, a specific evaluation must be carried out.

**Presence of capacitor banks.** The presence of lumped devices such as capacitor banks determines a decreasing of signal strength: if the length of the cable line connecting the capacitor banks to the MV busbar is too short there is a dramatic worsening of the signal strength.

With reference to the scheme of fig.14 the diagram of fig.15 shows how the cable length can influence the signal strength.

![Fig. 14 Single line diagram of MV busbar with capacitor banks](image)

![Fig. 15 Attenuation in R as a function of length x](image)

**EXPERIMENTAL VERIFICATION**

In order to verify feasibility of the presented protection two measurement campaigns have been carried out. The MV network is a 20 kV radial system. The composition of the network is rather complex so that two opposite situations have been chosen for experimental validation of DLC-based protection. In the former the set of experiments was conducted over an approximately three kilometre cable line (see fig. 16) with a dispersed generator.
The same MV busbar supplies other six feeders with a mixture of cable and overhead lines: moreover there is 95 m long cable line supplying a 3.6 Mvar capacitor bank.

Fig. 16 Measurement Campaign : urban feeder

The field measurements have shown very low attenuation: for a 2,838 km long cable line, at 72 kHz the attenuation is about 20 dB (the transmitted signal is 14 dB) as fig. 17 clearly shows. Fig. 18 shows a comparison between measured and computed values. The comparison has been performed in a frequency range which is very close to CD bandwidth because of the matrix algorithm considers the CD as ideal components. The agreement between measured and computed values is rather good considering the uncertainty in the distribution line data. The latter experimental case was conducted over a MV rural network (see fig. 19): the distance between the primary substation and the secondary substation is about 8 km. The MV/LV transformer is located at the end of a 450 m long lateral spur.

The main characteristics of the other feeders of the MV busbar are reported in fig. 19: the lengths of the lines are extremely long, up to 50 km.

CONCLUSIONS

It has been verified that the distance limit between T and R can be set up to about 10 ± 15 km. If there are longer distances, the use of repeaters must be taken into consideration in order to provide acceptable signal performance. The high frequency matrix algorithm represents a powerful and suitable tool for investigating the signal strength in any location of a MV network. For each situation, it is able to foresee if an anti-islanding DLC-based protection can be installed without drawbacks assuring a high degree of reliability and effectiveness.

ACKNOWLEDGEMENTS

Authors are grateful to Ing. S. Rogai and Ing. A. Cerretti (Central Direction - Engineering Dept.) and Ing. L. Cardin (Regional Responsible) of ENEL Distribuzione Spa, for their permission to perform tests on some distribution networks in Veneto Region. Besides authors thank R. Zago and E. Boldrin (ENEL personnel) for their helps in performing tests monitoring.
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