MESHING AC DISTRIBUTION NETWORKS: THE OPPORTUNITIES OF MVDC LINKS

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ABSTRACT

Penetration of DC systems in distribution networks can increase flexibility and controllability of power systems. The analyses consider network management issues, i.e. network overload conditions, for a typical urban AC distribution grid meshed with MVDC links by means of Voltage Source Converters (VSC).

Optimal Power Flow (OPF) analyses were performed with an optimization tool and results were evaluated by means of lines and converters loading. Moreover, Load Shedding (LS) was assessed with respect to the total load of the feeder.

INTRODUCTION

DC systems in distribution networks are nowadays under great interest. DC links between AC networks can increase flexibility and controllability of power systems [1], [2].

Among the opportunities offered by MVDC (Medium Voltage Direct Current) systems, the most relevant are:

- the decoupling among the interconnected networks;
- the control of the power exchanged among the meshed grids;
- the reverse feeding opportunities.

However, the current knowledge about MVDC requires further addressing for their development in distribution networks [3], [4].

The analyses presented in this paper is part of a wider research activity carried out in collaboration with Unareti (Italian DSO active in northern Italy); it considers network management issues for a typical urban AC distribution grids meshed with MVDC links by means of VSCs [5], [6].

Main topic of research is the evaluation of the impact of MVDC links for the management of network overloads.

In Section I, the considered MV meshed networks used in the simulations are presented.

In Section II, the approach adopted for analysing the network is described: the OPF studies are carried out with ACRE+, an optimization tool developed in GAMS (General Algebraic Modelling System).

The simulation results are shown in Section III, by means of lines and converters loading.

Finally, Section IV provides paper conclusions.

Nomenclature is summarized in Tab. 1.

Tab. 1 - Nomenclature

Name	Description
A_c	VSC converter actual power
A_{cr}	VSC converter rated power
A_{tr}	Transformer rated power
C	Converter
ΔL	Variable for line load index exceeding
F	Feeder
f_0	OPF objective function
GAMS	General Algebraic Modeling System
h	Slack variable
I	Actual line current
I_r	Rated line current
K_c	VSC converter loading index
K_l	Line loading index
K_{lmax}	Maximum admissible line loading index
L	Line
LF_{tot}	Total feeder loading
LS_{tot}	Total load shed
LS	Load Shedding
LS	Load Shedding index
M	"Big M method" constant
N	Number of converters in meshed network
nL	Number of lines exceeding K_{lmax}
OPF	Optimal Power Flow
P_j	Network losses
P_l	Load rated active power
t	Time
p.u.	Per Unit
V_{cacr}	VSC converter rated AC voltage
V_{cdcr}	VSC converter rated DC voltage
V_{tHVr}	Transformer rated high voltage
V_{tlvr}	Transformer rated low voltage
X_{tcc}	Transformer short circuit reactance
VSC	Voltage Source Converter

I – MESHED MV NETWORKS

Distribution network meshed with MVDC links requires the usage of AC-DC power converters to link different

AC sections and control active and reactive power flows. In some cases, such DC connections are DC lines with considerable length, as in present study; in other cases, back-to-back configuration inside power stations is preferred [7]. In this work, Optimal Power Flow (OPF) simulations have been performed on the same MV network meshed in two ways. The first one (Solution A) is shown in Fig. 1, the second one (Solution B) is shown in Fig. 2. The HV network is represented as an equivalent interconnected grid with infinite short circuit power.

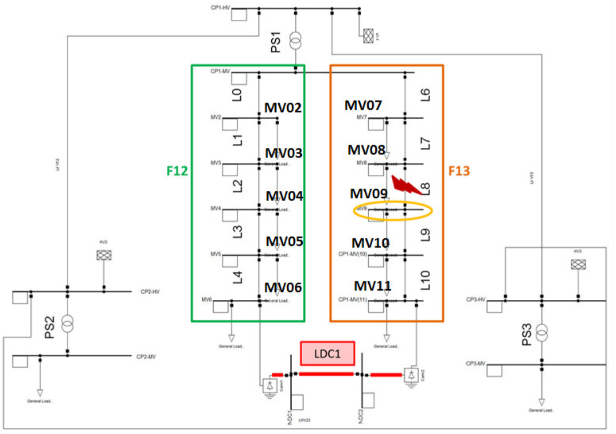

Fig. 1 – Solution A network topology: single MVDC line (LDC1) between two AC feeders (F12 and F13).

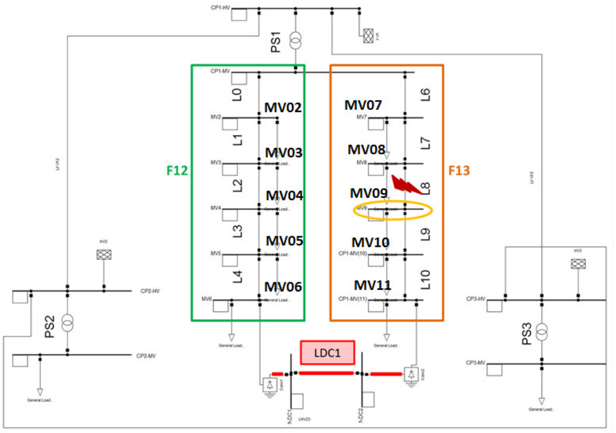

Fig. 2 – Solution B network topology: MVDC link (LDC1) between two AC feeders (F12 and F13) and a second MVDC link (LDC2) between DC grid and power station PS3.

Power stations main data (step down transformers) are listed in Tab. 2.

Tab. 2 – Power stations data (step down transformers)

Name	Description	Value	Unit
A_{tr}	Rated power	55	MVA
V_{tHVr}	Rated high voltage	220	kV
V_{tlvr}	Rated low voltage	23	kV
X_{tcc}	Short circuit reactance	9	%

AC-DC converters are VSC type, so they can be controlled as active/reactive power sources or as DC voltage generators.
During simulations, OPF will decide one DC voltage source, while the remaining ones will be set as power sources.
Converters are all equal and the related main data are listed in Tab. 3.

Tab. 3 – AC-DC converters main data

Name	Description	Value	Unit
A_{cr}	Rated power	7	MVA
V_r	Rated AC voltage	23	kV
V_{rdc}	Rated DC voltage	9	kV

Several load distribution along the feeders are possible, as shown in Fig. 3.

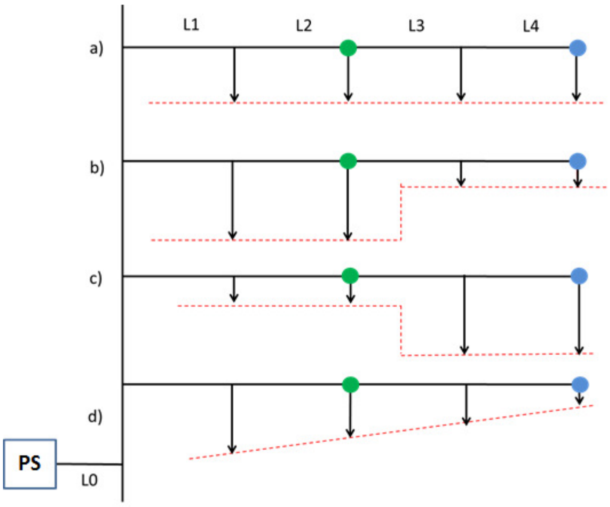

Fig. 3 – Considered load distributions along a radial feeder: a) equally distributed; b) concentrated at feeder beginning; c) concentrated at feeder ending; d) decreasing distribution along the feeder.

With no grid meshing, line sizing was depending on load displacement along the feeder.
Reverse feeding implies instead an adequate sizing along the whole line length, no matter what power supply is coming from.
During research activity, some cases have chosen and they have been successfully simulated.
In this work, simulation results of case a) are presented, according to Tab. 4.
A distributed load of about 10 MVA has been connected to each feeder; to be as much as possible realistic, total feeder load is equal, single loads themselves not all exactly equal.

Tab. 4 – AC loads data

Name	Feeder	Busbar	Value	Unit
P_{l2}	F12	MV02	1.7	MVA
P_{l3}	F12	MV03	1.5	MVA
P_{l4}	F12	MV04	3.3	MVA
P_{l5}	F12	MV05	1.5	MVA
P_{l6}	F12	MV06	2.5	MVA
P_{l7}	F13	MV07	2.2	MVA
P_{l8}	F13	MV08	1.8	MVA
P_{l9}	F13	MV09	2	MVA
P_{l10}	F13	MV10	2.1	MVA
P_{l11}	F13	MV11	1.8	MVA

II – OPTIMAL POWER FLOW (OPF)

OPF is resulting under the condition of compliance with network constraints, avoiding as much as possible load shedding.

For each line (L) a loading index (K_l) was defined as the ratio between the actual current (I) and the related rated value (I_r):

$$K_l(L) = \frac{I(L)}{I_r(L)} 100 \quad [\%] \tag{1}$$

While for each VSC (C) a loading index (K_c), defined as the ratio between the power transferred by a converter (A_c) and its rated power (A_{cr}), was considered:

$$K_c(C) = \frac{A_c(C)}{A_{cr}(C)} 100 \quad [\%] \tag{2}$$

Load Shedding index (LS) was evaluated in percentage with respect to the total load of the feeder (LF_{tot}):

$$LS(F) = \frac{LS_{tot}(F)}{LF_{tot}(F)} 100 \quad [\%] \tag{3}$$

with $LS_{tot}(F)$ as actual load shedding on a given feeder (F).

Calculations have been performed taking into account several combinations of the following:

- various number of MVDC terminals (two or three) and MVDC connection points;
- different sets of network constraints (e.g. lines and converters maximum transfer);
- N or N-1 network conditions;
- load profiles (i.e. equally distributed along the feeder, decreasing load and step distribution load).

In N condition, the maximum acceptable (K_{lmax}) was assumed to be 75%, while the maximum K_c was set to 80%, allowing an operational margin in case of “emergency” (i.e. N-1 conditions). In N-1 conditions the constraints are relaxed, and the lines and the converters can transfer their maximum.

In the specific case, the OPF objective function (f_0) is the following:

$$f_0 = \min(P_j + LS_{tot} + nL) \tag{4}$$

In which:

- P_j: network losses;
- LS_{tot}: total load shed;
- nL: total number of lines that exceed K_{lmax} according to above statements.

OPF constraints are set by means of a system of many inequalities; the most relevant ones are here presented:

$$h(t,L)\frac{1000}{I_r(L)} - \Delta L(t,L)M \leq \frac{K_{lmax}(L)}{100} \tag{5}$$

$$h(t,L)\frac{1000}{I_r(L)} - \Delta L(t,L)M \geq \frac{K_{lmax}(L)}{100} - M \tag{6}$$

$$h(t,L) \leq I(t,L) \tag{7}$$

$$h(t,L) \geq -I(t,L) \tag{8}$$

In which:

- h: slack variable;
- t: time;
- L: given network line;
- I_r: rated current of the given line (in kA);
- ΔL: binary variable set to one when K_l is greater than given K_{lmax} , zero otherwise;
- M: “big M method” constant.

Variable t was included in the model for future development, in case load profiles are set as time-variant (e.g. hour by hour).

M is a quantity that is set to be greater than any other value in the inequality; in this case as (5) and (6) are expressed in per unit (p.u.) and they are limited within [-1;1], M is set to 1.1.

III – SIMULATION RESULTS

OPF results of Solution A and Solution B in N condition (no faults both on AC and DC) are shown in Fig. 4, in blue and red, respectively.

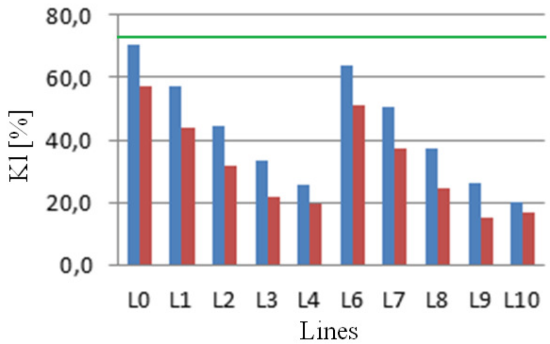

Fig. 4 – OPF results with Solution A (blue) and Solution B (red) in N condition. Green line is maximum loading of 75%. No line exceeded the limit. Loading is split line by line according to Fig. 1 and Fig. 2

With two terminals (Solution A), the highest K_l is reached by L0 (70.2%), and the DC link (LDC1) is loaded at 14.2%.

With three terminals (Solution B), the highest K_l decreases to 57.3% (L0) while the DC links LDC1 and LDC2 are loaded at 18.1% and 49%, respectively.

In order to evaluate N-1 conditions, a fault on line L8 was simulated.

Protection logics and fault clearance strategies for meshed grid faults have been already evaluated in other works [8], [9], [10].

As a result, after L8 disconnection, in a traditional MV radial line L9 and L10 are islanded by AC grid. However, in a meshed grid, L9 and L10 can be fed by LDC1 in Solution A and by both LDC1 and LDC2 in Solution B (reverse feeding [11]).

OPF allows redistribute power flows through MVDC links in order to optimize loading indexes, avoid LS and minimize network losses.

OPF results of Solution A and Solution B in N-1 conditions are shown in Fig. 5, in blue and red, respectively.

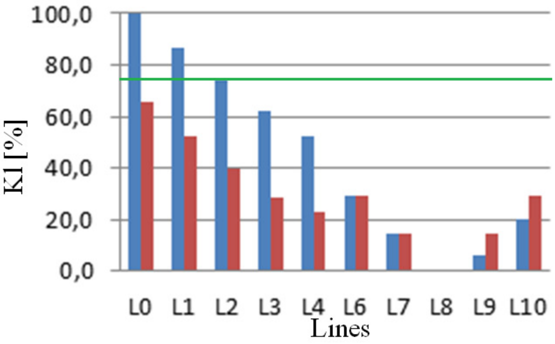

Fig. 5 – OPF results with Solution A (blue) and Solution B (red) in N-1 condition (AC permanent fault on line L8). Green line is maximum loading of 75%. In N-1 condition, no line exceeded the limit. Loading is split line by line according to Fig. 1 and Fig. 2.

In N-1 conditions (fault on line L8), with Solution A the maximum K_l is 100% (L0), LDC1 is loaded at 61.1%.

With Solution B, maximum K_l is about 62% (L0).

Line loading numerical results for both N and N-1 conditions and network configurations are summarized in Tab. 5.

Tab. 5 – Line loading numerical results (K_l)

	N condition		N-1 condition	
Line	Sol. A	Sol. B	Sol. A	Sol. B
L0	70.2	57.3	100	62.5
L1	58.2	43.2	84.5	52.1
L2	43.6	37.5	74.9	40
L3	38.4	21.2	62.4	28.4
L4	24.3	20	52.3	22.2
L6	62.2	56.1	29.5	29.5
L7	56	39.1	16.1	16.1
L8	39	23	0	0
L9	24.2	17.5	7.2	8.1
L10	20	18.6	20	29.7
LDC1	14.2	18.1	61.1	23.1
LDC2	-	49	-	55.6

In N-1 conditions with Solution A, LS (17.2%) occurs on bus MV9 (in orange in Fig. 1); with Solution B, no LS occurs.

Load shedding results are summarized in Tab. 6.

Tab. 6 – Load shedding results (*LS*)

	N condition		N condition	
	Sol. A	Sol. B	Sol. A	Sol. B
LS	0	0	17.2	0

IV – CONCLUSIONS

In this work, the impact of meshing distribution networks via MVDC links was evaluated, considering different configurations and set of constraints.

An AC network with equal load distribution has been modelled, then two different AC-DC meshing solutions by means of VSC converters were applied.

Optimal Power Flows in case of intact network (N conditions) and after a permanent fault (N-1 conditions) have been carried out with ACRE+ software.

Simulation results remarked the effectiveness of MVDC links to mesh the network and avoid overloads.

In particular, with a double DC link, load shedding events have been fully avoided, even in case of fault; moreover, in N-1 condition, no line exceeded the 75% limit of loading.

MVDC links are therefore a viable solution for the development of evolved distribution networks.

In the near future, DC links will improve network management, allowing optimal distributions of the load among the interconnected networks and higher system controllability, especially under critical conditions.

DC oriented scenarios for networks are currently under development, both for medium and low voltage [12].

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REFERENCES

[1] D. Wolter, M. Zdrallek, M. Stötzel, C. Schacherer, I. Mladenovic and M. Biller, "Impact of meshed grid topologies on distribution grid planning and operation," in *CIRED - Open Access Proceedings Journal*, vol. 2017, no. 1, pp. 2338-2341, 10 2017.

[2] T. Caldognetto and P. Tenti, "Integration and control of heterogeneous power sources in meshed distribution grids," *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Vancouver, BC, 2016, pp. 1-7.

[3] A. Musa, S. Rehan, L. Sabug, F. Ponci, A. Monti, "Modeling and design of hybrid distribution network: operational and technical features", 26th-29th September 2017, Torino.

[4] M. Monadi, C. Koch-Ciobotaru, J. I. Candela, P. Rodriguez, "A protection strategy for fault detection and location for multi-terminal MVDC distribution systems with renewable energy systems", 2014 ICRERA, 19th-22nd October 2014, Milwaukee.

[5] R. Zuelli, "La magliatura in c.c.: valutazione di un possibile caso applicativo nella rete di distribuzione MT di Milano", (http://www.rse-web.it), in press.

[6] R. Zuelli *et al.*, "The impact of MVDC links on distribution networks," *2018 AEIT International Annual Conference*, Bari, Italy, 2018, pp. 1-5.

[7] F. Belloni, R. Chiumeo, C. Gandolfi, M. Brenna, "Application of back-to-back converters in closed-loop and meshed MV distribution grid", AEIT Annual Conference, 18th-19th September 2014, Trieste.

[8] F. Belloni, R. Chiumeo, C. Gandolfi, S. Pugliese, "Simulation model of a protection scheme for active distribution networks", ICREPQ, 20th-22nd March 2013, Bilbao.

[9] F. Belloni, R. Chiumeo, C. Gandolfi, S. Pugliese, "Coordinamento delle protezioni di rete e selettività logica", AEIT Annual Conference, 3th-5th October 2013, Mondello.

[10] F. Belloni, R. Chiumeo, C. Gandolfi, A. Villa, "A protection coordination scheme for active distribution networks", 47th UPEC Conference, 4th-7th September 2012, Uxbridge.

[11] F. Belloni, R. Chiumeo, C. Gandolfi, D. Palladini, A. Villa, "Reverse supply of an AC distribution feeder through a medium voltage DC link", ICREPQ, 4TH-6TH May 2016, Madrid.

[12] C. Chiappa, C. Gandolfi, A. Villa, R. Zuelli, "La rete di distribuzione in corrente continua: dalla media alla bassa tensione", (http://www.rse-web.it), February 2017.