FUNCTIONAL MODELS FOR THE TECHNICAL-ECONOMICAL ANALYSIS OF NOT TRADITIONAL DISTRIBUTION ELECTRIC SYSTEMS CONFIGURATIONS

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SUMMARY

As to the strategical planning of the electric distribution systems, the Authors have proposed and applied a modular approach based on the use of particular models (functional models), each one representative of a system stage.
In this paper an enrichment of the functional models is proposed through the introduction of structural singularities (DC connections and local small generators) and their more efficacious definition by some economic indices (linked with the complexity of the network structure, the systems management, etc.) and some indices of quality (as to the power unavailability, the voltage dips frequency and the unbalance degree of voltages).

INTRODUCTION

In the last years the evolution of the electric energy markets towards competition and technical-economical efficiency, the greater demand for the supply quality and the considerable development of information technologies and of power electronics suggest the possibility of substantial changes both in the distribution networks structure and in the electric vectors and the adopted management criteria
In order to allow to direct the technical-economical choices both in planning phase and in the adaptation, reinforcement and development actions of existing networks, the Authors are developing an optimization procedure based on a preliminary definition and implementation of particular models (functional models), each one representative of a realization and management scheme of a system stage (vectoring module). The combination of a certain number of models selected defines a possible configuration of the whole distribution system that, optimized as to all the parameters considered as variable (entrance and exit voltage from the supply node, power of supply node and the branch points, number, extension and section of lines, etc.), will be able to be compared with other possible configurations.
For a detailed description of any problems implied in the characterization and implementation of functional models, see other papers already published by the Authors. In particular, in [1] and [2] the concepts of module and functional model have been introduced and the link of interdependence among the electrical, geometrical parameters, the main cost expressions and the constraints of the problem has been characterized. In [3] the analysis of reliability in the models in relation to the management techniques and to the reserve levels has been deepened, while in [4] it has been shown how the employment of an evolutive genetic algorithm for the optimization procedure can allow to fully exploit the flexibility of the modular way of models composition and to get to sub-optimal solutions of the problem, with restricted margins of error and limited computation costs.
The methodology described has been applied up to now making reference to a set of modules which structurally follow traditional schemes of MV and LV distribution. Besides these, the developments of the research also provide the implementation of modules that outline not traditional distribution schemes. Considering however as realistic that the transition to more sophisticated schemes cannot happen but in a progressive way, we have preferred to take an intermediate step, providing the possibility to enrich each of the functional models already defined with structural singularities including:

- point-to-point direct current connections;
- nodes supplied by local small generators, besides the main node (substation) supplied by the upper voltage network.

For a more efficacious characterization of all the models, furthermore, some economic indices have been introduced (linked with the complexity of the network structures, with the problems relative to the plants installation and management, etc.) and some indices of quality (expressing the power availability, the expected frequency of the voltage dips and the unbalance degree of voltages among the phases). These indices can be usefully treated both as variables of the general planning problem, making recourse to multiobjective optimization techniques, and as to make comparative analysis of the different alternative solutions, even at equal cost.

STRUCTURAL SINGULARITIES AND FUNCTIONAL MODELS

The implementation of functional models involves the definition of a set of structured relations so that the link of the modules combining one another for the realization of a system configuration is made particularly easy [4].
On the other hand the presence of an electric structural uniformity, typical of the traditionally considered modules, facilitates the formulation of these functional relations and contributes to reduce the complexity of every model and of the optimization procedure.
When the possibility to introduce the structural singularities is foreseen, the need to endow every model with means of easy coding rises, to characterize the level of disuniformity

and to recognise the eventual existing singularities. To this purpose a *matrix of disuniformity* has been defined:

$$[D] = \left[\begin{array}{c|ccccc} d_{11} & d_{12} & . & d_{1j} & . & d_{1(n+1)} \\ . & . & . & . & . & . \\ d_{i1} & d_{i2} & . & d_{ij} & . & d_{i(n+1)} \\ . & . & . & . & . & . \\ d_{N1} & d_{N2} & . & d_{Nj} & . & d_{N(n+1)} \end{array}\right] \qquad (1)$$

of binary kind and with $N{\cdot}(n+1)$ order, N being the number of the lines and n the number of the branch-points for every line. This matrix has been articulated so that:

- the elements d_{i1} ($i=1,2,\ldots,N$) of the first column can be given a unitary value, in presence of point-to-point DC connections, or a null value, if they are lines with features uniform as to those of the considered module;
- all the other elements d_{ij} ($i=1,2,\ldots,N$ $j=2,3,\ldots,(n+1)$) can assume a unitary value, if the relative nodes are fed locally, or null value in the other cases.

The so-defined matrix [D], associated to any basis vectoring module (with uniform electric and geometric features, as those traditionally considered) and particularized according to the hypotheses made every time by the planner, allows the computation procedure to shape new functional models, relative to hybrid modules that can include one or more singularities among those introduced in this work.

Modules including point-to-point direct current connections

It has already been since some years that the employment of direct current in distribution networks has aroused great interest as a possible solution, which in some cases can be more advantageous than adopting the traditional electric vector [5][6]. With reference to low voltage, indeed, the introduction of direct current connections could allow:

- to increase the transmission capacity of cable lines (to face the greater demand in urban and metropolitan areas), adopting a voltage level higher than that existing for the vectoring, compatibly with the insulation levels of the employed cables;
- to get a considerable reduction in losses owing to the increasing in voltage and the absence of reactive flows (this last aspect would produce a reduction in losses in the whole supply network);
- to assure higher levels of service continuity, through the use of direct current storage systems;
- to filter the propagation of unbalances among the phases, voltage dips and other disturbances, thanks to the interposing of converters between the network and the users;
- to supply the users with a constant voltage level independently from the voltage profiles in the supply network.

In order to allow, even in planning phase, to take into account the main technical-economical implications of these solutions, it seemed opportune to define two simple hypotheses of vectoring:

- a connection between the secondary bus-bars of a distribution substation and a DC load point through a cable bus with the interposition of a AC/DC converter and a storage system (Fig.1A);
- a connection analogous with the preceding but in which to convert the electric vector (in AC) again near the load point has been supposed (Fig.1B).

Coherently with the characteristic structure of the functional models [1][4] already existing in the implemented file, a mathematical model has been associated with each of the above illustrated connections. This model is in general made up of a set {**I**} of variable parameters and of a system {**F**} of functional relations including:

- a set {**FC**} of cost relations;
- the set {**FI**} of the link relations among the interfacing parameters;
- a set {**V**} of constraint relations;
- a set {**QU**} of expressions characterizing the module performance in terms of quality .

With particular reference to the set {**FC**}, the main expressions used for the formulation of the installation costs are synthetically reported in appendix.

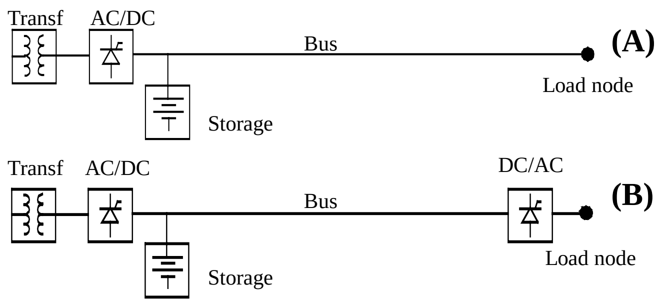


Fig.1 – Scheme of the considered point-to-point connections, with DC (A case) and AC (B case) load node

Through the modelling adopted, by particularizing the matrix [D] it is possible to easily define new functional models, relative to hybrid modules derived for example from structures of traditional networks and enriched with one or more DC connections.

This possibility can be particularly useful for the study of actions of adaptation and development of the existing distribution networks for which, for example in the urban areas, the traditional reinforcement could result problematic and particularly expensive [5]. In this case, in fact, the hypothesis of a gradual substitution of the traditional electric vector would lead to a progressive transformation of the system, beginning for example from the existing LV main feeders, according to integrated AC-DC distribution configurations.

Modules with nodes supplied by small groups of local generation

One of the aspects that could characterise the future development of distribution systems regards the appearance of new producers that, in a context of liberalised energy market, could consider as entrepreneurially attractive the idea to make investments in new production plants, of small or medium size, able to employ new technologies with

quite high efficiency and economical benefits deriving from the possibility to use eventual incentives linked with the kind of production (for example from renewable fonts).
In order to evaluate the technical-economical impact of such a presence on the electric system, with reference to the new networks or to the existing configurations to which one or more generating groups are linked, it has seemed opportune to provide the possibility to suppose as locally supplied some nodes of the network modules used as elementary nuclei. To this purpose, the singularity schematically represented in Fig.2 has been introduced, supposing that the generation group can work both in parallel to the network (in conditions of normal operation) and on a part of the loads supplied by the line in case of loss the main feed node.

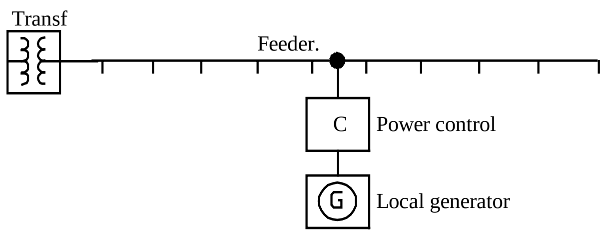


Fig.2 – Scheme of a feeder with a node locally fed.

In the model definition the length, section and line voltage have been included in the set {**I**} of variable parameters, while the active and reactive power produced by the local generator and the distance between the two feeding nodes have been considered as input quantities. In the formulation of costs (set {**FC**}) the installation and management expenses of the generation group have not been included, being it assumed as property of a third party (indipendent producers, municipalized firms, private in general).
The presence of one or more of these singularities in a network module (that will be taken into account, for the purpose of the model, giving unitary value to the matrix [*D*] elements relating to the locally fed nodes) allows to introduce different elements of technical-economical comparison, as to the traditional solutions, in virtue of:
- the reduction in power flows in the network, with a consequent saving in terms of sizing and losses;
- the greater power availability by the users, deriving from the presence of one or more independent generation nodes,

with the varying of generator groups position, number, power and type and in different hypotheses of the system articulation.

COSTS-QUALITY INDICES

In order to get a more efficacious characterization of all the functional models already defined, as a means of analysis of any possible hypothesis of distribution network realization and management, in view both of costs and of quality, it seemed opportune to introduce some particular economic and quality indices. They can be usefully treated as variables of the general problem of planning, making recourse to multiobjective optimization techniques, or as to make comparative analyses among alternative solutions.

Economic indices

The terms representative of the installation and management costs (maintenance and losses), traditionally employed in the planning procedures to express the system total cost (objective function) in relation to a fixed time horizon, are generally referred to the main components of the network (lines, substation, converters, etc.) in normal management conditions. This representation of costs, essentially due to a need for simplification indispensable in this kind of study, can become scarcely representative of the real system costs while increasing the structural and functional network complexity, because of the greater incidence of the expenses linked with the installation and management of all the other plant components (break and switch devices, switchboards, automatism, ...) and with the main problems of environmental impact (places necessary to contain the installations, underground lines realisation, etc.)
In order to take into account these aspects, without introducing an excessively heavy analytical work in the models definition and use, it seemed opportune to express the incidence of the above mentioned expenses introducing for each of the three main cost elements (installation, maintenance and losses) a multiplying factor, defined in relation to the values given to two particular economic indices by the planner. In particular the following functions have been defined:

$$\begin{aligned} X_I &= X_I\,(STRUCT,\ MANAG) \\ X_M &= X_M\,(STRUCT,\ MANAG) \\ X_{\Delta P} &= X_{\Delta P}\,(STRUCT,\ MANAG) \end{aligned} \tag{2}$$

aimed at expressing the incidence of the system complexity respectively on the installation, maintenance and losses costs. To this purpose, the *STRUCT* index, which refers to the network structure, has been related to the number of line levels in a module (network arborescence degree), to the average redundancy degree, that can be associated with the network, and to an environmental impact level, determined on the basis of the placing conditions (overhead line, underground cable) and of the features of the lands to be electrified. The *MANAG* index, which is aimed at taking into account the economic impact of the system management, has been expressed in semiquantitative terms in relation to the automation degree estimated in normal conditions (systems of automatic reconfiguration and reactive flows optimization) and in the presence of faults (diagnostic control systems).
With the introduction of these factors, to be determined every time for each vectoring module according to the network structure, the management hypotheses and the environmental context, the objective function (total cost) can be formulated like this:

$$F_{OBJ}\,(\cdot) = X_I\,C_I\,(\cdot) + X_M\,C_M\,(\cdot) + X_{\Delta P}\,C_{\Delta P}\,(\cdot) \tag{3}$$

indicating with $C_I\ (\cdot)$, $C_M\ (\cdot)$ e $C_{\Delta P}\ (\cdot)$ respectively installation, maintenance and losses costs, expressed in function of the unknown parameters of the problem.

Quality indices

As it has already stressed, the problem of service quality plays a fundamental role in the electric firms' strategies, influencing the investments destination, the networks conception, the components choice, and the management policies. The treatment of this problem, therefore, cannot be confined to the realisation of the only measures directed to solve every time eventual critic points happening on the networks, but it must follow a general approach which, even beginning from the system strategical planning and investments programming phases, aims at reaching quality objectives according to a global optimization.

According to this criterion, considering the close correlation among the network structure and its components features, the provided management techniques and the main aspects characterising the electric supply quality, some simple quality indices have been introduced, defined and computed so that they can sufficiently express the performance of every network analysed module. To this purpose, in consideration of the importance of the disturbances occurring in the distribution networks, the indices introduced regard in particular:

- the long interruptions (more than one minute) due to fault events;
- the voltage dips and the short interruptions;
- the voltage unbalances due to single-phase loads feed.

With reference to these aspects, the indices to the purpose used will be synthetically reported and treated later on.

Interruptions. According to the traditional strategical planning studies, the service continuity has taken into account evaluating the yearly cost of the interrupted energy in the same way of the other costs contributing to determine the total network cost. This approach, that has been largely followed in the past and is still the most used one, has the limitation of requiring an evaluation, not always easy and/or significant, of the unitary cost of the not provided energy.

Taking into account these difficulties and in consideration of the multiobjective approach followed in this research, on the basis of which it is not necessary to express the system performance in only economical terms, it has seemed preferable to make reference to the power unavailability in every studied network node, meant as the probability at regime that the node is not fed because of the faults that can occur in any system element. In particular, for a generic network module made up of equal lines *N*, each of them feeding *n* nodes, the functions of *average unavailability* (Υ_{av}) and the *maximum unavailability* (Υ_{max}) have been assumed as indices of (not) continuity and expressed as:

$$\Upsilon_{av} = \frac{\sum_{i=1}^{n} \Upsilon_i}{n} \qquad \Upsilon_{max} = \max\ (\Upsilon_i) \tag{4}$$

For the formulation of the unavailability Υ_i in the different nodes of a vectoring module, see the work [3], which develops a methodology based on the employment of Markov's processes to express in parameter form the link among the reserve degree (provided in the machines and lines sizing), the network structures, the management techniques adopted in the occurrence of faults and the system power availability.

Voltage dips. As it is known, it is a quite widespread conducted disturbance in the distribution systems, generally associated to the occurring of faults in the network. In these cases, in fact, the circulation of high currents in the line where the fault occurs provokes a voltage dip on the supply substation bars, which propagates in the other operating lines afferent to the same bars system for a duration equal to the time passing between the occurring of the fault and the intervention of the protection systems. The analysis of this phenomenon soon stresses the influence of the network structure, of its electrical and geometrical features and of the protection criteria adopted both on the origin of voltage dips and on their propagation in the network.

Without speaking about a complex characterization of this kind of disturbance, in terms of disturbance class, amplitude and duration [7], to the purpose of this research, the *average expected frequency of voltage dips and short interruptions* in each of the lines belonging to the same module has been assumed as the characteristic index of every network module. In particular, as to a generical vectoring module made up of *N* lines of equal length *L* supplied by the same bus-bars, this frequency has been expressed as:

$$B_f = L\left[N\lambda_t + (N-1)(M_{sp}\lambda_{sp} + M_p\lambda_p)\right] \tag{5}$$

λ_t, λ_{sp} and λ_p indicating the rates respectively for transient, semipermanent and permanent faults, M_{sp} the number of reclosing operations made by the protection system to eliminate the semipermanent faults, and M_p the number of reclosing necessary to detect the permanent faults.

In formulating the (5), for every line, reference has been made to :

- the voltage dips due to the occurring of three classes of fault (transient, semipermanent and permanent) in all the other lines;
- the short interruptions deriving from the possible transient faults in the same line.

The semipermanent and permanent faults have not been considered because they determine long interruptions in the same line in which they occur.

Voltage unbalances. The problem of the voltage unbalances assumes a great importance in the distribution networks because just in the electric final stages system (MV and LV), this kind of disturbance rises, mainly because of the imperfect compensation among the phases of the single-phase loads, and spreads showing its effects on the loads themselves.

Supposing that once more reference is made to a generic module working in alternating current, made up of *N* lines of equal length *L* afferent to an only bars system, on the simplifying assumption that the whole load supplied by every line is considered as applied at *L/2* from the bus-bars, the degree of voltages unbalance can be approximately expressed as:

$$S_{sq} = \frac{E_i}{E_d} = \frac{\left|\dot{Z}_{TR} + \dot{z}_L \frac{L}{2N}\right|}{3\ E_d^2}\ m\ A_r \tag{6}$$

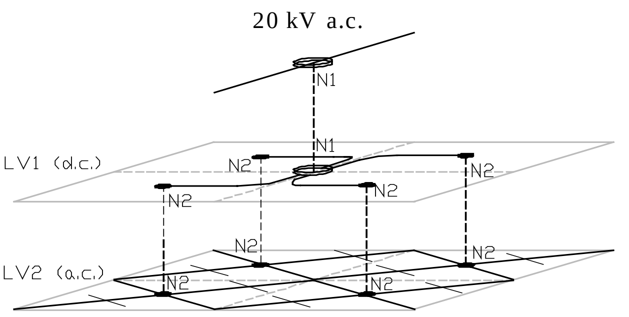
indicating with:

- E_d, E_i respectively the positive and negative component of the voltage system;
- Z_{TR} the transformer impedance;
- z_L the unitary impedance of every line;
- A_r the apparent power altogether requested by the loads;
- m the rate of unbalancing power, due to an equivalent set of single-phase loads supplied by the same phase.

The computation of the unbalance degree as belove expressed, assumed as index of disturbance, has been made on the further simplifying assumptions that the contribution of propagation, due to the network feeding the primary bars of the substation, is neglected, and even the impedance of lines compared with those of loads are disregarded [8].
Even if with the limitations of the assumed approximations, (6) puts into evidence the nature of the interdependence link among the main network parameters characterising the propagation of voltage unbalances with their relevant effects. It is therefore evident how opportune taking into account this aspect even in planning phase is, following the ratio of a global network characterisation and optimization.

EXAMPLE OF POSSIBLE APPLICATIONS OF THE MODULAR APPROACH

In order to illustrate, even if synthetically and schematically, the application ways of modules including structural singularities, Fig.3 gives a scheme of a possible configuration that, meeting (for example) the need for an existing LV network reinforcement, rises from the hypothesis to split a network portion into two stages: one LV2 stage of distribution by the final users (400 V AC) and one LV1 stage with a higher unknown voltage (DC) that uses the existing LV main feeders.
According to this hypothesis, with a traditional MV supply (20 kV AC), the whole distribution system would articulate in three stages, schematically represented in Fig. 3 as to the influence area of an only MV/LV substation.
In order to get to a model that can be used to the purpose of the proposed methodology, for each of the three networks a vectoring module can be selected and given the matrix [D] to take into account the existing singularities.



N1: MV/LV1 transformation node and AC/DC conversion
N2: DC/AC conversion node and LV1/LV2 transformation

Fig.3 - Example of a possible system articulation

In particular, in the above representation it has been supposed to assume:
- a module made up of some point-to-point DC connections (N1-N2), with an unknown voltage in the first low voltage network (LV1);
- a module with main feeders and derivations with a radial structure, working in 400 V AC, in the second low voltage network (LV2).

As to this last module, all the elements of the respective disuniformity matrix will be null, since the presence in them of any structural singularity is not provided, while LV1 will be given the following matrix:

$$[D]_{LV1} = \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ . & . \\ 1 & 0 \end{bmatrix} \qquad (7)$$

which, having all the elements of the first column as unitary, outlines a new model entirely supplied by direct current, as extension with N connections of the singularity shown in Fig.1B. As to all the possible modules that can be obtained particularising the matrix [D] in a different way (assuming for instance that a unitary value is given to an only element of the first column or to a part of it), the case above considered willingly represents a border-line case of uniformity that re-establishes inside the new network module since assumed as only made up of DC point-to-point connections. The articulation of the network assumed as to influence area of an only MV/LV substation can be extended to the whole homogeneous portion of the distribution system, like for instance that supplied by a HV/MV station. Supposing that a traditional module with a radial arrangement should be used, working in alternating current (20 KV), the set of interfacing relations $\{\mathbf{FI}\}$ of the three selected models will originate (Fig.4) the global model of the analysed system hypothesis. The procedure will allow to seek one or more sets of values for the unknown parameters (intermediate voltage level, transformation and conversion nodes power, connections number, section and length, etc.) by the application of suitable multiobjective optimization procedures [9], once the input parameters (load density and increasing rate, time horizon, actualization rate, etc.) have been given and the weight to be given to every objective (minimum cost, maximum availability, …) has been established in determining the general objective function.

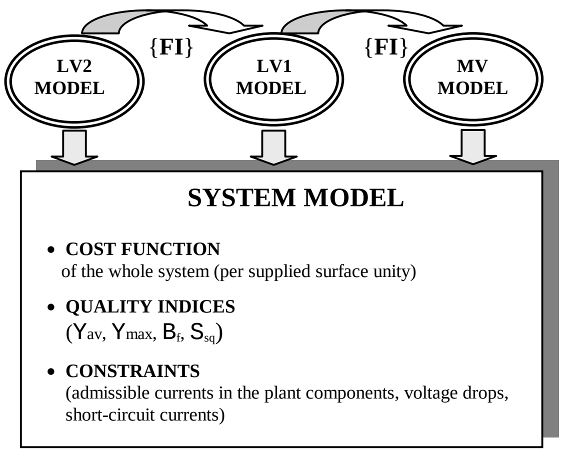


Fig.4 – General system model obtained combining the MV, LV1 and LV2 models

CONCLUSION

This paper shows the development of a research directed to enlarge upon the application possibilities of the functional models, for the technical-economical analysis of different distribution electric system configurations. To this purpose, coherently with the modular approach typical of the proposed technique and with the structure peculiar of functional models, attention has been paid:

- to enlarge the range of the system hypotheses that can be prefigured with not traditional configurations including point-to-point DC connections and/or groups of distributed generation;
- to reach a better characterisation of all the functional models through opportunely defined costs-quality indices.

Applying the means of technical-economical analysis synthetically described above can be useful both for in planning innovating distribution system configurations and in making comparative quality-costs evaluations in programming and transformation measures of existing networks.

In conclusion, it seems opportune to point out that the concept of singularity introduced in this paper, to allow to enlarge the analysis to not traditional network configurations, overcomes hypotheses of (electrical and structural) uniformity inside every elementary network module, but it does not regard the disuniformity due to the eventual coexistence of different modules in the same system stage. In this last case, that can be presented when the study is meant to be referred to extended system portion, to divide the area of interest into homogeneous portions will be necessary. For each of those areas, the general methodology can be applied.

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APPENDIX

The main expressions used for the formulation of installation costs of low voltage DC connections are later reported [5]. The costs are given in Euro.

AC/DC static converter cost

$$C_{radd} = 330{,}53\ A^{0{,}7} \qquad [€]$$

A [kVA] is the converter nominal power.

Storage system cost

$$C_{batt} = 0{,}826\ n \left[\frac{P}{n(8-1{,}5t^{0{,}4})} \right]^{0{,}85} \qquad [€]$$

for a battery (of capacity ranging from 50 to 5000 Ah) made up of n series cells with a constant power P [W] for a t [min] time.

DC/AC static converter cost

$$C_{inv} = 495{,}80\ A^{0{,}7} \qquad [€]$$

A [kVA] is the converter nominal power.

Substation box cost

A fixed cost has been taken for a box of sizes sufficient to contain a static converter and a storage system of medium size:

$$C_{box} = 6{,}714 \cdot 10^3 \qquad [€]$$