A GEOGRAPHIC INFORMATION SYSTEM (GIS) BASED ALGORYTHM SUPPORTING THE INTEGRATION OF DISTRIBUTED GENERATION TO THE LOW VOLTAGE NETWORK – SIGRAF –

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ABSTRACT

Since last decade, Enel Distribuzione has developed and operated a Geographic Information System (GIS), named SiGraf, for the purpose of mapping MV and LV network caracteristics and the geographical and electrical position of every single MV and LV customer.
More than being a mere cartographic tool, during last ten years SiGraf has been gradually integrated with many of the other Company IT systems, allowing systematic data sharing and updating with Smart Metering and Commercial applications, among others.
At the same time, an standard web interface has been developed in order to enable an easier and more powerful access to basic data and computational results, often made available towards a graphical rendition.
SiGraf electrical calculations have always been based on a statistical approach, in which electrical values are not meant as deterministic but are treated as variables with a certain probability of not being exceeded.
In order to support the integration of distributed generation (DG) within LV network, new algorythms have been developed, extending the principles of the former statistical approach, once applied only to final (passive) customers, to DG connections as well.
The paper describes basic and logic concepts used by the new calculation model, developed through a collaboration with CESI, which supports all calculations needed to verify LV network condition taking into account the presence of DG as well, performing all criticality analyses related to voltage profile and voltage variations, loading of components, short-circuit behaviour and the risk of undesirable islanding.

INTRODUCTION

The growing demand for network connection of low voltage (LV) by the new producers of electricity requires applications that can support the operator in the verification of the connection criteria to the BT network with a strong presence of distributed generation.

SIGRAF application was developed by ENEL Distribution to verify user connection to the BT network. It is based on a statistical approach: the power values at the nodes of the network are no longer being treated in a deterministic way, i.e. as time-depending, but rather in terms of statistical variables. The results (power flow and voltage), are statistical variables having a certain probability (based on a risk coefficient "**α**") not to be exceeded.

The nature of statistical calculation determines that the linear combination of random variables it is also a random variable characterized by:

- an average value which is a linear combination of the average values of the variables included,
- a variance which is a linear combination of the variances of variable components.

In this regard, it underlines the fact that the electric model SIGRAF, according to the coefficients adopted, evaluates electrical quantities (voltages and currents)characterized by a very low probability (**around 0.15%**) to be exceeded in the particular condition of operation to evaluate.

It's important to emphasize that the results obtained by the statistical method can not satisfy Kirchoff's laws. On the other hand, using a deterministic method would produce results that respect Kirchoff's laws on the network but it would have the disadvantage, certainly not acceptable, of repeating the calculation for time intervals in which it is assumed loads/generators remain constant, and then repeat the calculation, for example, at intervals of 15 minutes every day of the reference period (week, month, year).

New Load-flow

The load-flow calculation implemented in SIGRAF is based on statistical representation of the loads and generators seen as statistical variables with a Gaussian statistical distribution. Each load or generator is represented by its mean value, standard deviation of its statistical distribution and is also associated with a certain probability of not being exceeded (identified by a risk factor). The load-flow calculation is performed under the following hypothesis:

- the generators are treated as negative loads,
- LV busbar voltage can be set by the operator to a value different from the rated one
- the balance node (slack) is defined on the MV side of the MV / LV transformer, based on the knowledge of the

value of the LV side voltage and the load of the transformer

- the cos (φ) value is not considered as constant for all nodes in the network because loads and generators with different cos (φ) are connected
- the voltage drop of the section is calculated by means of the statistical combination of all the generators / loads present drop of section itself
- loss of active power / reactive in the branches are due to the impedance of the conductors and are evaluated using an iterative process
- generators / loads may be connected to different phases and then the calculation is made on each phase.

Load/Generator model

The loads model can be expressed with the following relationship

$$C_{Mi} = M(C_{ui}) + \alpha_c \sigma(C_{ui})$$

where:

- $M(C_{ui})$ is the average of the statistical distribution of the power of the generic user. It is worth noting that the average value of each user is obtained on the basis of the annual Energy Consuption;
- $\sigma(C_{ui})$ is the standard deviations from the mean value of the generic user in question, whose value can be evaluated through the relationship

$$\sigma(C_{ui}) = \frac{C_{Mi} - M(C_{ui})}{\alpha_c}$$

- α_c is the coefficient related to the risk taken to overcome the power values of the generic user. Typical values are 3 for a number of users up to 6 and 2 for a higher number. This allows to assume that the excess of the value has very low probability of being exceeded (less than 2.3%).

Using well-known statistical rules of composition it is possible to express the active power on the network section considered (C_{rp}) for n users connected to the section under consideration:

$$C_{rp} = \sum_{i=1}^{n} M(C_{ui}) + \alpha_C \sqrt{\sum_{i=1}^{n} \sigma^2(C_{ui})} \qquad \text{(n) passive users}$$

Regarding the reactive power contribution, the loads have fixed power factor (cosφ) constant and equal to 0.9.

For each (ith) user passive / active, the expression of the reactive power absorbed is thus a function of its active power:

$$Q_{Mi} = [M(C_i) + \alpha_c \sigma(C_i)] tg(\varphi_i)$$

Using the rules of the statistical composition the reactive power is obtained at the section of the network under consideration (r th) for passive loads connected:

$$Q_{rp} = \left[\sum_{i=1}^{n} M(C_{ui}) + \alpha_c \sqrt{\sum_{i=1}^{n} \sigma^2(C_{ui})}\right] tg(\varphi) \qquad \text{(n) passive users}$$

The generators are considered as negative loads so that their behaviour is similar to that of the loads. The difference is that the would can take into account

- the type of generation, photovoltaic and other,
- a different power factor for each generator (cos (φ)) according to each type. The active power on the network section considered (G_{rp}) for n active users connected to the section under consideration is given by:

$$G_{rp} = \sum_{j=1}^{m} M(G_{uj}) + \alpha_g \sqrt{\sum_{j=1}^{m} \sigma^2(G_{uj})}$$

The reactive power is instead given by

$$Q_{G-rp} = \sum_{j=1}^{m} M(G_{uj}) tg(\varphi_j) + \alpha_g \sqrt{\sum_{j=1}^{m} \sigma^2(G_{uj}) tg^2(\varphi_j)}$$

Operation conditions under consideration

It should be stressed that, in general, there is no time coincidence between the maximum generation and peak load condition. For example, Figure 1 shows a qualitative diagram of load and PV production. Then the SIGRAF application considers two conditions (A and B) to calculate

- maximum generation and corresponding load (A)
- maximum Load and corresponding generation (B).

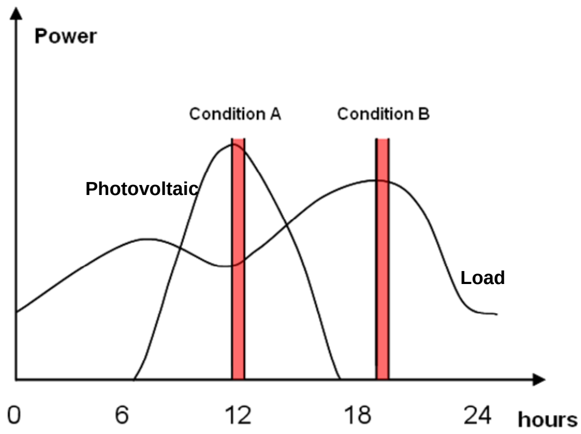

Fig. 1- Typical daily load and PV generation

The two above-mentioned operating conditions refer to a situation where:

- the voltage along the line is high (condition of maximum difference between generation and load: Condition A)
- the voltage along the line is low (condition of maximum difference between load and generation: condition B).

Electric calculations

Voltage reference (slack node)

With reference to Figure 3, a reference voltage on the MV network (slack node) is assumed for the calculation of load-flow.

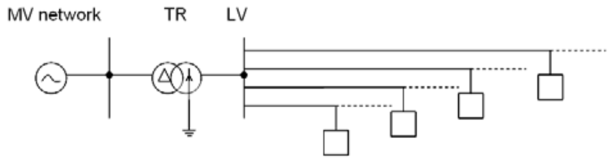

Fig. 2- Schematic LV network representation

The above voltage ($V_{f,slack}$) is calculated based on LV side voltage ($V_{f,ese-BT}$), and active and reactive power flowing on the MV / LV (P, Q) according to the relationship

$$\left|V_{f,slack}\right| = \left|V_{f,ese-BT}\right| + \frac{R_{TR}\cdot P + X_{TR}\cdot Q}{\left|V_{f,ese-BT}\right|}$$

It's important to remember that P and Q do not derive from the statistical composition of loads / generators in the LV network, but they are evaluated according to the transformer load knowledge.

Active and reactive power

Based on the characterization of the load and generation models, it is possible to define the following expression of the total active and reactive power at the beginning of a section (r-th).

$$P_{r,tot} = k_1 C_{rp} - k_2 G_{rp,\mathrm{Photovoltaic}} - k_3 G_{rp,P1} - k_4 G_{rp,P2}$$

$$Q_{r,tot} = k_1 Q_{rp} - k_2 Q_{G-rp,\mathrm{Photovoltaic}} - k_3 Q_{G-rp,P1} - k_4 Q_{G-rp,P2}$$

where the terms with subscript P1 and P2 refer to generation different from photovoltaics. The load-flow calculation is performed on each of the three phases of the BT network, associating to each phase

- the value of three-phase load or generation to the relevant phase (one third),
- the single-phase loads, whose connection is known,
- the single-phase loads, whose connection is not known, according to the relationship below that involves a greater load on one phase taken as a reference (phase r). For phases less loaded (phases s, t) we have:

Voltage and Current in the line section

After defining the expressions of active and reactive power at the begining of the line ($P_{r,tot}$, $Q_{r,tot}$). As a function of customer characteristics, starting from the MT-voltage (assumed to be fixed the slack node) on the network MV the voltage on the LV busbar is evaluated through the expression

$$\overline{V}_{f,BT} = \overline{V}_{f,slack} - \overline{I}_{TR}\overline{Z}_{TR}$$

where $\overline{I}_{TR}$ is the current flowing through the MV / LV transformer.

Similarly, it is possible to assess current and voltage on each section of the network, for each phase, adopting the following procedure:

1. Calculation of $P_{i,tot}$, $Q_{i,tot}$ of total loads /generators connected downstream the r-th section
2. Calculation of the currents in the r-th section (between nodes "i-1" and "i")
3. Calculation of i-th voltage node
4. Calculation of active and reactive losses in each branch "r-th"
5. Calculation of active and reactive power loads / generators in all branches including losses
6. Repetition of steps 2) and 3) based on new values $P_{i,tot}$ e $Q_{i,tot}$.

The above procedure does not consider the voltage drop on the neutral conductor, because the distribution system is TT and then the neutral conductor is grounded at several points along the LV line. On the other hand, it is important to underline the method takes into account the current (to two loads / generators single-phase connection) flowing into the neutral conductor, as described in the following.

Current flowing into the neutral conductor.

In order to determine the neutral conductor condition, the value of neutral current in the r-th is estimated

$$\overline{I}_{r,n} = \overline{I}_{r,s} + \overline{I}_{r,r} + \overline{I}_{r,t}$$

Where $I_{r,r}$ $I_{r,s}$ $I_{r,t}$, are the three currents phasors flowing into the three phases of the LV network.

Short circuit current

For the evaluation of the short circuit current at any line section of the LV grid a procedure based on the superimposed current theorem is applied.

In the following picture the above procedure is described.

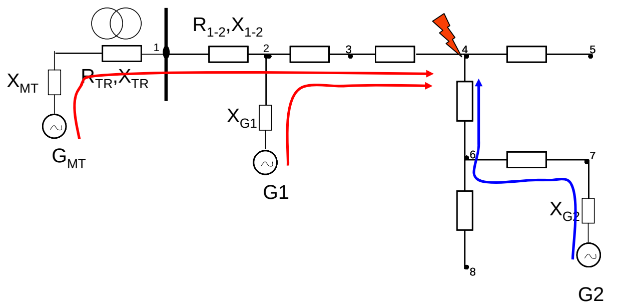

Fig. 3 – Procedure for the evaluation of short circuit current

Whith reference fig.3:

1. the graph is oriented towards the BT network that goes from the bar MV (node 1) to the end according to a numbering of the nodes in sequence

2. Contributions of different sources are separately evaluated and stored for each node of fault location in three-phase short circuit conditions, two-phase and single phase. Please note that it is not necessary to store the direction of the short circuit current as the LV network is assumed radial.
3. maximum and minimum value for each branch are

VERIFICATION OF CONNECTION

The verification of connection are provided by SIGRAF

- **Exploitation of the MV \ LV**

The verification of the exploitation of the processor, in each of the two operating conditions considered (A and B) is to assess the value of the power flowing on the MV / LV transformer (A_{BT}) respects the constraints of exploitation

$$A_{BT} < 0{,}7 A_n$$

- **Exploitation of the Lines**

To verify the loading of line is necessary to assess the commitments of each branch in the two operating conditions considered (A and B).
With regard to section (i-th) must be verified the following expression

$$|I_i| = \frac{\sqrt{P_i^2 + Q_i^2}}{|V_i|} < 80\% I_{Z,i}$$

Where $I_{Z,i}$ is the extent of the conductor in question. A similar check should be made with the neutral current which affects the neutral conductor of the section (ith)

- **slow voltage variations**

The verification for the slow variations of voltage is carried out on all the nodes of the network, the operating conditions A and B. Since $V_{f,ese-BT}$ nominal voltage, V ' the voltage calculated in working condition "A" and working condition, "B", the condition to check is:

$$\Delta V = \left| \frac{V' - V_{f,ese-BT}}{V_{f,ese-BT}} \right| < 0.08$$

- **fast voltage variations**

The verification is conducted by comparing the calculation of load-flow with and without the presence of the new customer in the two conditions (A and B) and verifying that it is not exceeded a certain value (eg 5%)

- **selectivity of the protections against the contribution to the short circuit on the other line**

The verification for the selectivity of the protections in the head line should evaluate the possible intervention of the untimely overcurrent protection of line which is connected distributed generation in the presence of a fault on another line.
The calculated values of short circuit ($I''_{k,\ GD\ line}$) are compared with the current value set for the release of magnetic phase I_m. The test is passed if it:

$$I''_{k,linea\ GD} < 0.7 \cdot I_m$$

- **verification of the thermal resistance to short-circuit**

The verification is needed to assess the coordination of K^2S^2 cables with the switch before the line.Analytically the verification is passed if, as K^2S^2 the maximum tolerable value of specific energy from the conductor. For each branch of the BT network is obtained

$$I_{ramo,i}^2 t \le K^2 S_i^2$$

where I_{ramo-i} is the current in branch i-th and t is the time to intervention of the head of the line.

It is noteworthy that because of this generation down the line, the switch is not passed through by all the fault current but only a part of it (ie the contribution of the upstream network of the transformer and that of the other generations lines).

Switch, due to the production of energy along this line is not crossed by all the fault current but only a part of it (but only by the contribution of the network upstream of the transformer and that of these generators on the other lines).

The time t you should therefore be assessed with reference to the latter.

Such verification shall be made by considering the two conditions of maximum short circuit current (short time of the protection line) and minimum short-circuit (long time of the protection of the line).

- **The risk of undesirable islanding**

The undesirable islanding only occurs if the power (both active and reactive) to start working online or on the MV / LV transformer is close to zero. This can happen in a business generally different from the conditions A and B regarding the calculation of load-flow.

Therefore, to be able to island-wide Junk MV / BT or BT

line, it is necessary that the generation curve intersects the load curve (see Figure 4, Figure 5 and Figure 6).
Verification is considering such a degree that can be considered equal to ± 20%.

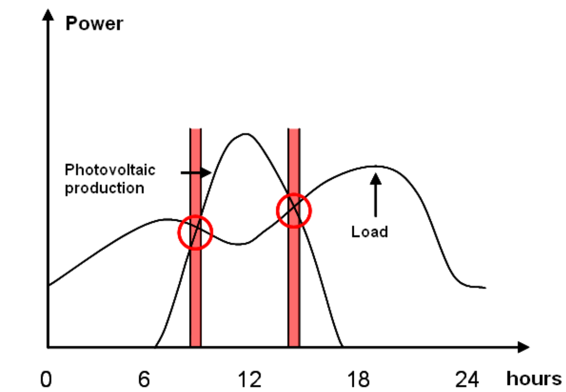

Fig. 4- **Identifying operating conditions: PV production and load**

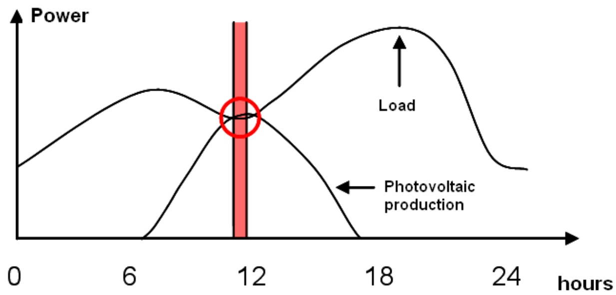

Fig. 5 - **PV production and load: threshold condition for undesirable inslanding**

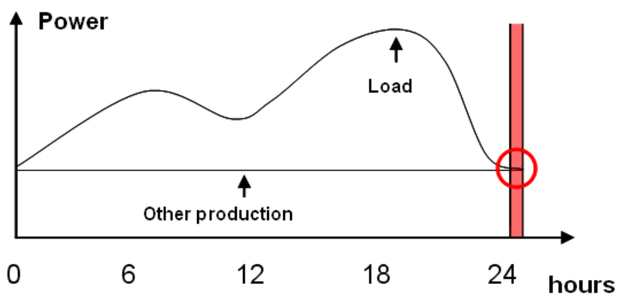

Fig. 6 – **Wind generation and load: threshold condition for undesirable inslanding**

OUTPUT

At the end of the procedure for verification of new connections, the application SIGRAF shows, a summary of its results through the typical representation of the "traffic lights" (green = ok, red = ko - critical, yellow = see later) in all three phases of the system and the neutral wire as the following:

RIEPILOGO VERIFICHE				
	Fase r	Fase s	Fase t	Neutro
Variazioni lente di tensione:	ok	1	ok	ok
Variazioni rapide di tensione:	ok	1	1	ok
Capacità di trasporto linee BT:	2	ok	ok	ok
Sfruttamento del trasformatore MT/BT:	OK			
Potere di interruzione interruttori di Linea:	OK			
Potere di chiusura interruttori di Linea:	1			
i2t	1			
Selettività protezioni	1			
Possibilità isola indesiderata linea	1			
Possibilità isola indesiderata trasformatore	1			
Consistenza della rete	Numero nodi		Numero rami	
	15		7	
	Non presenta criticità			
	Criticità lieve			
	Criticità			

REFERENCES

[1] V. Medved R. Schinco, 1993, *Le correnti di corto circuito negli impianti elettrici*, Editore Delfino, Milano, Italia, 221-224.