REDUCTION OF REACTIVE POWER FLOWS AND POWER LOSSES IN ENEL DISTRIBUTION SYSTEM

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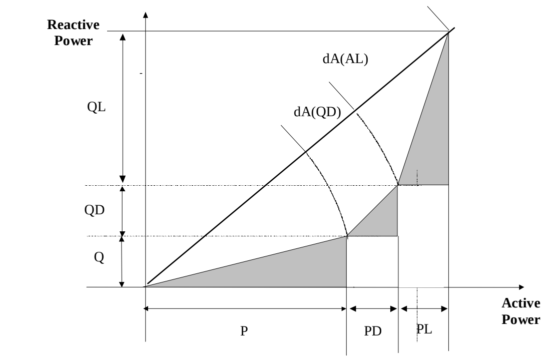
ABSTRACT

The report deals with the reduction of reactive power flows and power losses in ENEL distribution system in order to reduce upstream system sizing and energy losses.
At first the methodological approach to the describe the physical phenomenon is presented. The general criteria and the models are described to establish the per unit costs of reactive power flows and losses at the different stages of the ENEL system, necessary for economic evaluations.
Then all actions undertaken by government and ENEL in last years are described, such as, on demand side, government tariff policies and ENEL advertising campaigns to contain power factor and, on internal side, ENEL policies of installation of capacitor banks and development of high efficiency components. Finally the main results achieved in last years are shown.

INTRODUCTION

The **reactive power demand** downstream a given section of the system produces a first negative effect due to the need of *over-sizing* the upstream system (see dA(QD) for the immediate upstream stage in fig.1). Moreover the reactive power demand increases upstream active and reactive power losses, giving raise to an additional over-sizing of the upstream system. The over-sizing of the upstream system is necessary to keep the load factors of the upstream system within suitable limits to guarantee the re-supply capability levels established by planning and operation criteria.
A second negative effect of reactive power demand is represented by the *increase of upstream active energy losses* due to the increase of upstream power losses.
Beside the reactive power flow also the **power losses** in the stage are responsible of the *over-sizing* of the upstream system (see dA(AL) for the immediate upstream stage in fig.1) and of the *increase of upstream active energy losses.*
In a given section of the system the reactive power flows can be reduced either reducing the downstream reactive power demand or reducing the downstream reactive losses.
On the contrary the active power flows can be reduced only reducing the downstream active losses, as active power demand must be considered as an independent variable.
The reduction of the reactive power demand and reactive losses brings benefits to all upstream stages with the exception of the generation stage, which is designed for active power flow.
On the contrary the reduction of active power losses brings benefits to all the upstream stages, generation included.
In the case of ENEL, with about the 80 % of thermal generation, the benefits at the generation stage may be roughly evaluated as the 50 % of total benefits.



P, Q : downstream side flow;
PD, QD : downstream side Demand (load);
PL, QL : stage Losses;
dA(QD) : increase in power flow due to reactive power QD;
dA(AL) : increase in power flow due to power losses AL
AL sqrt $(PL^2 + QL^2)$

Fig.1 Basic diagram

It can be observed that initial improvement actions to reduce the reactive power demand and / or the power losses generally produce greater benefits than subsequent ones of the same size and cost. Therefore it is convenient to push the reduction of the reactive power demand and / or the power losses to its optimum extent, that correspond to the balance between the economical benefits of the reductions and the costs of the interventions.

GENERAL EXPRESSION OF THE COST OF REACTIVE POWER FLOWS AND POWER LOSSES

As concerns the economic aspects connected to the reactive power flows and power losses it is necessary to take into account the overall electric system, the generation stage included, which is influenced only by the active power.
In the following the general analytical expressions are given for the economic evaluation of the negative effects produced by reactive power demand and power losses at any stage of the network.

Cost of reactive power demand

The general expression, which shows the total system costs C_{QDi} related to the flow of reactive power demand QD at the downstream side of the generic stage "i" of the system, is given by:

$$C_{Qi} = c_{ai}\, d\, A_i(Q_i) + \sum_{j=1}^{i} [c_{pj}\, d\, PL_j(Q_i)] + \sum_{j=1}^{i} [c_e\, d\, EL_j(Q_i)]$$

where:
- the sums concern all the "j" upstream stages of the system (the given stage "i" included)

- c_{aj}, c_{pj} and c_e are the per unit costs of apparent power, active power losses due to current and active energy losses due to current;
  the value of the coefficients c_{aj} and c_{pj} changes as a function of the stage of the system, while c_e is the same for all the stages considered;
  c_{aj}, c_{pj} and c_e take into account only the contribution due to current losses, since voltage losses (iron losses in the transformers and dielectric losses) are independent from power flows;
- the terms dA_i, dPL_j and dEL_j indicate respectively the *additional*:
  . apparent power flows at the downstream side of the stage "i"
  . active power losses in the stage "j"
  . active energy losses in the stage "j"
  originated by the reactive power demand QD_i at the downstream side of the stage "i"

Cost of power losses

The general expression, which shows the total system costs C_{ALi} related to the power losses AL originated at the generic stage "i" of the system (for simplicity sake the total losses are considered, including those caused by downstream reactive demand and losses), is similar to that for reactive power flows:

$$C_{ALi} = c_{ai}\, d\, A_i(AL_i) + \sum_{j=1}^{i-1} [c_{pj}\, d\, PL_j(AL_i)] + \sum_{j=1}^{i-1} [c_e\, d\, EL_j(AL_i)]$$

where:
- the terms dA_i, dPL_j and dEL_j are originated by power losses AL_i at the stage "i".

Practical determination of costs

The practical use of the above expressions requires:
- to determine the per unit costs c_{ai}, c_{pi} and c_e
- to determine the technical negative effects dA_i, dPL_i and dEL_i, or better the technical benefits in reducing dA_i, dPL_i and dEL_i with improving actions

DETERMINATION OF PER UNIT COST OF POWER FLOWS, ACTIVE POWER LOSSES AND ACTIVE ENERGY LOSSES

The knowledge of the per unit cost of power flows and active power and energy losses due to the current in a given distribution system is essential in order to convert the technical evaluations of system over-sizing and additional energy losses, due to reactive power flow and power losses, into economical parameters.
The relevant values vary from country to country mainly in relation to the primary sources used to produce electric power. The evaluation is made by means of a suitable model of the system. Fig.2 shows the number of downstream stages in which the system has been split.
The model differs from the present system because it does not take into account all the differences, in terms of loads and network characteristics, among the parallel stages. In other words the load and the network characteristics are the same for each parallel stage.

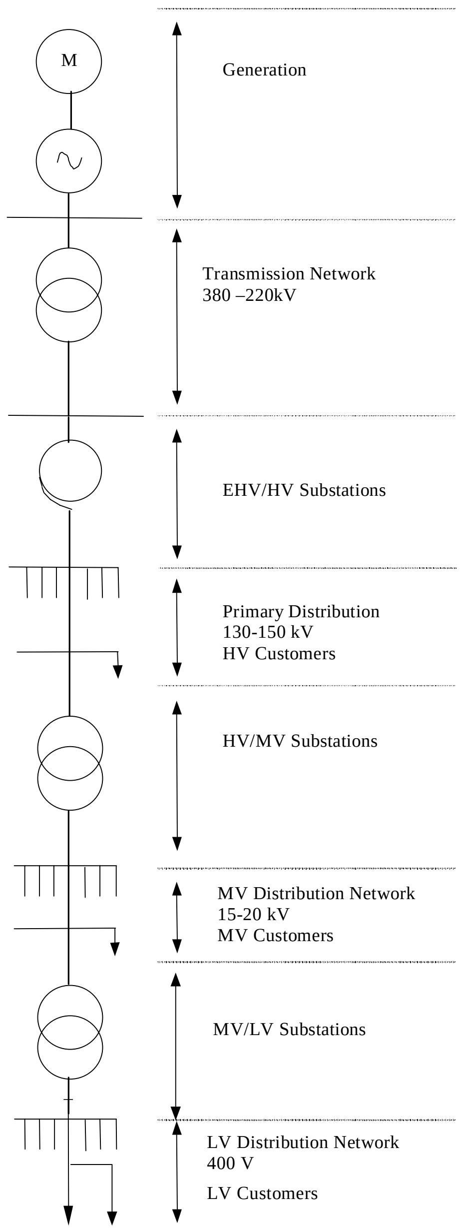


Fig.2 Basic model of ENEL system

Per unit cost of power flow

It is possible to evaluate the per unit cost c_{ai} of the power flow A_i at the stage i, through the following expression:

$$c_{ai} = \sum_{j=1}^{i} c_j\, df_{ji}$$

where:
- the sum concerns all the "j" upstream stages of the system (the given stage "i" included)
- c_j is the ratio between the yearly share of the total cost of the stage and the peak power A_j flowing through it
- df_{ji} = factor of diversity between stages j and i

The total cost of the stage j is calculated on the basis of:
- total costs of the installations of the stage
- interest rate
- duration of technical depreciation, also called "useful life span" of the installations of the stage

The total cost of the installations of the stage j is evaluated as a cost of full reconstruction, on the basis of a mix of the different plants in the present system and of the corresponding per unit costs.

The following items are disregarded in the evaluation of the total cost of stage j:

- operating charges and particularly those associated with the personnel, with the exception of the generation stage, as they may be considered, at least as a first approximation, independent from the reactive power flows and power losses
- reactive power demands as terms of second rank
- power losses as terms of second rank
- additional losses caused in the upstream stages by reactive power demand and power losses at the given stage as terms of second rank

The factor of diversity between stages j and i is given by the following expression:

$$df_{ji} = \frac{A_j(i,t_j)}{A_j(i,t_i)}$$

where:

- $A_j(i,t_j)$ is the contribution of the stage i to the power flow occurring at the j stage at the peak instant t_j of the stage j
- $A_j(i,t_i)$ is the contribution of the stage i to the power flow occurring at the j stage at the peak instant t_i of the stage i

Going downstream in the system, the per unit power costs c_{ai} tend to increase because of the costs of the added stages and to decrease because of the diversity factor between the downstream side of the stage i and the upstream sides of the parallel stages i + 1 (fig.3).

Per unit cost of power losses due to current

As said above only the contribution of losses due to current is considered, as losses due to voltage are not affected by the improvement actions on reactive power demand and/or power losses. It is possible to evaluate the per unit cost c_{pi} of the active losses due to the current at the stage i, through the following expression:

$$c_{pi} = \sum_{j=1}^{i} \frac{c_j \, df_{ji}^{\;2}}{\cos\varphi_j}$$

The expression of c_{pi} differs from the expression of c_{ai} as:

- the square of the factor of diversity df_{ji} is considered, since active power losses are proportional to the square of power flow
- the power factor $\cos\varphi_j$ is considered, since active power losses are dealt with and the relationship: $c_a A = c_p P$ must be fulfilled

As the per unit power costs c_{ai}, also the per unit active power losses costs c_{pi} tend to increase because of the costs of the added stages and to decrease because of the factor of diversity between stages (fig.3).

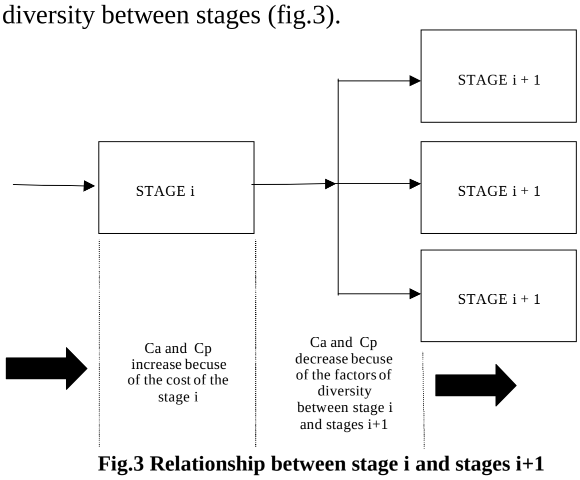


Fig.3 Relationship between stage i and stages i+1

Per unit cost of energy losses due to current

The per unit cost of active energy losses c_e is independent of the stage originating the losses and, at least in systems where thermal generation prevails, it can be estimated as the cost of the fuel consumption necessary to produce 1 kWh.

Per unit cost of power flows and losses in ENEL distribution grid

By using the methodology explained above, the average unit costs of power flows (c_a), active power losses (c_p) and active energy losses (c_e) at the different stages of ENEL system have been evaluated and reported in table 1.

Table 1 - Per unit costs of power flows and losses

stage	c_a EURO/kVA year	c_p EURO/kVW year	c_e EURO/kWh
HV	89.36	90.29	0.03
MV	97.99	91.58	0.03
LV	93.00	74.23	0.03

POSSIBLE IMPROVING ACTIONS ON DEMAND SIDE AND IN THE DISTRIBUTION SYSTEM

The reduction of reactive power flows can be accomplished installing capacitor banks.

In principle capacitor compensation by the loads is highly preferable to capacitor compensation in the upstream stages of the network as:

- the benefits of power flows reduction involve all the upstream stages, whilst in case of capacitor compensation in the network they involve only part of the upstream stages
- the capacitor compensation needed by the loads is lower than that needed by the upstream stages, which must take into account also downstream losses

With reference to the whole system (public grid and private plants) the improving actions of the distribution utility may be resumed as:

- *customer side*: tariff policies and promotional actions aimed at improving the customer power factor
- *public grid side*: capacitor compensation at different levels of the distribution system

The economic charge of the compensation of reactive power demand is attributed in any case to the customer, who is responsible for the disturbance introduced in the system by the reactive power demand.

The reduction of power losses can be accomplished:

- increasing the size of components (such as cross section of conductors)
- replacing actual components with low losses components (such as low losses transformers)

In case of present public systems, in which topology and asset normally do not completely minimise active power flows, other more general actions can be undertaken, such as:

- upgrading network topology (such as reducing circuit length)
- upgrading network capacity (such as operation at a higher nominal voltage)
- upgrading network operation (such as determining the most convenient network asset)

EVALUATION OF TECHNICAL BENEFITS OF IMPROVING ACTIONS

The evaluation of the technical effects of the reduction of the reactive power demand and / or the power losses requires the knowledge of active and reactive power flows and power and energy losses in the system.
This is achieved at first by means of direct measurements in the network, although the information is limited to the existing situations and direct measurements do not allow a correct evaluation of losses. Nevertheless direct measurements help in defining a suitable load model employed in network calculations [1].
Load-flow calculations are required in order to evaluate power flows and losses both for present and future alternative situations. This can be accomplished by suitable programs, available in the frame of the information system describing the distribution network, and designed to simulate alternative of future network developments [2].
In practice the technical benefits in terms of reduction of power flows and power and energy losses at a given stage are evaluated by making the difference between the power flows and the power and energy losses calculated before and after the simulation of improving interventions on the network.

IMPROVING ACTIONS UNDERTAKEN BY GOVERNMENT AND ENEL

In the following the actions undertaken by government and ENEL both in the specific field of capacitor compensation and reduction of losses and in other more general fields concerned with power flows reduction are illustrated.

Actions on demand side

As already said the policy to control the flows of reactive power proves to be more effective if the power factor correction is performed closer to the source.
Benefits are thus derived both for customer, since the penalties envisaged in cases of excessive withdrawal of reactive power are not applied, and for the distributor, since losses in the network and voltage drops are reduced. Moreover the customer obtains the same benefits of the utility in its own distribution network.
In the following information on the steps made by government and ENEL in the last 30 years are given.

Tariff policies. Even before the Italian electrical industry was nationalised, the scales of charges in force envisaged suitable warning of an economic nature, to push customers to limit their consumption of reactive power.
In particular the CIP (Inter-ministerial Prices Committee) regulation 949/1961 required customers to ensure for the cosφ an instantaneous value (in relation to the maximum load) $\geq$ 0.6 and an average monthly value $\geq$ 0.8.
For customers with subscribed power up to 10 kW, the control of the withdrawal cosφ was executed in relation to the maximum load by installing a magneto-thermic circuit breaker limiting the current.
The nominal value of the breaker is calculated by the following equation:

$$I_n = P_i / (V_n \cos\varphi)$$

where:
- P_i = subscribed power
- V_n = nominal voltage
- cosφ = 0.8 in relation to the maximum subscribed power

By means of such a device, with the same active power withdrawn, any values of the power factor lower than 0.8, involving current values higher than the nominal characteristics of the circuit breaker, caused the opening of the tripping switch within the time defined by its load curve.
For customers with a subscribed power greater than 10 kW, the control of the average monthly power factor was executed by installing meters able to measure the active and reactive energy withdrawn and, through the ratio between reactive and active energy, tracing the average monthly value of the tgφ to obtain the monthly power factor value.
If this value proved to be lower than 0.8, the price of the active energy withdrawn was increased by 1% for each hundredth part of the average value lower than 0.8.
More recently, the CIP regulation 1/1975, recognising the need for a closer control of reactive power flows, raised the instantaneous cosφ value (in relation to the maximum load) to 0.7 and the average monthly value to 0.9.
The control of reactive power was carried out on the peak load value for customers with subscribed power lower than 20 kW and on an average monthly value for those with subscribed power $\geq$ 20 kW. In the last case, if the average monthly cosφ was lower than 0.9, the price of the active energy was increased by 1% for each hundredth part of the average value lower than 0.9.
The later CIP regulation 12/1984 introduced a new penalty criterion for operation with a low power factor. It established different charges in relation to the quantities of reactive energy withdrawn compared with active energy and with input voltage.
Finally the CIP regulation 15/1993 established the charges shown in table 2..

Table 2: Charges for reactive energy withdrawal

Amount of reactive energy	LV customers (EURO/KVARH)	MV, HV customers (EURO/KVARH)
50% - 75% active energy	0.0325	0.0147
Over 75% active energy	0.0418	0.0186

Campaigns undertaken to rationalise energy consumption. In orienting demand towards rationalisation of electric energy consumption, ENEL has utilised, a part from its tariff scale, also effective information and advertising campaigns.
Beside internal use of specific publications devoted to the power factor correction of both LV and MV loads, ENEL performed its first advertising campaign (1979-82) in collaboration with ANIE (National Electric and Electronic Industries Association), the Installers Associations and the Chambers of Commerce.
The result of the campaign was the installation of a power of 1,600,000 KVAR.
A second campaign, also supported by financial incentives and by a complete information package, was carried out between 1989-92.

Actions on internal side

Installations of capacitor banks in public grid. The most common policy to compensate the reactive power consists in the installation of capacitors banks in HV, MV and LV networks.
Significant advantages can be achieved if the capacitor compensation is applied by means of spread capacitor banks installed in distribution network nodes.
If the capacitors are of the switched type it is possible to avoid the negative effects both on the voltage drops and on the losses in the network, in hours (for instance in the night) when abundance of reactive capacity power is present.
In recent years international literature [3] has treated the distributed optimum capacitor compensation problem.
The availability of evolved software systems allows an optimisation both at the design level (number and ratings of banks to be installed and their location in the network) and at the operation level.
At the operation level the reactive compensation is established by needs of voltage regulation and energy losses reduction (this means considering power losses instant by instant, taking into account the daily load curve).
Nowadays the total installed capacity of capacitor banks in ENEL grid is some 9000 MVAR, mostly of them on MV system, whilst synchronous machines have been abandoned due to their very high costs of investment and maintenance.
The compensation on the low voltage circuits, which would be technically correct, was limited in the last years by the difficulties in periodic maintenance of the wide spread capacitors banks.

Replacement of existing transformers with high efficiency transformers. In large distribution systems both HV/MV and MV/LV transformers are used, since three voltage levels are normally provided.
While the main functional characteristics of these transformers have not varied substantially with time, important improvements occurred with the aim at reducing losses and the emitted noise, as well as to increase reliability.
The characteristics of low losses HV/MV transformers are given in table 3.

Table 3: Low losses HV/MV transformers

Rated power (MVA)	Iron losses (KW)	Load losses (KW)
25	17	125
40	25	187
630	33	285

The series of low losses MV/LV transformers, ranging from 50 KVA to 630 KVA, is characterised by iron and load losses ranging from 70% to 80% of the correspondent losses in traditional transformers.

Upgrading nominal voltage level. An important *indirect* way to reduce network losses is the replacement of old voltage insulation levels below 20 kV by 24 kV, to gradually operate all existing MV circuits either 15 or 20 kV.
The process, undertaken by ENEL since several years, was aimed mainly:
- at improving the capacity of the network
- at eliminating the obsolescent components

At the moment the process is nearly completed for overhead lines, whilst, for underground cables in urban areas, the process is slow, although since several years all new cables and substation are 24 kV insulated.

Reduction of circuit length. The reduction of circuit length, by means of installations of new primary substations, is another *indirect* way to reduce losses, as these actions take place mainly:
- to increase the capacity of the network
- to improve the quality of supply reducing the number of interruptions and voltage dips felt by customers

At present the average length of each MV circuit in ENEL is about 15 km.

RESULTS ACHIEVED IN ENEL SYSTEM

The natural power factor on MV and LV ENEL networks at the maximum load instant and the correspondent value for the compensated network 15 years ago were 0.9 and 0.97 respectively. Nowadays such values are 0.93 and 0.98. It can be observed that the present average value of power factor 0.98, as confirmed by many studies that literature reports, corresponds to the economical optimum.
As concerns energy losses an important decrease of energy losses (from 9.1% to 6.6% of the energy demand) took place in the last 15 years. Nowadays the total amount an ENEL system, corresponding to 6.6% of the energy demand, is some 15,000 GWH.

CONCLUSIONS

The reduction of reactive power flows and power losses in public distribution system gives economical benefits in terms of reduction of the upstream system sizing and energy losses.
The improvement actions in this field must be pushed to reach the balance between the economical benefits of the reactive power and/or losses reductions and the costs of the interventions to obtain these reductions.
Following these criteria ENEL achieved in Italian public distribution grid important results by means of a series of specific actions, such as improving customers power factors, installing distributed capacitors, introducing new high efficiency components.
An important contribution was given also by other more general actions of network upgrading, such as increase of nominal voltage, reduction of the current path and of the length of circuits, increase of cross sections of conductors, balancing of the loads in normal conditions.

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