APPLICATION TO AN ITALIAN DISTRIBUTION SYSTEM OF A MULTIOBJECTIVE OPTIMAL VOLT/VAR CONTROL STRATEGY: IMPROVEMENTS AND MANAGEMENT PROBLEMS

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ABSTRACT

In this paper, the experiences and results deriving from the application of a multiobjective optimal management strategy to a distribution network supplying an area in province of Palermo, Italy, are presented. The adopted strategy allows, through the interventions on the Under Load Tap Changers (ULTC) of the primary substations and on tie-switches, to reduce power losses and improve the voltage profiles. To solve the optimization problem, an evolutionary approach has been adopted; it employs fuzzy logic for an adequate and simultaneous fulfilment of the different objectives. The application section presents a deep technical and economical analysis of the results attained, applying the optimization algorithm, together with other interesting operational solutions.

INTRODUCTION

The networks reconfiguration in distribution systems is possible due to their slightly meshed topology and to the presence of tie-switches. During normal operation, a number of tie-switches, that equals the number of independent loops, is opened in order to exploit all the benefits deriving from the radial operation mode. During outages, reconfiguration allows to restore supply at some of the loads in the affected area by connecting them to another HV/MV substation. Some of the main objectives that can be attained during normal operation by means of the reconfiguration are the losses reduction and the improvement of voltage profiles. In the same way, also other elements, such as the Under Load Tap Changers (ULTC) and capacitor banks can be used to improve these objectives. The technical literature on the subject has widely treated the problems of reconfiguration, compensation and Volt/VAR control in distribution systems. The optimization problem is non linear, constrained and combinatorial, therefore, in many cases, heuristic algorithms have been used (Genetic Algorithms, GA; Simulated Annealing, SA; Tabu Search, TS; Artificial Neural Networks, ANN; Evolution Strategies, ES; etc…) [1-6]. In this paper, the results of the application of a multiobjective optimization strategy for Volt/VAR control in a real large distribution system are reported. This strategy co-ordinates the intervention of tie-switches in the network (reconfiguration) and of the ULTCs of the primary transformers as the loads vary. The studied system is composed of a MV network (20 kV) that is meshed and that is supplied by two primary substations, in an area near Palermo. The network is normally operated in radial configuration. The studied system does not comprise capacitor banks on the MV busbars and along the feeders. There are three HV/MV transformers installed, as it will be detailed in a later section, in two different primary substations. The network is not entirely automated, only some of the branches are equipped with tie-switches. The objectives are the power losses minimization and the voltage profile regularisation. The technical constraints concern the check about currents in branches, that must not exceed their ampacity, and the daily number of manoeuvres for remotely controllable elements. The control variables are the status of the tie-switches and the positions of the ULTCs. These variables can be easily turned into mixed-integer strings. For these problems then the search space is quite large. An exhaustive search can not be carried out in affordable calculation times. Moreover the multiobjective formulation and the presence of many constraints suggest the application of heuristic techniques. The overall solution strategy is an ES that uses Fuzzy logic to manage the different objectives [2].

PROBLEM FORMULATION

The problem of finding the optimal operation strategy in normal working conditions along 24 hours has been formulated as a mixed-integer multiobjective optimization problem. The solution approach is a Fuzzy Evolution Strategy Fuzzy-ES, [2], where the management of the different objectives is carried out using the Fuzzy Sets theory. The objectives are: the power losses minimization in the branches and in the HV/MV windings

$$\min \Delta P(\delta) = \min\left(\sum_{i=1}^{N_{SS}} R_i I_i^2 + \sum_{j=1}^{N_B} R_j I_j^2 \right) \quad (1)$$

the voltage profile regularisation

$$\min \Delta V(\delta) =$$

$$= \min\left\{ \frac{1}{N_e} \sum_{i=1}^{Ne} \left|\Delta V_i\right| = \frac{1}{N_e V} \sum_{i=1}^{Ne} \left[\sum_{j \in Bi} \left(R_j P_j + X_j Q_j \right) \right] \right\} \quad (2)$$

where: N_{SS} is the number of HV/MV substation transformers; N_B is the number of branches some of which are provided with remotely controlled tie-switches; R_i is the resistance of the i-th HV/MV transformer, R_j is the resistance of the j-th branch, I_i and I_j are the relevant currents; P_j and Q_j are the real and reactive power flows on the j-th branch or in the j-th transformer; ΔV_i is the voltage drop at the i-th node evaluated with respect to the MV supply node; X_j is the reactance of the j-th branch; B_i is the set of branches connecting the i-th node to the MV supply node; N_e is the number of extremity nodes; V is the rated voltage value. The optimization string δ is the mixed-integer vector of control variables; it is composed of: the boolean string δ_S expressing the status of the tie-switches and the integer string δ_{ULTC} expressing the ULTC (tap positions) status. It turns that:

$$\delta = \{\delta_S, \delta_{ULTC}\} \tag{3}$$

Else than the normal technical constraints concerning the current ampacity, in this formulation it is required that the number of manoeuvres over the remotely controllable components in 24 hours must be limited. This integral constraints are considered by linking the solution attained to the solution of the preceding hours and suitably restricting the search space. Even though the strategy can also handle the management of capacitor banks, the studied network does not show any and the utility does not consider their installation in the near future. The proposed management strategy implies the voltage regulation at the primary substation by means of the ULTCs installed the HV/MV transformers secondaries. In order to keep into account the presence of these components the model proposed in [4] is adopted.

THE STUDIED SYSTEM

The studied system (figure 1) is a part of a larger 20 kV MV system in the western part of Sicily (Italy). The supplied area is a medium load concentration area where the largest part are residential customers and a smaller part are hospitals, sport plants and small industrial sites. The principal elements characterising the system are: N_{SS} = 3 HV/MV transformers (rated powers: 25 and 40 MVA) all equipped with Under Load Tap Changer and a fast automated voltage regulation system; 4 main MV feeders; 159 buses; 164 branches.

The network buses can be classified in the following way: tie-switches, public MV/LV substations, MV customers, branching nodes. The topology of the system is typical of medium size urban sites. The system is radially operated and has 5 meshes and some ‘clusters’ of loads on a few rural lines. The model used for load flow calculations hypothesizes that the primaries of the three transformers are connected at the same busbars. The model adopted for the loads representation is a constant current model.

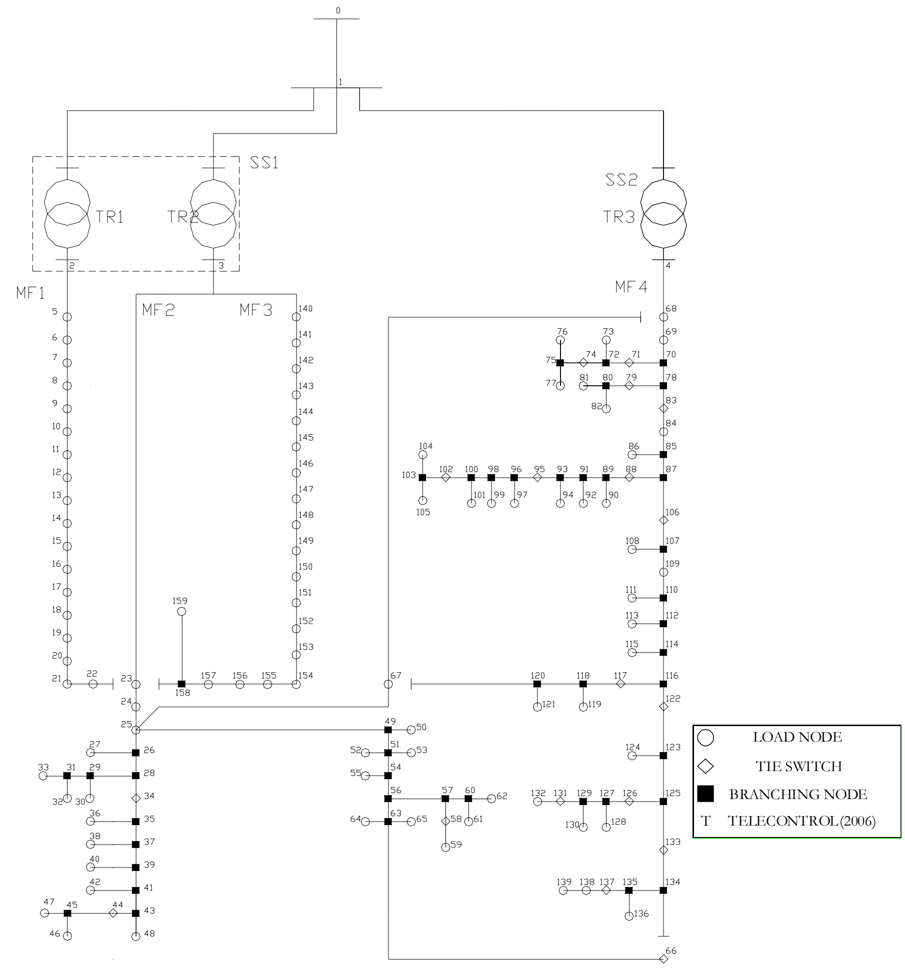

Figure 1 – Studied system

APPLICATION

In this section, the optimal management solutions attained by means of the optimization tool proposed in [2] are presented and discussed. Then other less cost management solutions that can be derived from the first are also proposed. These management solutions keep a fixed configuration along the 24 hours. In this way, it is possible to reduce the investment cost required to install remotely controllable elements. All the proposed solutions are analysed in technical and economical terms. In order to perform these evaluations it was necessary to fix a price for the lost kWh. The authors have executed the average of the selling prices of year 2005.

The cost of losses considered for the analysis is 71.855 €/MWh. The optimal management algorithm here proposed uses the following parameters for the loads estimation: maximum power for each customer; daily load diagram for each customer. In order to attain the 24 hours strategy, it has been necessary to identify a daily load diagram that could be assumed as representative of the behaviour of the system in a larger time-frame. The study has been carried out following the indications of the utility and analyzing the situation of the third Wednesday of the month of December of year 2004 (15/12/2004). This is indeed the day that the local electrical utility considers as standard when it performs calculations and analyses.

Optimal solution applying the Fuzzy-ES

In the application here carried out, the authors have hypothesized that the network is equipped with: remotely controllable ULTCs at the primary substations (17 insertion steps); remotely controllable tie-switches in all branches.

The management solution attained applying the Fuzzy-ES is made up of the layout of these elements along 24 hours as the load changes. The constraints concern: the current in the branches not exceeding their ampacity; the number of manoeuvres for ULTCs, nmanULTC, not exceeding 30 in 24 hours and the number of manoeuvres of tie-switches, nmansw, not exceeding 4 in 24 hours: nmanULTC$\leq$ 30 in 24 hours, nmansw $\leq$ 4 in 24 hours. With this formulation and with these assumptions, the algorithm else than an optimal management strategy also gives an indication about the most promising sections for automation in terms of losses reduction and voltage profile regularization. Table I shows a cumulative picture of the attainable economic benefit improvements in one year (ΔVx% is the maximum voltage drop in % of the rated voltage).

TABLE I - Fuzzy ES results

Current configuration		Fuzzy-ES, hourly reconfiguration		
Yearly Losses [kWh]	ΔV_x%	Yearly Losses [kWh]	ΔV_x%	Yearly Economic benefit [€]
312715	1.59	167440	0.96	10439

It can be observed that together with the economical benefits deriving from the proposed optimal management strategy (10439 €), also the improvements in terms of quality of service and namely of the voltage profile regularisation must be considered. The total number of manoeuvres required by the optimal strategy in 24 hours is 4 both for ULTC and for tie-switches. The implementation of the proposed strategy requires some modification of the current situation; in particular, the following interventions must be carried out on the network: modification of the voltage regulation mode; installation of six more remotely controlled tie-switches; setting up of an adequate tele-control center; installation of a suitable data transmission system. As far as the first point is concerned, it must be underlined that the current mode for voltage regulation at the primary substations is different from the one proposed by the algorithm; this would certainly imply some additional investment costs. It must be here evidenced that the number of tie-switches interested in the reconfiguration process is quite limited as compared to the network size. The economical analysis about the practical implementation of this solution requires an analysis of the tools and components today available for the local electrical utility. As it was shown in the preceding paragraphs, the adoption of a 24 hours optimal management strategy certainly implies some technical obstacles and also some costs. It is clear that the adoption of automation within distribution systems management is a choice of the distributor based on strategical choices. Other technical problems that may arise during opening/closing manoeuvres are connected to the transients. It can be thus interesting to evaluate the benefits deriving from a permanent modification of the configuration following the indications given by the algorithm. Finally the most evident result of the application of an optimization algorithm is that the current configuration is certainly not the best in terms of economical operation of the studied system. In the following sections a couple of stable configurations will be analysed in economical and technical terms.

Solution A

Solution A is a stable configuration, chosen among those indicated by the Fuzzy ES along the 24 hours strategy, that allows to attain the best results in 24 hours in terms of power losses. In order to minimize the costs impact for this analysis, the ULTCs contribution has been not considered. On the basis of the hypotheses above, the economical savings attainable in this case are reported in Table II.

TABLE II - Solution A results

Current configuration		Solution A, hourly reconfiguration		
Yearly Losses [kWh]	ΔV_x%	Yearly Losses [kWh]	ΔV_x%	Yearly Economic benefit [€]
312715	1.59	167934	0.97	10403

For the implementation of solution A, 4 new remotely controllable tie-switches installations are required. The normal and outage operation of the network requires indeed the presence of some remotely controllable ‘boundary’ tie-switches allowing the load transfer during serious faults interesting the main feeder or the primary substation. None of these sections will be automated in the near future (within 2006). So these installations should find a justification only on the basis of the economical and qualitative benefits that the utility can get. The cost for the installation of each remotely controllable tie-switch can be quantified in about 6000 €. The proposed investment, considering the economical benefit connected to the losses reduction, can be covered in, approximately, a time-frame smaller than 3 years. Indeed, also the variation of the cost of losses as well the interest rate and the amortization factors should be considered. Voltage drops also improve.

Solution B

The configurations analysed in the preceding sections require the installation of new components; for this reason, investment costs are also needed for the new installations. In this section, the advantages that can be attained by simply modifying the current configuration, with no further investment, are analysed. The solution suggested is that to adopt a different network configuration attainable simply by changing the already installed tie-switches statuses. Therefore no new installations are needed. Solution B shows the closest layout to solution A. The yearly economical benefit has been thus calculated (8160 €) and the results are reported in Table III. As it can be observed there is a smaller economical benefit as compared to solution A, and the management solution over 24 hours, but on the other hand no investment costs are needed in this case.

TABLE III - Solution B results

Current configuration		**Solution B, hourly reconfiguration**		
Yearly Losses [kWh]	**ΔV_x%**	**Yearly Losses [kWh]**	**ΔV_x%**	**Yearly Economic benefit [€]**
312715	1.59	199153	1.21	8160

In figure 2 the losses course along the 24 hours for the considered layout (actual, hourly reconfiguration, solution A and solution B) is reported.

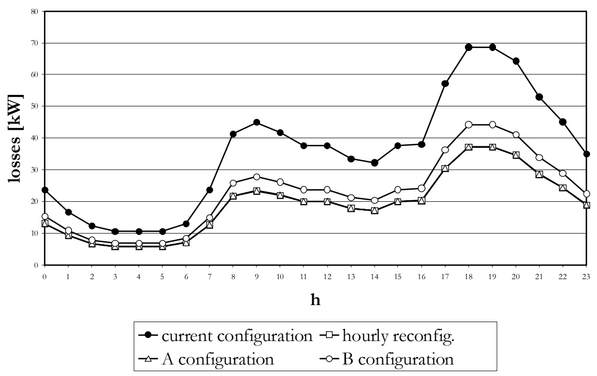

Figure 2 - Losses course.

CONCLUSIONS

This paper gives an analysis of the potential offered by the use of new technologies in the field of operation and planning of distribution systems. In particular, the advantages of optimal operation in terms of losses reduction and of the improvement of the voltage profiles have been analysed in technical and economical terms. Starting from a real distribution system, the optimal operation performed by reconfiguration and change of status of other elements such as ULTCs has been analysed. The optimal management strategy allows to set the status of tie-switches and ULTCs along 24 hours on the basis of a standard load diagram that has been provided by the utility in a real distribution network in the area of Palermo, Sicily. The economical benefit of the attained solution operational strategies has also been evaluated. Further results concern the possibility to identify two operational configurations to be kept fixed along the 24 hours. Of these configuration, one requires less investments, the second does not require investments at all. In both cases, an economical benefit has been observed. The attained results suggest that often real system are operated not in optimal conditions and that most of the times further analysis should be carried out in order to better evaluate each situation and improve the energy efficiency.

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