# Volt-VAR Multiobjective Optimization to Peak-Load Relief and Energy Efficiency in Distribution Networks

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***Abstract*—This paper addresses the integrated volt-var control for distribution network operation via multiobjective optimization. This paper seeks to explore the problem of energy savings and peak demand relief through the voltage reduction procedure. Currently, due to the emergence of the distribution smart grids, these procedures are gaining renewed interest and attention. The proposal presented here is for the operation phase, with a strategy based on an hourly load forecast for the next day/week, taking into account the active power intake reduction, and the voltage deviation. Therefore, the result is a set of nondominated optimal solutions, and then one may decide when, where, and how to apply them to meet different goals. The obtained solutions, for two typical distribution networks, describe relevant economic and technical benefits.**

***Index Terms*—Distribution systems, integrated volt-var control, multiobjective optimization, voltage reduction.**

## NOMENCLATURE

| | |
|---|---|
| $E_{\text{saving}}$ | Total energy savings. |
| $\Delta V$ | Voltage drop at the substation bus. |
| $Pl_i$ | Active load power at bus number $i$. |
| $P_{n,i}$ | Active load power at the rated voltage and frequency at bus $i$. |
| $Ql_i$ | Reactive load power at bus number $i$. |
| $Q_{n,i}$ | Reactive load power at the rated voltage and frequency at bus $i$. |
| $k_p$ and $k_q$ | Voltage exponents of active and reactive load power. |
| $V_i$ | Voltage magnitude at bus number $i$. |
| $V_n$ | Nominal voltage of the system. |
| $\Delta V_{ij}$ | Voltage drop between buses $i$ and $j$. |
| $r_{ij}$ | Line resistance between buses $i$ and $j$. |
| $z_{ij}$ | Line impedance between buses $i$ and $j$. |
| $P_{in}$ | Active power intake on the system. |
| $Q_{in}$ | Reactive power intake on the system. |
| $P_{load}$ | Total active load power. |
| $P_{loss}$ | Total real power losses. |
| $f_j$ | Objective function $j$, of the multiobjective problem, $j = 1, \ldots, k$. |
| $nb$ | Set of buses. |
| $V_{\min}$ | Minimal voltage level. |
| $V_{\max}$ | Maximum voltage level. |
| $Pg_i$ | Active power generation at bus $i$. |
| $Qg_i$ | Reactive power generation at bus $i$. |
| $QC_i$ | Reactive power injection by capacitors at bus $i$. |
| $\theta$ | Voltage angle. |
| $RG_i$ | Regulation ratio of the device at bus $i$. |
| $tap_i$ | Selected tap of the device at bus $i$. |
| $\Delta \text{tap}_i$ | Step of voltage variation of the device at bus $i$. |
| $tap_{\min,i}$ | Minimum tap of the device at bus $i$. |
| $tap_{\max,i}$ | Maximum tap of the device at bus $i$. |
| $pf_{sys}$ | System power factor. |
| $pf_{\min}$ | Minimal system power factor. |
| $pf_{\max}$ | Maximum system power factor. |
| $nsw_i$ | Selected position of the switched capacitor at bus $i$. |
| $nsw_{\max,i}$ | Maximum number of positions of the switched capacitor at bus $i$. |
| $\Delta C_i$ | Step of reactive power variation of the capacitor at bus $i$. |
| $C_i^{sw}$ | Reactive power injection by the switched capacitor on bus $i$. |
| $P_i(\theta, V, tap)$ | Active power injection on bus $i$. |

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| | |
|---|---|
| $Q_i(\theta, V, tap)$ | Reactive power injection on bus $i$. |
| $N$ | Dimension of the population for NSGA-II. |
| $F_i$ | Pareto frontier $i$ of nondominated solutions $i = 1, \ldots, k$. |
| $D_{m_i}^{F_j}$ | Crowding distance of individual $i$ of frontier $j$. |
| $f_m^{F_j^{i+1}}$ | Value of objective function $m$ of individual $i+1$ of frontier $j$. |
| $f_m^{F_j^{i-1}}$ | Value of objective function $m$ of individual $i-1$ of frontier $j$. |
| $f_m^{F_j^{\max}}$ | Maximum value of objective function $m$ at frontier $j$. |
| $f_m^{F_j^{\min}}$ | Minimum value of objective function $m$ at frontier $j$. |
| $SO$ | Set of studied objectives. |
| $P_t$ | Population of NSGA-II algorithm in the generation $t$. |
| $R_t$ | Set composed by parent and offspring population in the generation $t$. |
| $Q_t$ | Offspring population in the generation $t$. |
| MAX | Set of nondominated solutions with maximum energy savings. |
| MOD | Set of nondominated solutions with moderate energy savings. |
| MIX | Set of nondominated solutions with the MAX case for the peak-load period and MOD for the rest of the day. |

## I. Introduction

The PROCEDURE of increasing energy efficiency by voltage reductions on medium-voltage (MV) distribution networks has received great attention, since relevant benefits have been presented [1]. This approach has been called conservation voltage reduction (CVR) or conservative voltage reduction [2], and can be considered from the utilities point of view, a possibility for demand management, which is always available and can be used once it is needed. Currently, due to the emergence of the distribution smart grids, the CVR procedures are gaining renewed interest [3].

These new networks should receive significant improvements in computation and communication technologies, and the integrated volt-var control (IVVC) should become much more effective than with traditional technologies, such as on-load, tap-changing transformers (OLTCs), automatic voltage regulators (AVRs), switched capacitors, and other devices operating autonomously [4]. Moreover, the voltage control will be present to enhance the performance of the distributed generation [5]. The necessary investment to transform the current distribution networks into smart grids could be very high, and it has been predicted that a third of the applications should be on integrated volt-var control, including CVR [6].

Therefore, this paper seeks to mitigate the problem of voltage reduction application via multiobjective optimization using a nondominated sorting genetic algorithm (NSGA-II) [7]. The proposal presented here is for the operation phase of the network, with a strategy based on an hourly load forecast for the next day/week, taking into account the demand reduction, and the voltage deviation, considering the presence of OLTC, AVRs, and capacitors. Thus, the result will be a set of nondominated optimal solutions and then one may decide when, where, and how to apply them to meet different goals, considering different feeders or even different utilities. The new approach allows a distinguished view over advantages and possible applications for energy savings and MVA peak reliefs.

Many studies have been presented to solve the problem of volt-var control, but mainly, for distribution planning purposes; however, few contributions have emerged thinking in multiobjective optimization solutions and energy efficiency. The following sections will present an overview of some important contributions on volt-var optimization and on CVR and loads in MV distribution networks.

## II. Volt-Var Optimization, CVR, and Loads

Many methodologies have been designed for the optimal allocation of volt-var control devices in distribution networks. A detailed analysis of capacitor and AVR placement was discussed in [8]; some years later, another well-known work [9] presented a mathematical formulation for optimal capacitor placement, modeled as a nonlinear mixed-integer programming problem. Proposals using multiobjective optimization have arisen recently: the authors of [10] have presented a tabu-search-based approach to capacitor placements, trying to solve the conflict between costs and loss reductions; in [2], a solution has been presented for the capacitor allocations; however, taking into account the CVR, the objectives to be minimized were costs, voltage deviation, and the reduction of losses and demand; [11] shows a micro-genetic algorithm to AVR allocations, and the objectives were the power losses and the reductions in voltage drops; in [12], a mixed-integer linear programming model is used that considers the costs and the voltage deviations as the objectives to allocate the AVRs; in [13], a genetic algorithm is employed to simultaneously solve the planning problem of capacitor and AVRs placement, considering the losses, the voltage deviation, and the costs as objectives, and in [14], a nondominated sorting genetic algorithm is presented for the allocation of capacitors and AVRs and for cable replacement, considering costs and the voltage deviations.

All of these proposals have been designed to be applied to the planning phase of the distribution networks and do not take into account the utilization of CVR, with the exception of the proposal [2] that considers the reduction of energy demand for capacitor placement.

Although the problem of volt-var control for planning purposes could be more complex in terms of combinatorial nature, the operation problem, with CVR and several control devices, gains importance as well due to the need for balanced solutions. This case is to be dealt with multiobjective optimization. So the presented problem is not to be solved easily, and this work will be applied in the NSGA-II algorithm.

### A. CVR

The expression CVR is defined as being the practice of controlling the voltage levels on the network in order to promote a reduction in energy demand, considering that loads in the MV networks are predominantly voltage dependent. It can be considered as a form of demand management, especially in networks with a strong presence of residential and commercial customers. Mathematically, the CVR factor can be defined as follows [3]:

$$\text{CVRf} = \frac{E_{\text{saving}}\%}{\Delta V\%}. \quad (1)$$

This factor can be indicative of the response of the system in terms of total energy savings ($E_{\text{saving}}$) caused by a deliberate reduction of the voltage on the head of the feeder ($\Delta V$), and might be used for comparative studies, but only in cases where the voltage control is made at the head of the feeder.

Many practical applications have produced results with remarkable energy savings, outlining a CVRf up to 2.4 [1], [15], [16], and [17]. Lately, some approaches have sought to include, in these studies, the dynamic load models [3], and to consider the presence of distributed generators [18], showing encouraging results.

Nevertheless, it should be noticed that the percentage of gains depends on the possibilities to perform voltage reduction (initial voltage level sufficiently above the minimum regulatory value, and control devices), and on feeder load characteristics.

### B. Loads on MV Feeders

The loads on MV feeders are usually devices connected through low-voltage distribution transformers, and can be characterized as serving mainly residential, commercial, and industrial consumers. The vast majority of these loads presents voltage-dependent behavior. These devices can be represented by a large number of static and dynamic models, and have received great attention from IEEE and CIGRE task forces in recent years. However, for most studies of MV networks, two static models are highlighted [19]: polynomial (ZIP) and exponential models. In this paper, the exponential model, as shown in (2) and (3), will be considered

$$Pl_i = P_{n,i}\left(\frac{V_i}{V_n}\right)^{k_p} \quad (2)$$

$$Ql_i = Q_{n,i}\left(\frac{V_i}{V_n}\right)^{k_q}. \quad (3)$$

Values for the parameters of the exponential model can be found in some publications [20]. Table I shows a sample, where one can notice that feeders with many commercial customers produce more energy savings (in kilowatt-hours), by the CVR application, than those with a predominance of industrial consumers. But this analysis cannot be so direct when many volt-var control devices are present in the feeder.

TABLE I
VALUES OF $kp$ AND $kq$ FROM [20]

| Loadtype | Kp | Kq |
|---|---|---|
| Residential | 1.04 | 4.19 |
| Commercial | 1.50 | 3.15 |
| Industrial | 0.18 | 6.00 |

## III. PROBLEM FORMULATION AND SOLUTION TECHNIQUE

The volt-var control, using CVR for distribution systems operation, is a nonlinear, mixed-integer, and multiobjective optimization problem with a given number of equality and inequality constraints. The central point is to minimize the energy demanded from the substation, and the voltage deviation on buses of the MV network, considering tap changing in OLTC and AVRs, and capacitor switchings.

### A. Objective Functions

When energy savings by voltage reductions are pursued, the first function to be minimized is active power intake on the distribution system from the substation, as considered in [2]. This power is the active power demand by the loads plus the active losses on lines, both of which are voltage dependent, and then the objective function to be minimized can be written as

$$f_1 = P_{\text{in}} = P_{\text{load}} + P_{\text{loss}} \quad (4)$$

where

$$P_{\text{load}} = \sum_{i \in nb} Pl_i\,(V_i) \quad (5)$$

$$P_{\text{loss}} = \sum_{i \in nb}\sum_{j \in nb} \Delta V_{ij}^2 \frac{r_{ij}}{Z_{ij}^2}. \quad (6)$$

Another function to be minimized is the voltage deviation on buses of the network, and here will be considered a formulation similar to [13], and that is written as (7). This function is fundamental because the best value of voltage is the nominal in all buses

$$f_2 = \frac{1}{nb}\sum_{i \in nb}(1 - \mu_i) \quad (7)$$

where

$$\mu_i = \begin{cases} \frac{V_i - V_{\min}}{V_n - V_{\min}} & \text{if } V_{\min} \le V_i \le V_n \\ \frac{V_{\max} - V_i}{V_{\max} - V_n} & \text{if } V_n \le V_i \le V_{\max} \end{cases}. \quad (8)$$

### B. Constraints

The equality and inequality constraints are necessary to allow the correct operations of all components of the networks. The equalities, mathematically, are represented by the power flow

$$Pg_i - Pl_i - P_i\,(\theta, V, tap) = 0 \quad (9)$$

$$Qg_i - Ql_i + QC_i - Q_i\,(\theta, V, tap) = 0. \quad (10)$$

The inequalities are represented by voltage limits (regulatory voltage quality conditions) on all buses, and power factor limits (technical and economic operational conditions) at the substation of the system, as shown in (11) and (12), respectively

$$V_{\min} \leq V_i \leq V_{\max} \tag{11}$$

$$pf_{\min} \leq pf_{\text{sys}} \leq pf_{\max}. \tag{12}$$

Transformers with tap variables and voltage regulators are devices which may control the output voltage through the load tap-changing mechanism. Hence, these devices can lead to variations of the output voltage in steps ($\Delta tap_i$), values in per unit or percent, with a specified number of tap positions. So the final regulation ratio of these devices may be given by

$$RG_i = 1 - tap_i \Delta tap_i \tag{13}$$

where $tap_i \in \{tap_{\min,i}, \ldots, tap_{\max,i}\}$.

The banks of switched capacitors have adjustments to control the capacity of reactive power injected into the distribution network. They are composed of several modules (with individual capacity $\Delta C_i$) and having a maximum number of steps ($nsw_{\max}$); therefore, they may assume positions in between zero and $nsw_{\max}$. Hence, the power supplied in each condition of operation ($C_i^{sw}$) is given by

$$C_i^{sw} = nsw_i \Delta C_i \tag{14}$$

where $nsw_i \in \{0, 1, 2, \ldots, nsw_{\max,i}\}$.

### C. Solution Technique

The multiobjective algorithm "Elitist Nondominated Sorting Genetic Algorithm – NSGA-II" [7], and [21] was chosen to solve the previous formulated problem. The NSGA-II provides good characteristics of convergence and it is easy to implement and consumes low computational time. Concerning the practical problem under analysis, the use of NSGA-II allows mapping the discrete variables of the set of solutions of the problem through an integer representation. The crossover and mutation operators generate feasible solutions considering the radiality constraint of the distribution electrical power systems.

For a multiobjective problem having $k$ objective functions to be simultaneously minimized, a solution $x$ is said to dominate the other solution $y$ if $x$ is better than $y$ for at least one objective $f_i$ and is not worse for any other $f_j$, where $j = 1, \ldots, k$ and $j \neq i$. The sets of solutions that compose the Pareto frontiers are obtained through this dominance concept.

The algorithm is initialized with a parent population of size $N$ which is randomly generated. This population is sorted according to the nondomination individual levels, classifying in frontiers of nondominated solutions $F_1, F_2, \ldots F_i$ (the sorting is done considering that the smaller the rank of the front, the better the solution). Tournament selection, crossover, and mutation are applied to obtain an offspring population of size $N$ [21].

The selection process used on NSGA-II is based on tournament selection, and incorporates small changes to deal with multiobjective problems. These changes refer to the use of the crowding distance operator (15) during the tournament. This operator calculates the population density around a solution, without requiring predefined parameters, enabling the more dispersed solutions in a specific frontier to be selected, providing greater diversity to the population [21].

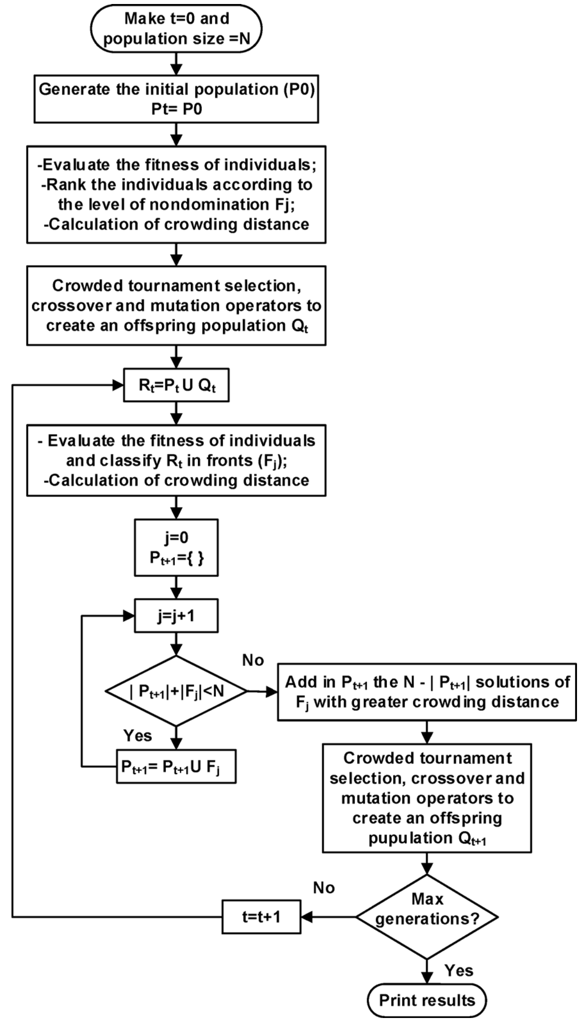


Fig. 1. Main steps of the NSGA-II algorithm.

$$D_{m_i}^{F_j} = \sum_{m \in SO} \frac{f_m^{F_j^{i+1}} - f_m^{F_j^{i-1}}}{f_m^{F_j^{\max}} - f_m^{F_j^{\min}}}. \tag{15}$$

Thereafter, the parent and offspring population are combined to form a population $R_t$ of size $2N$ which is ranked in $F_1, F_2, \ldots F_i$ fronts according to the level of nondomination. Taking into account that $N$ solutions of the current population can be part of the population $P_{t+1}$, $N$ solutions of $R_t$ should be discarded. Thus, the population $P_{t+1}$ is composed of the individuals that belong to the fronts $F_1, F_2, \ldots F_i$ while $|P_{t+1}| + |F_i| < N$. Each set $F_i$ must be placed in its entirety in $|P_{t+1}|$. When inserting a set $F_i$ such that $|F_i| > N - |P_{t+1}|$, only the $N - |P_{t+1}|$ more dispersed solutions $F_i$ should be inserted in the population $P_{t+1}$. Convergence criterion adopted in this paper is based on a predefined number of generations. Fig. 1 illustrates the main steps of the algorithm.

In the solution technique implemented here, the decimal codification was set up, where the chromosome was divided in three

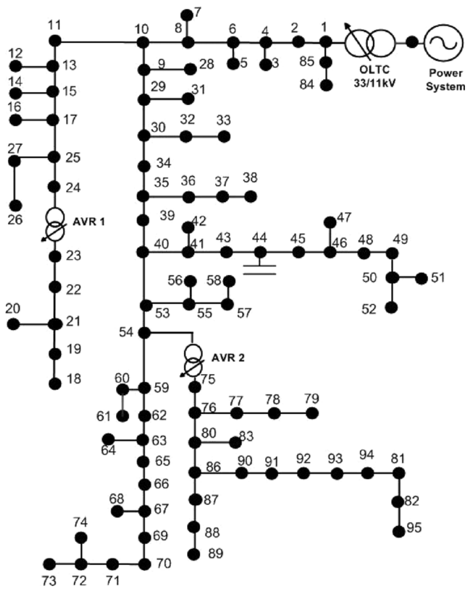


Fig. 2. UKGDS-95 buses system.

TABLE II
LOADS OF THE UKGDS 95 BUSES AT HOUR 19:00

| class | $pf_{sys}$ | $P_{load}$(%) | $Q_{load}$(%) |
|---|---|---|---|
| R/U | 0.90 | 41.08 | 33.19 |
| R/E | 0.95 | 22.38 | 26.65 |
| CO | 0.91 | 25.96 | 29.08 |
| IN | 0.92 | 10.58 | 11.08 |

TABLE III
BASE CASE FOR COMPARATIVE PURPOSES

| Time (h) | OLTC | AVR1 | AVR2 | $nsw_{44}$ |
|---|---|---|---|---|
| 17-20 | 1.05 | 1.05 | 1.05 | 5 |
| 15-16; 21-22 | 1.0375 | 1.05 | 1.05 | 3 |
| 8-14; 23-24 | 1.0125 | 1.05 | 1.05 | 2 |
| 1-7 | 1.0 | 1.0 | 1.0 | 1 |

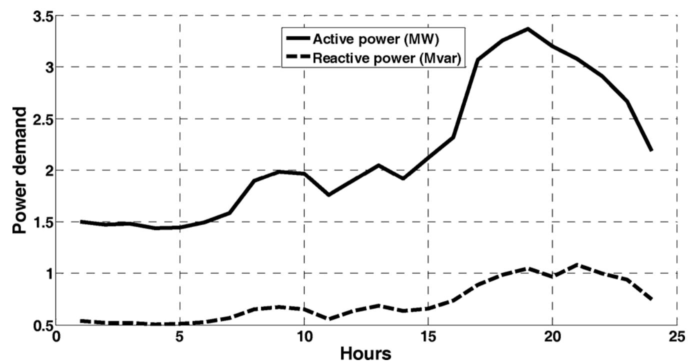


Fig. 3. Daily demand curves for the BASE case.

subsets to represent the capacitor banks, OLTC, and voltage regulator taps.

The crossover and mutation operators are applied independently to the subsets that represent the capacitor banks, OLTC, and voltage regulator taps. The convergence criteria adopted is the maximum number of generations performed by the NSGA-II, avoiding the premature process convergence.

## IV. RESULTS

The results were taken from the UKGDS-95 buses system [22], and the IEEE 34-bus feeder [23]. The data of the IEEE 34-bus feeder do not present any daily demand curves, and then, in this paper, the method of [22] will be used to obtain the load profile of each bus of the system.

### A. UKGDS-95 System

The topology of this distribution system is shown in Fig. 2. The operational limits used for this system were: $V_{\min} = 0.95$ p.u.; $V_{\max} = 1.05$ p.u.; $pf_{\min} = 0.96$; and $pf_{\max} = 0.99$ lag. Notice that the lower voltage limit should include the voltage drop along the distribution transformers, secondary lines, and service drops. In general, the voltage limits are in between $+10\%$ and $-10\%$, as in the U.K. [24] ($+10\%$ and $+6\%$) and in Brazil [25] ($+5$ and $-7\%$).

For the tests performed here, some modifications were done on the original network. Three new loads were added on buses 18, 50, and 95, with an annual maximum power of 135 kW on the commercial class. This maximum power is used for obtaining the daily load profiles for each consumer. A switched capacitor bank was installed at bus 44 with $\Delta C_{44} = 100$ kvar and $nsw_{\max,44} = 6$. Two voltage regulators—AVR1 and AVR2—have been installed, as shown in Fig. 2, both of which have the ability to regulate $\pm 10\%$ of input voltage, with $\Delta tap_{23} = \Delta tap_{75} = 0.00625$ p.u., $tap_{\min,23} = tap_{\min,75} = -16$ e $tap_{\max,23} = tap_{\max,75} = +16$, being that these values are typical for AVRs [26]. The OLTC may regulate $\pm 5\%$ in steps of $\Delta tap_1 = 0.0125$ p.u., with $tap_{\min,1} = -4$ and $tap_{\max,1} = +4$. The distributed generators were not considered in this phase of the research.

Originally, the UKGDS-95 buses system presents unrestricted residential (R/U), economic residential (R/E), commercial (CO), and industrial (IN) consumers, and the main differences between R/U and R/E consumers are the amount of monthly energy usage and the daily demand curve. In addition, in this paper, the loads will be represented by the exponential model with the values $k_p$ and $k_q$ shown in Table I, and the power factor and the participation of each consumer class, at hour 19:00 of a typical day, are shown in Table II.

*1) Base Case:* The base case shown in Table III will be considered, in order to verify the quality of different solutions obtained with the NSGA-II algorithm for the operation of the distribution system.

After the power-flow solutions for this base case, in Fig. 3, the curves of the active and reactive power for this system and the voltage profiles for a typical weekday (Fig. 4) can be observed. The jumps in voltage curves are due to buses being in lateral branches or in the outputs of AVRs.

*2) Set of Nondominated Solutions:* As previously mentioned, the proposal presented here is for the operation phase of the network, with a strategy based on hourly load forecast for the next day/week; then a set of nondominated solutions will be

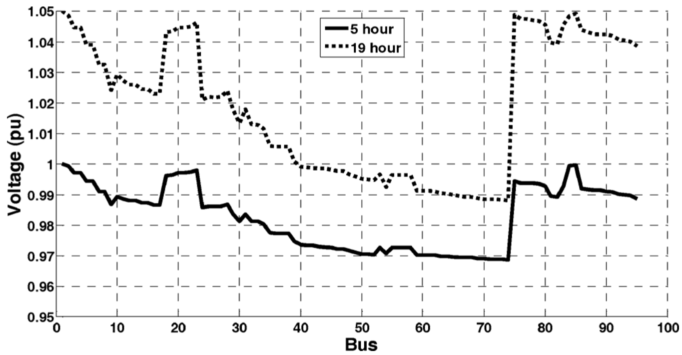


Fig. 4. Voltage profiles for the BASE case at hours 5:00 and 19:00.

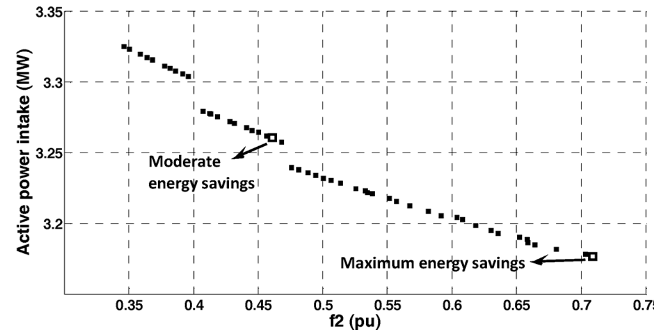


Fig. 5. Nondominated solutions of the Pareto front obtained at hour 19:00.

obtained for each hour of the day. To investigate the effect of the technical and economic benefits and their relation to the voltage quality, the set of nondominated solutions, obtained with the proposed NSGA-II algorithm, will be evaluated. Fig. 5 shows this set of solutions for the peak-load level at hour 19:00. Two solutions are highlighted in the figure for future analysis.

This same set of solutions is also shown in Fig. 6, emphasizing the minimum voltage which arises on at least one bus of the network, and the active power intake on the system.

The voltage profiles of the two solutions pointed out in Fig. 5 are shown in Fig. 7. For the "Maximum energy savings," it is observed that the minimum voltage on the network, at hour 19:00, is 0.9507 p.u. on bus #95; meanwhile, the minimum voltage for the "Moderate energy savings" occurs on bus #74 and reaches 0.9671 p.u.

To facilitate the presentation, the following three types of solutions will be given for the 24-h period:

- MAX—this type of case includes the achievement of a set of nondominated solutions for each hour of the day; then, for each hour, the one with the maximum energy savings is chosen, such as the "Maximum energy savings" solution in Fig. 5. Here, voltages may arise far below the rated ones, as can be seen in Fig. 7, but all voltages are still inside the statutory range (0.95 to 1.05 p.u.) defined for this distribution system.
- MOD—in this case, as in MAX, nondominated solutions are necessary, but now moderate energy savings solutions are looked for. Therefore, for each hour, the solutions utilized will be those placed near the center of the Pareto front, as shown in Fig. 5. These solutions generally show good values of voltage, as can be seen in Fig. 7.
- MIX—here, the solutions of the MAX case are used for the peak-load period (17 to 20 h) and the MOD solutions for the remainder of the day.

*3) Energy Savings:* The energy savings that can be achieved during one day are shown in Fig. 8, where the $P_{in}$ curves for the BASE, MOD, and MAX cases are drawn. It is worth noting that the optimal solutions for the MAX case produce 4.55% of energy savings during the 24-h period. It should also be added that voltage reduction does not compromise the supply quality for any consumers.

The solutions of the MAX case in Fig. 8 have a relevant economic benefit on energy savings for a specific period of time or for the entire day.

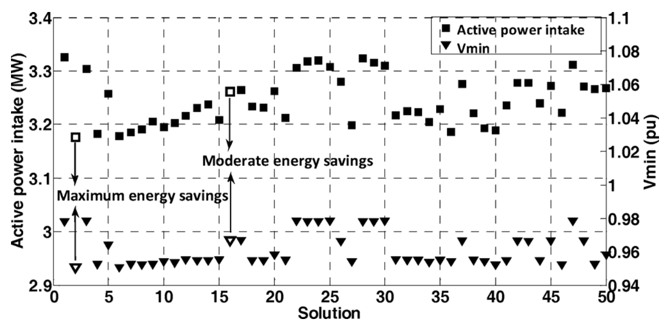


Fig. 6. Active power intake and minimum voltage on the network for the solutions of Fig. 5.

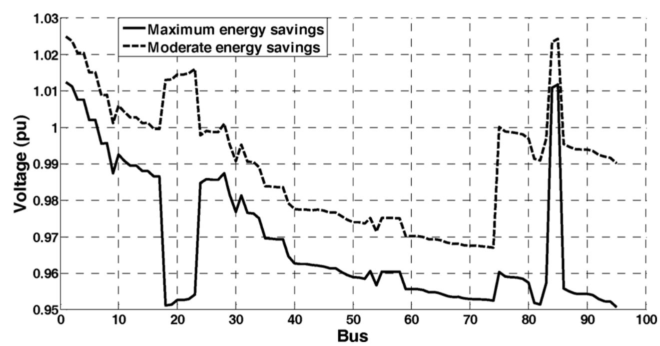


Fig. 7. Voltage profile for the "Maximum energy savings" and "Moderate energy savings" solutions at hour 19:00.

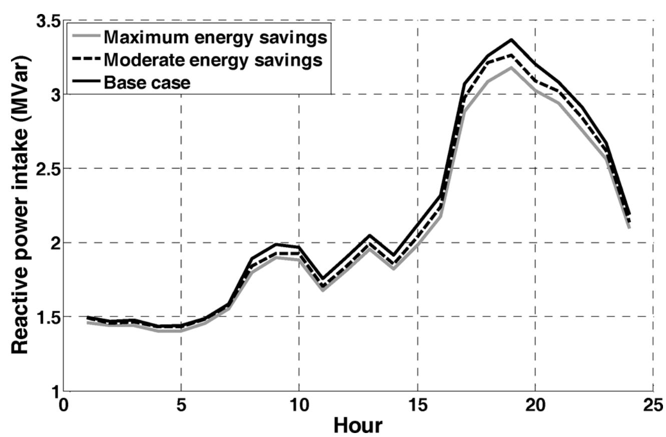


Fig. 8. Active power intake profiles for BASE, MOD, and MAX cases.

However, in other instances, one may wish for less aggressive solutions in terms of energy savings, or in voltage reduction,

TABLE IV
SUMMARY FOR THE 24-h PERIOD

| cases | BASE | MOD | MAX | MIX |
|---|---|---|---|---|
| *Energy*(MWh) | 52.02 | 50.84 | 49.66 | 50.46 |
| *Loss* (kWh) | 1219.24 | 1181.56 | 1162.52 | 1176.07 |
| *Vmim*(pu) | 0.9570 | 0.9651 | 0.9501 | 0.9501 |
| $pf_{min}$ | 0.9418 | 0.9705 | 0.9665 | 0.9665 |
| $\Delta Energy$(%) | - | 2.28 | 4.55 | 3.00 |
| $\Delta Loss$(%) | - | 3.09 | 4.65 | 3.54 |

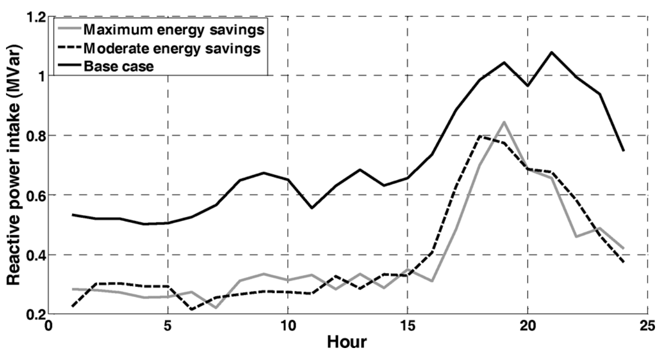


Fig. 9. Reactive power intake profiles for the BASE, MOD, and MAX cases.

TABLE V
TAP POSITIONS OF THE DEVICES AT HOUR 19:00

| cases | BASE | MOD | MAX |
|---|---|---|---|
| OLTC | 4 | 2 | 1 |
| AVR1 | 4 | 3 | -5 |
| AVR2 | 9 | 5 | 1 |
| $nsw_{44}$ | 5 | 6 | 4 |

such as the "Moderate energy savings" in Fig. 5 and, thus, such solutions can be found, as shown in the $P_{\text{in}}$ profiles for the MOD case in Fig. 8. Now, an energy savings of 2.28% during the 24 h can be observed, but with less voltage reduction than in the MAX case.

The performance of the MAX, MOD, and MIX solutions, for energy savings, is summarized in Table IV, showing that, besides the energy savings, the loss reduction and the control of the power factor can be seen as important advantages as well.

*4) MVA Peak-Load Relief:* The load profiles described in Fig. 8 shows the active power peak reduction, that is, 5.62% and 3.11%, respectively, for the MAX and MOD cases at hour 19:00.

Even though these gains are significant, it is also important to observe the behavior of reactive power intake, and then to compute the MVA peak-load relief. Therefore, Fig. 9 shows the reactive load profiles for the MAX, MOD, and BASE cases, and Table V describes the number of capacitors in operation at hour 19:00.

The solutions of the MAX case in Fig. 9 have positive technical benefits to decrease the reactive peak-load level; for example, a remarkable reduction of 19.23% is obtained at hour 19:00. It should be noted that at hour 19:00, in the BASE case, the capacitor bank is injecting 500 kvar; meanwhile, in the MAX, only 400 kvar is being injected. This means that the reduction of the reactive peak-load level is due solely to the load reduction provoked by the voltage variations; and this high reduction, in relation to active power, can be explained

TABLE VI
SUMMARY OF THE SOLUTIONS AT HOUR 19:00

| cases | BASE | MOD | MAX/MIX |
|---|---|---|---|
| $P_{in}$(MW) | 3.36 | 3.26 | 3.18 |
| $Q_{in}$(Mvar) | 1.04 | 0.77 | 0.84 |
| $S_{in}$(MVA) | 3.52 | 3.35 | 3.29 |
| $P_{loss}$(kW) | 104.37 | 101.85 | 100.59 |
| *Vmim*(pu) | 0.9882 | 0.9671 | 0.9507 |
| $pf_{sys}$ | 0.9551 | 0.9730 | 0.9665 |
| $\Delta P_{in}$(%) | - | 3.11 | 5.62 |
| $\Delta Q_{in}$(%) | - | 25.96 | 19.23 |
| $\Delta S_{in}$(%) | - | 4.90 | 6.73 |
| $\Delta P_{loss}$(%) | - | 2.42 | 3.63 |

TABLE VII
LOADS OF THE IEEE 34-BUS FEEDER AT HOUR 19:00

| class | $pf_{sys}$ | $P_{load}$(%) | $Q_{load}$(%) |
|---|---|---|---|
| PQ | 0.92 | 32.93 | 30.82 |
| I | 0.90 | 32.30 | 34.37 |
| Z | 0.91 | 34.77 | 34.81 |

by the load model adopted. In Table I, it can be seen that the maximum value of $k_p$ is 1.5, whereas $k_q$ can reach up to 6.0.

Similar performance can be observed for the MOD case, as illustrated in Fig. 9, showing a reduction of 25.96% at hour 19:00.

The performance of the MAX, MOD, and MIX solutions, for peak-load relief, are summarized in Table VI, highlighting up to 6.73% on MVA peak-load alleviation.

### *B. IEEE 34-Bus Feeder*

The topology of this distribution system and the data can be seen in [23]. Here, it was considered it to be an equivalent single-phase network, and the operational limits used for this system were $V_{\min} = 0.95$ p.u.; $V_{\max} = 1.05$ p.u..; $pf_{\min} = 0.96$; and $pf_{\max} = 0.99$ lag.

The OLTC and the two AVRs of the system present the same characteristics of the devices of the UKGDS-95. A switched capacitor bank was considered at bus 844 with $\Delta C_{44} = 100$ kvar and $nsw_{\max,44} = 7$. The IEEE 34-bus feeder presents consumers with constant power (PQ), constant current (I), and constant impedance (Z) loads. Then, the loads will be represented by the exponential model with the values $k_p$ and $k_q$ being zero, one, and two for the PQ, I, and Z load types, respectively. The power factor and the participation of each consumer class, at hour 19:00 of a typical day, are shown in Table VII. The daily load curves were obtained in the same way as for the UGKDS95 system.

Since the IEEE 34-bus feeder presents a nearly 67% Z and I load model, then the energy savings and the peak-load relief are substantial, as can be seen in Figs. 10 and Table VIII. The same values of Table III were applied in this base case for this system as well.

### *C. Final Remarks*

Considering the previous results, the decision maker can choose a solution in order to meet a specific objective of a particular period. For example, if the proposal is a reduction around 6% in the peak demand (MVA) for the UKGDS-95, then he/she can choose the MAX solution of Table VI, but if

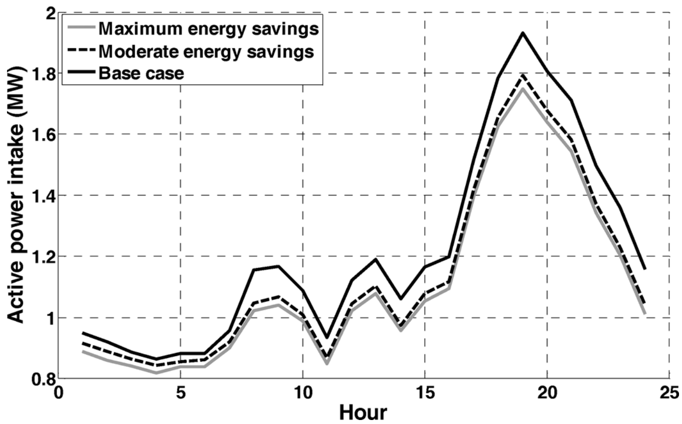


Fig. 10. Active power intake profiles for BASE, MOD, and MAX cases with the IEEE 34-bus feeder.

TABLE VIII
SUMMARY OF THE SOLUTIONS FOR THE IEEE 34-BUS FEEDER AT HOUR 19:00

| cases | BASE | MOD | MAX/MIX |
|---|---|---|---|
| $P_{in}$(MW) | 1.93 | 1.79 | 1.75 |
| $Q_{in}$(Mvar) | 0.41 | 0.35 | 0.33 |
| $S_{in}$(MVA) | 1.98 | 1.83 | 1.78 |
| $P_{loss}$(kW) | 177.28 | 168.91 | 166.10 |
| $Vmim$(pu) | 1.0035 | 0.9792 | 0.9502 |
| $pf_{sys}$ | 0.978 | 0.9818 | 0.9831 |
| $\Delta P_{in}$(%) | - | 7.25 | 9.33 |
| $\Delta Q_{in}$(%) | - | 14.63 | 19.51 |
| $\Delta S_{in}$(%) | - | 7.58 | 10.10 |
| $\Delta P_{loss}$(%) | - | 4.72 | 6.31 |

TABLE IX
RANGE OF TAP CHANGE DURING A 24-h PERIOD FOR UKGDS-95

| cases | BASE | MOD | MAX | MIX |
|---|---|---|---|---|
| OLTC | 0 to 4 | 0 to 3 | -1 to 1 | 0 to 2 |
| AVR1 | 2 to 9 | -4 to 3 | -5 to 2 | -5 to 3 |
| AVR2 | 4 to 13 | 1 to 7 | -1 to 3 | 0 to 5 |
| $nsw_{44}$ | 1to 5 | 3 to 6 | 3 to 6 | 3 to 6 |

the goal is to save about 3% of the daily energy (MWh), then the best choice is the MIX solution of Table IV.

Also, it is interesting to observe the behavior of the tap variations in Table IX: in the MAX case, the OLTC tap has taken on three different positions over the day: the AVR1 tap 8, the AVR2 tap 5, and the capacitor 4 positions, showing smooth changes. Similar behavior occurs with the MOD and MIX cases.

However, it should be highlighted that solutions with few tap changes are important to avoid damage to devices and oscillations in the network, and that this may be explored by splitting the daily load duration curve into four or five levels, instead of the 24 levels used here. This kind of solution is likely to be a bit less effective in terms of the 24-h period energy savings, but still can preserve the same performance for peak-load relief and savings; so it may obtain smoother curves for reactive power than the solutions in Fig. 10 for example.

In the tests taken in the previous subsections, the stopping criterion of the algorithm used was a maximum of 50 generations. The population size is set at 50 individuals, and a single point of recombination was adopted with an initial recombination rate of 0.7 and an initial mutation rate of 0.05. The average CPU processing time was 30.5 s, for the solution of each hour with the UKGDS-95 system, using a MATLAB code on a computer with processor Intel Core i5, running at 2.5 GHz, and with 4 GB of RAM.

## V. CONCLUSION

This paper has presented integrated volt-var control via multiobjective optimization solutions for distribution network operation, giving a different approach to the problem and a view of advantages and possible applications. The objective functions to be minimized were the active power intake on the system and the voltage deviation, and the results were a set of nondominated solutions suitable to be applied to prioritize a targeted objective or to meet a balanced application. The mathematical formulation was made in such way that other optimization techniques may be used to solve this multiobjective problem, and other load models may be added without significant changes to the central point of the proposal.

The obtained solutions described positive economic and technical benefits showing significant values of energy savings for a typical day of operation, and peak-load relief that is important for the distribution and transmission system. In addition, these advantages are obtained while maintaining the supply voltage quality for all consumers. Other important gains can be noted in the reduction of power losses and the maintenance of the power factor within a specified range.

The authors are currently pursuing additional distributed generators, batteries, and others for this problem setting. Now the range of control variables could be complex and nondeterministic, including DGs with or without the capacity of inject and absorb reactive power, and conventional or intermittent DG units. Then a strategy based on an hourly generation forecast for the next day/week. ill be required, along with DG control.

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