A Challenge in the Operation of Distribution Smart Grids: The Global Optimization

B. Tomoiagă and M. Chindriş

Abstract--**Modern power systems are in the process of entering in a new stage of development where will be fundamentally different from classical ones, which implies new challenges and approaches. By carrying out of command, control, protection, automation, metering and power quality monitoring complex systems, the prerequisites for an electricity distribution network to become intelligent ("smart grid") are created. However, a set of issues remains related to how such an infrastructure is used in order to maximize consumer supply safety, minimize losses of active power, optimize power quality indices etc. The central idea is that a "smart grid" must be an optimized network. In this paper, the authors present their vision on the issue of optimizing the operation of an electric distribution network.**

Index Terms-- **smart grids, multi objective optimization, Pareto optimality, genetic algorithms, power quality, artificial intelligence.**

I. NOMENCLATURE

ΔP – active power losses
E – set of system lines (branches)
X – set of system nodes
V_i – nodes voltages
V_{ni} – "nominal voltage" or "declared supply voltage" (established through an agreement between the supplier and the customer)
ε_{V_i} – voltage deviation
I_{ij} – electric current through the branch *ij*
R_{ij} – electric resistance of the branch *ij*
α_{ij} – binary variable, representing the status of a tie line (*0* – open, *1* - closed)
k^- – asymmetry (non-symmetry) factor
THD – total harmonic distortion

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B. Tomoiagă is with the Technical University of Cluj-Napoca, 400020 Cluj-Napoca, România (e-mail: bogdan.tomoiaga@eps.utcluj.ro).

M. Chindriş is with the Department of Power Systems, Technical University of Cluj-Napoca, 400020 Cluj-Napoca, România (e-mail: mircea.chindris@eps.utcluj.ro).

II. INTRODUCTION

MODERN power systems are in the process of entering in a new stage of development where will be fundamentally different from classical ones, which implies new challenges and approaches.

A direction that tends to substantially change the power distribution systems behavior is the wide appearance of distributed generation based on renewable resources (small hydro power plants, photovoltaic cells, wind turbines etc.). Thus, the development of these sources, with low powers but high levels of penetration and dispersion, is encouraged worldwide. The existence of distributed generation has major implications for the power distribution systems, transforming them from passive into active systems.

Another important implication is the emergence and implementation of digital multi-functional relays. We are witnessing a phenomenon of replacing conventional protective relays with multi-functional relays, featuring a wide variety of embedded functions:

- Protection and automation functions: instantaneous and time delayed overcurrent protection, instantaneous and time delayed neutral overcurrent protection, directional earth-fault protection, time delayed overvoltage, autoreclosing etc.;
- Non protection functions: fault locator, event and fault recorder, disturbance recorder etc.;
- Measurement functions: voltages, currents, powers, energies etc.);
- Equipment command and control.

Basically, by using these relays and placing them in communication systems, we witness the development of advanced command, control, protection and automation (and data acquisition) complex systems.

Power distribution systems operation in an open electricity market requires measuring transformers and/or transducers, and intelligent measuring devices with special classes of accuracy. By introducing intelligent measuring devices in communications systems, smart metering systems are obtained.

Another direction which is also one of the most important is related to power quality problems: continuity in power supply, voltage deviation etc. As a result, monitoring power quality systems have to be implemented.

Taking into account these considerations, by carrying out command, control, protection, automation, metering and power quality monitoring complex systems, the prerequisites for a power distribution network to become intelligent ("smart grid") are created. The most important problem is how to use such infrastructures in order to minimize active power losses, maximize consumer's supply safety etc. The central idea is that *a "smart grid" must be an optimized system*.

In this paper, authors present their vision on the problem of optimizing in the operation of a modern electric distribution network. The issue raised is referred to the scientific community to find more complete and better solutions (in accordance with [1]).

III. CRITERIA FOR OPTIMIZATION

A. Active Power Losses (ΔP)

For balanced and sinusoidal regimes, the active power losses (Joule-Lenz) can be calculated considering the following relationship:

$$\Delta P = \sum_{ij \in E} 3 \cdot R_{ij} \cdot I_{ij}^2 \cdot \alpha_{ij} \tag{1}$$

To evaluate this criterion, it is necessary to perform the power flow calculus; in radial electric systems, a specific method named backward - forward can be used [2]. For more accuracy, it is possible to assume the unbalanced and harmonic polluted regime using the algorithms presented in [3, 4]. In this case, the relationship (1) becomes as follows:

$$\Delta P = \sum_{ij \in E} \sum_{p=1}^{4} \left(\sum_{n=1}^{50} R_{ijn} \cdot I_{ijn}^2 \right) \cdot \alpha_{ij} \tag{2}$$

where: n – number of harmonic components; p – phase number (three active phases and neutral conductor, if it exists);

B. Nodes Voltages

Basically, each voltage r.m.s. value (V_i) of the network nodes must be framed within the allowable limits:

$$V_i^{\min} \le V_i \le V_i^{\max}; \forall i \in X \tag{3}$$

The limits of variation of voltages are in close accordance with the following power quality indices:

1) Voltage deviation: Is defined by the following expression (in stationary regime):

$$\varepsilon_{V\,\mathrm{i}} = \frac{V_i - V_{ni}}{V_{ni}} \tag{4}$$

Typically, $\varepsilon_{V\,\mathrm{i}} \in [-0.1,\ 0.1]$ is considered acceptable (for distribution systems) and the ideal value of $\varepsilon_{V\,\mathrm{i}}$ is zero. Else, in a power system node, we will have [5]:

- $\varepsilon_{V\,\mathrm{i}} > 0.1$: overvoltage (swell);
- $\varepsilon_{V\,\mathrm{i}} \in [-0.9,\ -0.1)$: undervoltage (dip);
- $\varepsilon_{V\,\mathrm{i}} \in [-1,\ -0.9)$: interruption.

2) *Voltage unbalance:* Voltage unbalance, among others, may lead to breaking the allowable limits of deviation on some nodes of the network (and additional losses of active power). The main indices that define the system unbalance are:

a) Unbalance factor

$$k_{V\,\mathrm{i}}^{-} = \frac{V_i^{-}}{V_i^{+}} \tag{5}$$

b) Asymmetry (non-symmetry) factor

$$k_{V\,\mathrm{i}}^{0} = \frac{V_i^{0}}{V_i^{+}} \tag{6}$$

The index $k_{V\mathrm{i}}^{-}$, in general, must not exceed 0.02 [5] and the ideal value is zero.

3) Voltage waveform distortion

Among other negative consequences (additional losses of active power, further movement of the neutral currents), this can lead to breaking the allowable limits of voltages. The most important indices for non-sinusoidal voltages are:

a) Total harmonic distortion

$$THD_{Vi}^{f} = \frac{V_{Di}^{f}}{V_{1i}^{f}} \tag{7}$$

where: V_{1i}^{f} represents the fundamental harmonic component of voltage in node i (for phase f) and V_{Di}^{f} is the dross for phase f:

$$V_{Di}^{f} = \sqrt{\sum_{h=2}^{n} | V_h^f |^2} \quad n = \{40{,}50\} \tag{8}$$

In common existing norms, this index (THD_{Vi}^{f}) must be smaller or equal than *0.08* [6] and the ideal value is zero.

b) Harmonic weight (level)

$$\gamma_{Vi\,\mathrm{h}}^{f} = \frac{V_{i\ h}^{f}}{V_{1i}^{f}} \tag{9}$$

where h represents the harmonic order.

The ideal value of this index is zero for each harmonic order (except the fundamental harmonic order) and there are more norms that impose limits (superior limits) for each harmonic order. Table I presents some limits required by [6]:

TABLE I
INDICATIVE VALUES OF PLANNING LEVELS FOR HARMONIC VOLTAGES

Harmonic order *h*	**Harmonic voltage weight**	
	MV	***HV - EHV***
2	0.018	0.014
3	0.04	0.02

Harmonic order *h*	Harmonic voltage weight	
	MV	*HV - EHV*
4	0.01	0.008
5	0.05	0.02
7	0.04	0.02
…	…	…

C. Reliability of the Electric System

The essential attributes of interruptions in the power supply of the customers are the frequency and the duration. While durations are predominantly influenced by the electrical system structure and the existent automations, the frequency is mainly influenced by the adopted working scheme; they can be minimized by the suitable choice of operation scheme. The reliability of a system can be considered from two different angles:

- *that of a particular customer:* average number of interruptions in the power supply, MTBF (mean time between failures), etc. These indices can represent possible objectives and/or constraints in the optimization problem (because some customers can impose maximal/minimal limits in the supply contracts);
- *that of the entire supply network:* in this case, the authors propose to consider the system average interruption frequency index (SAIFI), defined as: Total number of customer interruptions (longer than 3 minutes)/Total number of customers served [7].

D. Configuration of the System

Generally, electrical distribution systems are operated in radial configurations. This condition can be expressed as follows:

$$\sum_{ij \in E} \alpha_{ij} = n - p \tag{10}$$

where n is the number of nodes in the electric system and p is the number of connected components. In graphs theory terms, for a system with one source ($p = 1$) we talk about an optimal tree and for a system with more feeders ($p > 1$) we talk about an optimal forest with a number of trees (connected components) equal to that of source nodes.

E. Branch Load Limits through Lines

$$I_{ij} \le I_{\max, ij} ; \forall ij \in E \tag{11}$$

IV. MULTI OBJECTIVE OPTIMIZATION

The presented criteria are not unique but we consider that are the most important. Taking into account these criteria we can view the real dimension of the problem: “global optimization in operation” of an electric distribution network. A synthesis of the presented criteria is given in Table II.

The presented criteria (Table II) can be grouped in two different categories:

- *objective functions:* criteria that must be minimized;
- *constraints (restrictions)*: criteria that must be included within some bounds.

These criteria are incompatible from the point of view of measure units and often they are conflicting criteria. Moreover, some criteria can be (or it is important for them to be) modeled, at the same time, objectives and constraints. For instance, the *ΔP* criterion must be minimized but we can impose at the same time a maximal acceptable value (constraint). The problem is very large and in order to solve them, first of all, we must find the proper model.

TABLE II
CRITERIA CONSIDERED IN THE OPTIMIZATION PROBLEM

Concer-ning	Criteria	Objec-tive	Cons-traint	Ig-nore
System	ΔP (active power losses)	X	X	-
	SAIFI (system average interruption frequency index)	X	X	X
Nodes	Voltage deviation	X	X	-
	Number of interruptions	X	X	-
	MTBF (mean time between failures)	X	X	X
Branches	Loads limits through lines	-	X	-

A. General Aspects of Multi Objective Optimization

As previously stated, the optimization issue represents a *multi objective optimization problem*.

1) Classical methods

Different solutions for defining multi objective optimization problems can be found in the literature; among them, the most frequently used ones are:

a) *The main objective method (ε-constraint):* Frequently applied in the distribution systems optimization problems (e.g. through reconfiguration), which tries to solve the problem as follows: a main criterion is chosen, concomitantly indicating acceptable values for the other criteria. This approach has a major inconvenience because there are a lot of indices that must be taken into account in the optimization process and, without prior information about different criteria, choosing the acceptable value can be problematic. Anyway, this approach alters the essence of the original technical problem.

b) *The conversion of multi-objective problem to a single objective one (which assumes a sum, weighted or not, of the selected objective functions):* The major difficulty in this kind of problems consists in the incompatibility of different criteria. To create a global function, all criteria must be converted to the same measurement unit; a frequently used method is to convert them into costs (usually, a tricky and often inaccurate operation). In addition, subjectivity appears, caused by the introduction of weighting factors for different criteria.

2) Pareto optimality

The existence of a model that could take into account more objective functions (and constraints) at the same time is of great interest. Thus, we can use the *Pareto optimality* concept, that defines a dominate relation among solutions. In Pareto optimization, the central concept is named *un-dominated solution*. This solution must satisfy the following two conditions:

- there is no other solution that is superior at least in one objective function;
- it is equal or superior with respect to other objective function values.

Usually, the solution is not unique and consists of a set of acceptable optimal solutions (Pareto-optimal). The set of Pareto solutions form the *Pareto-front* associated to a problem. The Pareto-front allows making an informed decision by seeing an extensive range of options since it contains the solutions that are optimum from an overall standpoint.

B. Multi Objective Optimization in the Operation of an Electric Distribution Network

As a Pareto optimal multi objective problem, we propose the following form:

1) Objective function:

$$\min\{\Delta P, k^{-}_{V_i}, THD^{f}_{Vi}, \gamma^{f}_{Vi\,h}, \ldots, SAIFI, \ldots\} \quad (12)$$

where $i = \overline{1, X}$, $f = A, B, C$ and $h = \overline{1, 40}$.

2) Constraints

$$-0.1 \le \varepsilon_{V_i} \le 0.1 \quad (13)$$

$$k^{-}_{V_i} \le 0.02 \quad (14)$$

$$THD^{f}_{Vi} \le 0.08 \quad (15)$$

$$\begin{aligned} \gamma^{f}_{Vi2} &\le 0.018 \\ \gamma^{f}_{Vi3} &\le 0.04 \\ &\ldots \end{aligned} \quad (16)$$

$$I_{ij} \le I_{\max, ij}; \forall ij \in E \quad (17)$$

$$\sum_{ij \in E} \alpha_{ij} = n - p \quad (18)$$

C. Methods for Problem Solving

The most important technical measures which can improve the performance in the operation of a distribution system are:

- *reconfiguration of the system*, exchanging the functioning links between its elements. Since 1975, when Merlin and Back [8] have introduced the concept of distribution system reconfiguration for power loss reduction, till nowadays a lot of researchers have proposed diverse methods and algorithms to solve the reconfiguration problem [9];
- *variation (and control) of the voltage* by using on-load taps changers at power transformers;
- *variation (and control) of the reactive power flow through the network*;
- *changing of the operating scheme of the parallel connected power transformers* etc.

A very important aspect consists in the expected proactive behavior of sources and consumers in smart grids. *Having such a difficult problem and such a large set of tools, the major question is: How can we solve this problem?*

Electrical distribution systems are operated in radial configurations; as a result, *the utility must find the optimal solution by searching from a vast set of possible solutions* (the set of trees of the graph attached to the network, etc.). On the other hand, the optimization problem is one of the *multi objective optimization* types, where the solution is chosen after the evaluation of some indices, named partial criteria (e.g. active power losses, reliability, branches load limits, voltage drops limits, etc.), which represent multiple purposes. Taking into account these considerations, we can observe the fact that *this problem is difficult particularly from two points of view*:

- *the formulation of the problem*, because there is more than one objective;
- *the searching for the solution*, because of the prohibitive execution time demanded by applying an absolute method (which generates the entire space of candidate solutions in order to choose the best one).

The literature presents a lot of proposed methods to solve optimization problems. Due to the combinatorial nature of the question, most of them are based on different heuristic or meta-heuristic (branch exchange, branch and bound, simulated annealing, etc.). On the other hand, some authors have developed methods based on evolutionary computation techniques, particularly on genetic algorithms. In the case of multi-objective problems, literature proposes several Pareto-based genetic algorithms:

- MOGA - Multi Objective Genetic Algorithm [10];
- NPGA - Niched Pareto Genetic Algorithm [11];
- SPEA (SPEA-II) - Strength Pareto Evolutionary Algorithm [12];
- NSGA (NSGA-II) - Non-dominated Sorting Genetic Algorithm [13].

After many experimental simulations, the authors have to solve *the multi-objective optimization problem through reconfiguration* by using the NSGA-II algorithm with significant results (optimal solutions in a short time). The results are presented in [9]. The entire problem remains a challenge for the scientific community. An important question is the following: *how can one solve such a complex problem by applying artificial intelligence methods, in order to obtain a global optimum*?

V. CONCLUSIONS

The prerequisites of modern electric networks to become intelligent ("smart grid"), by carrying out of command, control, protection, automation, metering and power quality monitoring complex systems, are created. One of the most important questions for authors is: how is such infrastructure used in order to optimize the performance indices in the operation of such electric distribution networks?

In this paper, the authors have synthesized the criteria that should be optimized, proposed a general optimization problem formulation and pointed out possible ways to solve it. The paper is intended to be the first step in a series of studies and research on optimizing the operation of intelligent electric networks. However, the problem stated here is also considered a challenge to the scientific community in order to find out the proper solutions.

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