Optimal Shedding Against Voltage Collapse Based on Genetic Algorithm

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Abstract-The prevalent tendency in power transmission systems is to operate closer and closer to the energy limit, rendering system voltage instability a commonly widespread phenomenon. It is, therefore, necessary that certain remedial corrective controls need be undertaken whenever these systems tend towards failure. In this respect, load shedding stands as a major correction mechanism and such a failure can be prevented and nominal system voltage can be resumed. It is worth noting however that load shedding must be implemented very carefully to ensure the satisfaction of both the customer and the electricity-production company. In this context, our focus of interest is laid on load and machine shedding against voltage collapse as an effective corrective method. It is important to note that such a problem turns out to be commonly defined as an optimization problem under constraints. Using genetic algorithms as resolution methods, the application of the proposed methods was implemented on the 14-node IEEE test network, while considering a number of different case studies.

Keywords-power transmission; load and machine shedding; voltage collapse; genetic algorithm; 14-node IEEE test network

I. INTRODUCTION

Electric power plays a crucial role in almost every domain, particularly lighting, communication, and transportation. However, electricity production and transmission are not without serious hazards, likely to disrupt their normal operation and continuity. Actually, numerous disturbances are known to take place worldwide every year, often resulting in noticeable blackouts. Large-scale blackouts, though very rare to occur, could cause huge losses and severe damages to the society and the economy. In this respect, the electrical grid might well undergo or experience a severe voltage collapse phenomenon, bringing about serious consequences [1]. Such a phenomenon often finds its origin in unexpected cascades of events, causing sudden voltage drops, usually leaving little time, often just a few minutes, for the necessary protective measures to be implemented. Hence, the voltage stability margins are assigned even a greater effective role to meet market needs [2-5].

The inherent difficulties in analyzing the various voltage collapse associated problems result primarily from the more or less non-linear behavior of the electrical grid various components. In this regard, the incident cases reported to take place over the past few decades prove that most of the voltage collapse problems have been recorded to occur after a significant disturbance or sudden increase in the electrical grid load, wherein the latter turns out to be weakened and its reactive consumption increased. Accordingly, the phenomenon is characterized with a gradual voltage decrease in one or more consuming regions, immediately accelerating within a few minutes. Hence, the voltage degradation, at the load level, turns out to be so significant that it leads to service interruptions, culminating directly in increased reactive grid losses and voltage drops as major outcomes. Failure in voltage regulation, at the group terminal level, engenders an acceleration of the voltage plane degradation, likely to culminate in cascade tripping, of groups and lines, as well as voltage collapse of the general electricity network. Such faults could well affect the

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power converters' operation, bringing about a total shutdown of the entire electrical production chain [6-9].

The electricity companies usually charge the transmitted energy to the consumer per MWh, while aspiring for an optimization of the production cost. Accordingly, each of the generators' and plants' performance and contribution must be determined in such a way as to ensure the effective minimization of power producing cost throughout the power system operation process. In effect, the evolution in electrical energy consumption has resulted in significant increases in power transportation and generating costs, hence the importance of an efficient strategy aiming at minimizing the electrical energy exploitation and generation costs. The environmental impact of such processes turns out to be increasingly important and seriously considered when developing the electricity power production and transmission procedures. To achieve these goals, several optimization methods and strategies have been applied [10-11]. The classic methods would serve to solve the single-objective optimization problem (production cost optimization) whereas the most efficient generator supplied grid would not be useful. These methods were designed to obtain voltages in the necessary boundary zones reliable enough to ensure that the grid would remain in an operating point, far from a voltage collapse level, with maintained stability. In [12], for instance, the authors proposed a method in which the determination of the load shedding localization relies heavily on the two buses' phase angle sensitivity. More recently, however, several researchers have developed distinct load shedding methods, enabling to adjust the frequency and voltage within the required or demanded limits while reducing the amount of load shedding [13-18].

In the present paper, we opted for the genetic-algorithm methods which are suitable for treating a single-objective optimization problem. Noteworthy, this field of interest is very dynamic and is still exhibiting continuous development. Accordingly, the study's major objective is focused on applying these optimization methods through implementing genetic algorithms for optimal load and machine shedding against voltage collapses. Hence, to ensure the system's continuity within the available permitted limits while maintaining minimum production cost, two distinct shedding modes are envisaged, namely load shedding and machine shedding. In this context, the choice of the appropriate shedding scheme rests exclusively on the computation of the limit's required power. To this end, a test is administered on the load distribution program to set the limit's value. The process implementation procedure was conducted via the IEEE 14-node standard test network.

II. Shedding Against Voltage Collapse

With regard to the permanent mode, the study of voltage collapse provides a solution to the magnitudes of an electrical grid in normal balanced operation. In this respect, the relevant quantities involve the voltages, the node injected powers as well as the line flowing power, and the relevant currents and losses are deduced therefrom. Voltage drops accompany the power transfer between the consumption and the production points, under normal operating conditions. These drops are usually of a small percentage of the normal voltage. Actually, voltage collapse is most often due to increased load, lack of reactive power and/or short circuit. In effect, the process of shedding against voltage collapse depends on the knowledge of the required power limit value. At this level, an electrical grid is considered to be stable, from a voltage point of view, once each node's respective voltages are set within the allowable limit. In the load-distribution scheme, the power required is gradually increased until exceeding the admissible voltage limits. In this case, the associated power value is dubbed as the demanded limit power. It is in terms of the PD value (the demanded power) that the fit shedding type can be actually defined. Accordingly, for a PD greater than the demanded limit power (pdlim), the load shedding process is carried out, and, inversely, however, machine shedding is affected. Figure 1 illustrates the way the appropriate shedding type can be selected against voltage collapse.

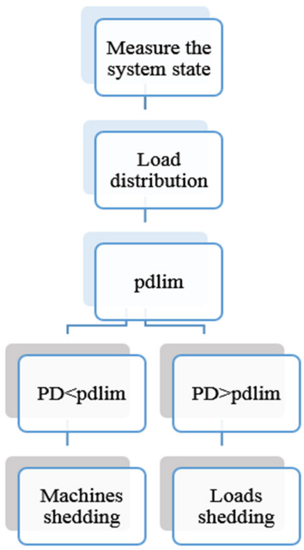

Fig. 1. Shedding type.

III. Formulation of the Genetic Algorithm Based Optimal Shedding Problem

The loads' and generators' optimal shedding with static constraints takes into account the nodes' voltage limits, the lines' powers transmitted, and the generators' outputs. In our problem formulation, two objective functions persist, one related to the loads, while the other deals with machines.

A. Loads and Machines' Shedding Objective Functions

The objective function, relevant to the load nodes to be minimized is:

$$F(x) = \sum_{i=1}^{nl} (C_{ti}\, \lambda_i) \quad (1)$$

where C_{ti} denotes the load shedding cost at node *I*, λ_{ti} stands for the load-shedding factor at node *I*, and *nl* designates the number of consuming nodes. The loads' associated cost is fixed ahead in accordance with the nodes' importance.

As for the generator node related objective cost function, it is formulated in the form of a generated power function, as illustrated through the following equation:

$$f(x) = \sum_{i=0}^{Ng}(a_i + b_i\, pg_i + c_i\, pg_i^2) \quad (2)$$

where Ng designates the number of generators, pg_i stands for the generated power, and a_i, b_i and c_i are the generated powers' relevant coefficients.

This problem type involves special control variables to be defined subsequently. Control variables designate the problem-associated input variables, likely to be adjusted to optimize the loads' and machines' objective functions as well as the constraints' adjustment. These variables are of the form: $x = \{v_i,\ P_i \text{ and } \lambda_i\}$, where v_i represents the voltage at node *i*, P_i denotes the active power at node *i*, and λ_i designates the shedding factor at node *i*.

B. Constraints

1) Equality Constraints

For loads:

$$P_{Gi} - (1 - \lambda_i)\, P_{Di} - \sum_{j=1}^{n}|V_i||V_j|\left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right) = 0 \quad (3)$$

with *i* = 1, ..., *n* is the number of loaded nodes, *n* denotes the set of nodes connected to *i*, PD_i designates the load active power at node's i level, G_{ij} represents the real part of the element in the nodal admittance matrix (*Ybus*) by corresponding row *i* and column *j*, B_{ij} is the imaginary part of the element in the nodal admittance matrix by corresponding row *i* and column *j*, and δ_i stands for the V_i voltage.

For generators:

$$P_{Gi}\,(1 - \lambda_i) - P_{Di} - \sum_{j=1}^{n}|V_i||V_j|\left(G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right) = 0 \quad (4)$$

where *i* = 1, ..., *n* designates the number of machine nodes, and *n* denotes the *i* connected nodes set.

2) Inequalities Constraints

These constraints reflect the limits set on the power system physical devices, along with the limits created to ensure the system's security. Indeed, for the sake of maintaining the electrical system's safety, transmission lines bear certain limits regarding the generated power, owing to thermal losses occurring at the conductor level, such as:

$$pg_i^{min} < pg_i < pg_i^{max} \quad (5)$$

where pg_i^{min} and pg_i^{max} designate the minimum and maximum generated power and pg_i denotes the power generated at the node *i*.

Additionally, the voltage level must be maintained within the allowable range to ensure the grid's smooth running smoothly, while preserving customer satisfaction. Any voltage drops would engender severe disturbances with respect to any load type, specifically:

$$v_i^{min} < v_i < v_i^{max} \quad (6)$$

where v_i^{min} designates a minimum voltage equal to 0.9pu, v_i^{max} denotes a maximum voltage of the range of 1.1pu, and v_i represents the node *i* corresponding voltage.

As the load and generator shedding factors are limited to specific minimum and maximum values, the entirety of the λ_i relevant values must be set between λ_i^{min} and λ_i^{max} ([0, 1]), such as:

$$\lambda_i^{min} < \lambda_i < \lambda_i^{max} \quad (7)$$

where λ_i stands for the shedding factor at the level of node *i*.

C. The Genetic Algorithm

Genetic algorithms are optimization algorithms with natural evolution drawn techniques: crossing, mutation, selection etc.. They help provide solutions to unresolved problems likely to be computed in an algorithmic finite-time manner [19]. Figure 2 depicts the genetic algorithm's structure, while the flowchart in Figure 3 highlights our suggested problem-solving algorithm sample. λg and λc stand for the machine and load associated shedding factors respectively.

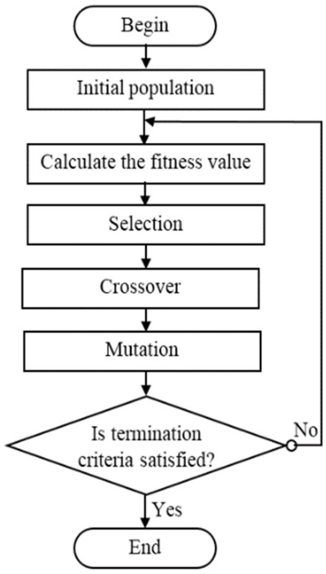

Fig. 2. Genetic algorithm structure.

The algorithmic steps shown in Figure 3 are:

Population initialization

If PD > pdlim

Calculation of the Pc and Qc load active and reactive power, respectively.

Solving these load values distribution problem: if the voltage is within its limit, we return to step 1, otherwise:

Formulate the optimization problem and determine the control parameters' limits

Solve the optimization problem using the genetic algorithm.

The best ultimately withdrawn individual represents the load's optimal shedding factor result.

Carry out the load shedding process.

Display the results.

If PD < pdlim

Same work with the generators' constraints and objective function.

End.

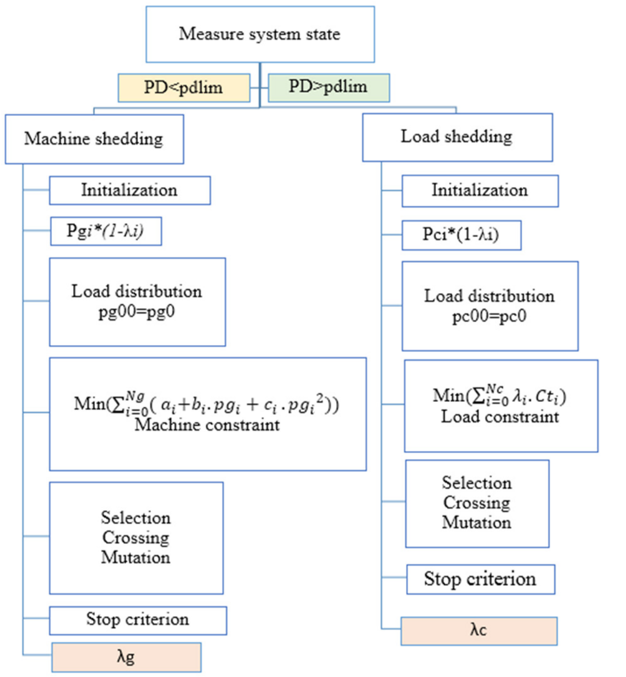

Fig. 3. Optimal load and machine shedding algorithm flowchart.

IV. APPLICATION AND SIMULATION RESULTS

A. *Application on the 14-Node IEEE Test Network*

For the implementation purposes of our scheme, we considered the 14-node IEEE test network, involving 5 generators, 9 loads and 20 lines, shown in Figure 4.

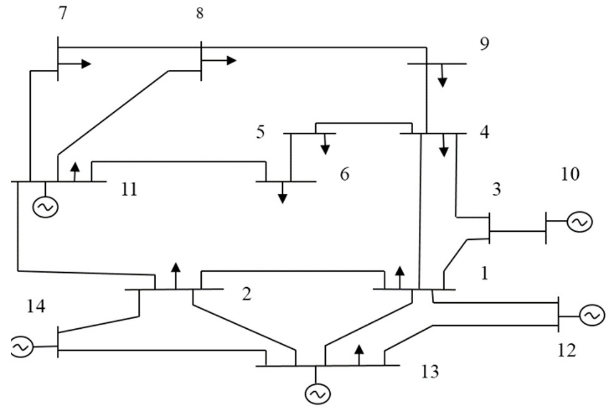

Fig. 4. Structure of the 14-node IEEE test network.

Line data, production limits, specific coefficient of each generator, voltage limits relevant data, load shedding cost functions associated coefficients, and the node data are illustrated in Tables I-IV. It is important to note that all the nodes limits' shedding factors are set between 0 and 1.

B. *Simulation Results*

MATLAB was utilized to solve the voltage collapse problem. The PD used is equal to 8pu, which exceeded the limit demanded power pdlim=5.4pu. Accordingly, the shedding type is loads shedding. Table V highlights the applied genetic algorithm associated parameters. The relevant convergence profile is illustrated in Figure 5. Accordingly, one could well note that the genetic algorithm appears to converge starting from generation number 55, which corresponds to the most optimal solution.

TABLE I. NODE RELEVANT DATA

Line number	Liaison	Impedance (pu)	Line number	Liaison	Impedance (pu)
1	1-2	0.01335+j0.04211	11	10-2	0.05695+j0.17388
2	1-3	j0.20912	12	10-11	0.04699+j 0.19797
3	1-4	j0.55618	13	11-1	0.06701+j0.17103
4	3-4	j0.11001	14	12-6	0.09498+j0.1989
5	10-1	0.05811+j0.17632	15	12-7	0.12291+j0.25581
6	4-5	0.03181+j0.0845	16	12-8	0.06615+j0.13027
7	4-9	0.12711+j0.27038	17	12-2	j0.25202
8	5-6	0.08205+j0.19207	18	13-3	j0.17615
9	7-8	0.22092+j0.19988	19	14-10	0.01938+j 0.05917
10	8-9	0.17093+j0.34802	20	14-2	0.05403 +j0.22304

TABLE II. PRODUCTION LIMITS AND PROPER COST COEFFICIENT RELEVANT TO EACH GENERATOR

Node N°	pgmin	pgmax	a($/h)	b($/M.W.h)	c($/M.(W^2).h)
10	0.1	0.7	1469	40	0.13
11	0.1	1.2	450	46	0.11
12	0.15	1	1050	40	0.028
13	0.2	1.4	1245	40	0.0354
14	0.1	2.5	1660	36	0.0211

TABLE III. DATA RELATING TO VOLTAGE LIMITS AND COEFFICIENTS OF LOAD SHEDDING COST FUNCTIONS

Node N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14
V_{min} (pu)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
V_{max} (pu)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Cost (Ct) ($)	100	400	200	550	900	250	450	500	50	*	*	*	*	*

* See Table II.

TABLE IV. LINE RELEVANT DATA

Node N°	Type	Active power generated (pu)	Active power consumed (pu)	Reactive power consumed (pu)	Voltage (pu)
1	P-Q	0	1.2550	0.1024	-
2	P-Q	0	0.1995	0.0420	-
3	P-Q	0	0	0	-
4	P-Q	0	0.7745	0.4358	-
5	P-Q	0	0.3912	0.1313	-
6	P-Q	0	0.3544	0.1523	-
7	P-Q	0	0.0919	0.0473	-
8	P-Q	0	0.2363	0.1523	-
9	P-Q	0	0.1602	0.0420	-
10	P-V	1.0502	0	0	1.0450
11	P-V	1.0502	0.2941	0.1969	1.0100
12	P-V	1.5753	2.4732	0.4988	1.0700
13	P-V	1.0502	0 .5697	0.3340	1.0900
14	Balance	2.2910	0	0	1.0600

TABLE V. GENETIC ALGORITHM PARAMETERS

Population size	800
Generation number	100
Probability of mutation	0.05
Crossover probability	0.9

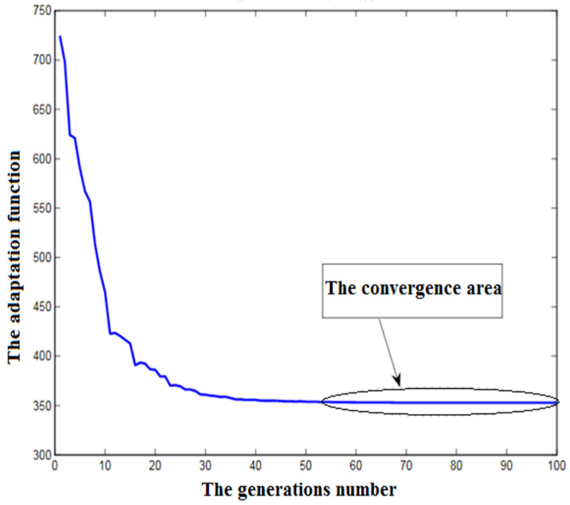

Fig. 5. The convergence curve of the genetic algorithm.

The cost and load-shedding factor profile, relevant to each load node, is depicted in Figure 6. We can see that the load shedding process proves to persist at the level of buses number 1, 3, 4, 6, and 9, displaying different importance degrees, specifically:

- "Low" with regard to nodes number 3 and 4,
- "Medium" with regard to node number 6, and,
- "Totally unloaded" regarding the nodes 1 and 9.

It should be noted that any increase in the load-shedding factor turns out to be closely associated with a load-cost reduction.

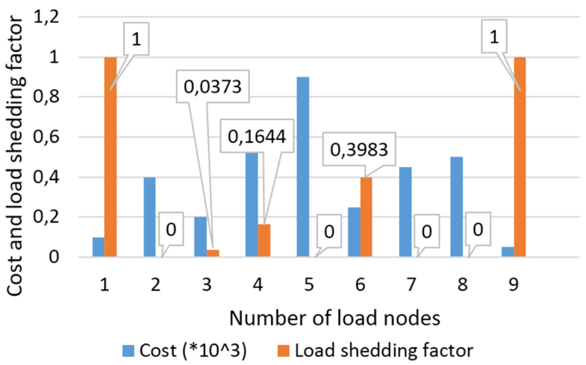

Fig. 6. The cost and load-shedding factor profiles of consumer nodes.

The pre and post load shedding power profiles of the aggregate node loads are highlighted in Figure 7. It can be seen that each load respective power turns out to decrease:

- Slightly at the level of nodes 2, 5, 7 and 8 due to the very high cost,
- totally at the level of nodes 1 and 9 due to the very low cost, and
- around 40% and 60% at the nodes 4 and 6, as cost at the level of node 4 appears to be rather high as compared to the other nodes (1, 3, 6 and 9).

The loaded nodes' pre and post load shedding voltage profiles are illustrated in Figure 8. It can be seen that there is an increase in the voltages of nodes 4, 5, 6, and 9, which is not within the allowable limit of stability before the load shedding. After load shedding, the voltages of the various load nodes are within their allowable limits, something that maintains the stability and continuity of the electrical network.

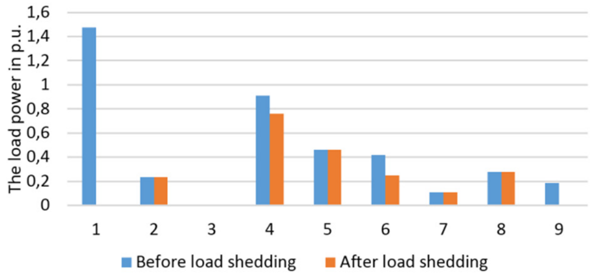

Fig. 7. The consumer nodes' pre and post load shedding power.

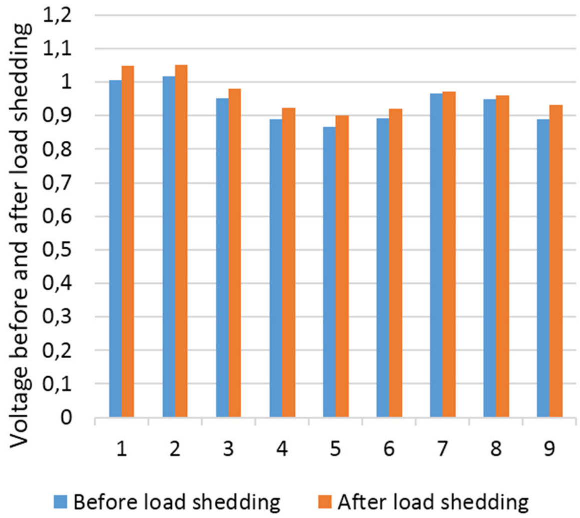

Fig. 8. The consumer nodes' pre and post load shedding voltage.

V. CONCLUSION

Several known registered voltage collapse events indicate that most of the observed power grids operate closely to their stability limits. This issue turns out to be further compounded coupled with the electricity market liberalization. Hence, for the sake of avoiding the electrical grid associated blackouts and for saving more energy, the implementation of an optimal shedding process on a 14-node IEEE test network was undertaken in this paper. In this context, two shedding types have been considered, namely, load and machine shedding. For the shedding type determination, a test has been administered on the load distribution program to set the exact shedding types. In order to avoid the voltage collapse problem, an implementation of the genetic algorithm for the shedding of a 14-node IEEE test network was realized. Based on the obtained simulation results, we were able to highlight the advanced optimization approach's remarkable performance and achieved effectiveness in terms of avoiding the blackouts while minimizing the production cost. The valuable contribution of the present research lies not only in minimizing the production cost, but also in combatting overloading lines, for an effective balance between energy generation and consumption. In view of future development, the proposed work can be expanded to other electrical grids containing renewable energy sources.

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