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Power System Adequacy: an Efficient Procedure Based on Genetic Algorithms

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Abstract-- **The paper presents a methodology which can be used to improve the static adequacy of high voltage (HV) transmission systems under contingency. The most suitable corrective actions for bringing the power system back to acceptable operation conditions are identified by means of a power system management software. The proposed procedure combines a micro genetic algorithm (μGA) optimization procedure with a load-flow program. The foreseen control actions consist in change of network configuration, generation re-dispatching, transformer tap setting, insertion and/or regulation (if variable) of shunt reactor and capacitor banks, load shedding. Several case studies, including an application to the Italian EHV/ HV transmission grid are presented and discussed in order to evaluate its possible use by a Transmission System Operator (TSO).**

Index Terms-- **Static adequacy; Network re-configuration; Power re-dispatching; Load shedding; Genetic algorithms.**

I. Introduction

AMONG the methods enhancing power system security, many contributions have been published presenting procedures aimed at the determination of corrective measures such as re-dispatching and/or switching operations, "in" or "out" of lines, bus-bars, transformers and compensation elements, to eliminate overloads and voltage violations in power networks, generally incorporated into SCOPF (Security Constrained Optimal Power Flow) algorithms [1], [2]. In recent years, stochastic optimization methods aroused great interest; amongst others, Evolutionary Algorithms (EAs) have been investigated by many authors because they are especially well-suited for solving non-linear multi-modal optimization problems. In particular, Genetic Algorithms (GA) [3] have been widely applied to the solution of power system operational problems, such as optimal network reconfiguration aimed at minimizing operational costs and network losses, contingency selection to evaluate and improve static security, reactive power/voltage control, service restoration, optimal load shedding [4]-[9]; moreover, GAs have also been applied in the study of service restoration and minimum loss reconfiguration in electric power distribution systems [10]-[13]. The present paper combines and integrates some foregoing studies [14], with several new features. In particular, combining a power flow program with an optimization procedure, based on a micro-genetic algorithms (μGA) scheme [15], [16], a code able to predict the "best" configuration for the power system is proposed. These solutions can be used by operators to adopt the corrective actions assuring security following single or multiple contingency.

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II. Optimization Procedure

Following a contingency, the genetic procedure tries to create a network configuration complying with the following requirements:

a) the maximum power injection capability at the slack bus must not be exceeded;
b) bus voltages should stay within a specified range around the nominal value (usually ±5%);
c) branch current flows in the network should not exceed a specified overload threshold.

The first solution provided by the procedure, simultaneously fulfilling the three above conditions a), b) and c) with a 20% overload threshold, is named first acceptable solution; if conditions a), b) and c) are fulfilled without any overload, a near optimal solution is reached.

The fitness function forces the genetic procedure to take into consideration corrective actions that, at first, include the switching-in of available disconnected elements; subsequently, the re-scheduling of generation as well as insertion and/or regulation (if variable) of shunt reactor and capacitor banks are foreseen. If convergence is not reached, load shedding is undertaken, with the further aim of minimizing shed loads. If, in any case, the network evolves towards voltage collapse or constraints are not still fulfilled, controlled disconnection of network components is attempted, with the additional constraint of minimizing the number of network structure changes; finally, islanding is allowed, when it is necessary for the rescue of the network.

The flowchart of the genetic optimization procedure is shown in Fig. 1. At every generation, the μGA procedure calls the load flow for each individual (i.e. a network configuration), in order to calculate voltages and currents; it then evaluates the fitness of all individuals in the population and, finally, it optimizes the fitness function. The fittest individuals of each GA population are selected by an algorithm that minimizes the following six parameters, listed in decreasing order of importance:

1. difference between the calculated active power demand and the active power limit at the swing bus (MW, zero if the power demand is within the limit);
2. average mismatch between actual and rated voltages

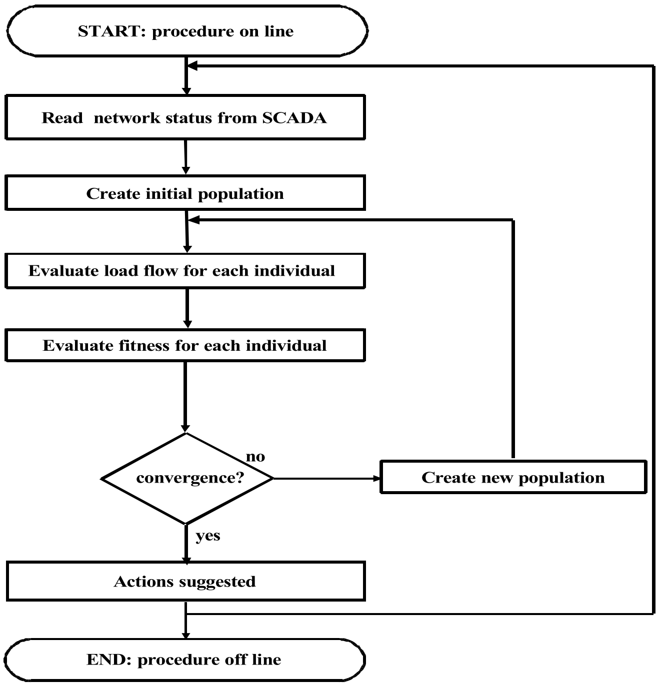

Fig. 1. Flow-chart of the procedure.

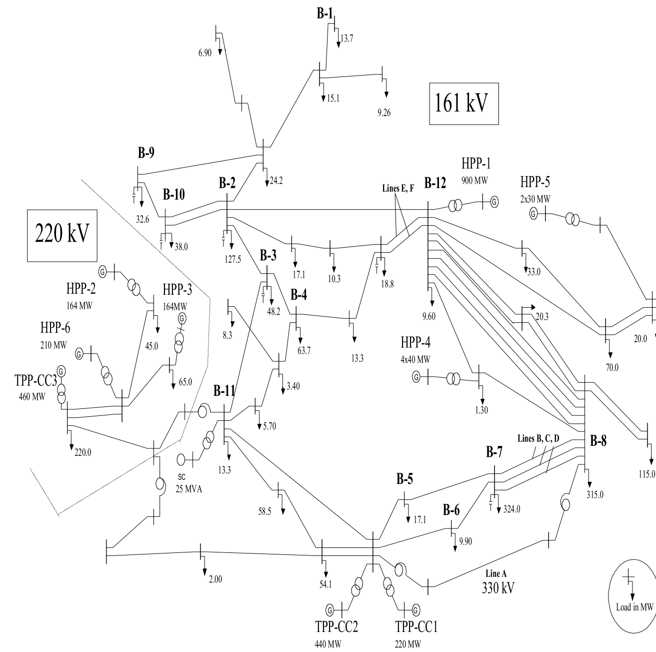

Fig. 2. 161/220/330 kV-50 Hz test network.

at nodes where voltage limits are violated (p.u. of nominal voltages, zero if all voltages are within limits);

3. maximum branch overload in the network (p.u. of current limit, zero if no branches are overloaded);
4. total real power losses in the network (MW);
5. number of topological changes in the network (line switching on/off, busbar splitting) performed in order to remove overloads;
6. shed load, in percent of maximum (pre-set) allowable load shedding.

III. Preliminary Studies

In this section, preliminary studies on two test networks are briefly discussed. All the simulations have been performed by a PC equipped with a Pentium 4 4.2 GHz processor and 3 GB of main memory.

A. 58 bus-83 branch test network

The 161/220/330 kV-50 Hz test network is shown in Fig.2; the aggregate power generation installed is 2802 MW, shared among 8 main power plants (hydro and thermal power plants are respectively named HPP and TPP-CC). In the base case the total active load absorbed is 1884 MW, while reactive power is 765 Mvar and total joule losses are 52.8 MW. The 12 buses where load shedding (up to 100%) is possible are named as B-1,..., B-12.

Case A1 - Outage of a 330 kV line. It causes 3 overloads, the biggest one being 20%. The first acceptable solution is reached in 5 s, with one overload (under 5%); active power losses are P_j=61.2 MW. The near optimal solution without any overload, is reached in 15 s; associated losses are P_j=60.7 MW.

Case A2 - Loss of the whole generation at bus TPP-CC-2. It causes 2 overloads (up to 13.7%); moreover, in the initial load flow the active power injection at the slack bus exceeds the plant rated power by 259.7 MW; however, spinning reserve for the simulated system is tailored to this extreme contingency (the possible activation of under frequency load shedding during the frequency transient should be checked, anyway). The first acceptable solution is reached in 15 s without overloads; P_j=73.2 MW. The near optimal solution is reached in about 1 minute; P_j=68.9 MW.

Case A3 – Simultaneous outage of two 161 kV lines, marked “B” and “C” in Fig. 2. There is a single initial 22.7% overload to be relieved. The first acceptable solution is reached in 5 s with 3 small standing overloads (up to 7.4%); P_j=62.1 MW. The near optimal solution is reached in about 5 minutes; P_j=56 MW, but 2% of total load has to be shed.

Case A4 – Simultaneous outage of lines “B”, “C” and “D”: this would cause the network voltage collapse. The first acceptable solution is reached in 1 minute with 1 standing overload (under 5%); load shedding (13%) is required; P_j=53.9 MW. The near optimal solution is reached in about 4 minutes; a 10% load shedding is still required; P_j=51.8 MW.

Case A5 - Network in normal operation with all system components in service. This case has been added to show the capability of the procedure to optimize power flows (i.e., minimize transmission losses) by means of the available corrective measures (redispatching, changes in network structure etc.). The solution proposed at the convergence of the procedure (in about 9 minutes) has P_j=51.6 MW.

For test cases based on a single contingency, solutions obtained in 15 seconds are close to the optimal solutions, that the procedure always proposes within 5 minutes. For test cases with multiple contingencies, the procedure usually provides an acceptable solution within one minute, even if the starting point potentially leads to a black-out. Furthermore it is remarkable that case A4 is a very "stressful" test case for a small network like the one considered and also unlikely in the network operation.

B. 164 bus-229 branch test network

Further tests have been performed on the 164-bus model of a 400/150 kV existing transmission system. The base case refers to a peak load condition, with 26950 MW and 6890 MVAR active and reactive load power, respectively. Network losses amount to 580 MW. A large number of single, double and triple contingencies have been analysed, but among them, three onerous and significant cases are detailed hereafter:

Case B1 - simultaneous outage of 2 lines supplying a 1000 MW load bus. This causes a 34% line overload, and the post-contingency active power injection at the slack bus exceeds the plant rated power by 41 MW.

Case B2 - simultaneous outage of 2 lines outgoing from a 2650 MW generation bus. This double contingency causes a 10% line overload, while the active power injection at the slack bus would exceed the plant rated power by 324 MW; moreover, 13 bus voltages are out of range.

Case B3 - as case B2, but with the outage of a third line from 2650 MW generation bus. This causes a 46% line overload, with an active power injection at the slack bus exceeding the plant rated power by 290 MW; 11 bus voltages are out of range.

Execution times for near-optimal solutions of the above test cases are reported in Table 1. Results show that the procedure always provides near optimal solution within 5 minutes; execution times for first acceptable solutions, always proposed by the procedure within 1 minute, are not listed in Table 1.

Although the 164 bus-229 branch network is significantly larger than the formerly analysed 58 bus-83 branch network, results reached for the two HV transmission systems are not only comparable in terms of effectiveness of the proposed corrective measures, but also of calculation times. It must be pointed out that the multiple contingencies analysed for the 164 bus–229 branch network are very heavy ones (notably case B3) and quite unlikely to occur; they were examined to test the performance of the procedure for critical network conditions.

IV. Case Study: The Italian EHV/HV Network

The proposed μGA-based procedure was applied to the EHV/HV Italian transmission grid, in order to assess its performance on a larger meshed network. The complete network at 380-220-150-132 kV voltage levels is made of more than 1100 buses and 700 branches, and about 1500 transformers (200 step-up transformers, 1300 substation and primary substation transformers). For the simulations carried out in the paper, only the 380-220 kV grid, consisting of 596 buses, 719 branches and 61 transformers, was considered. The 380 kV-50 Hz portion of the network is shown in Figure 3. Extensive statistical analyses, by means of the random generation of a large number of operation base cases, were carried out in order to evaluate the capability of the procedure to bring the power system back to acceptable operation conditions, following the occurrence of single, double and triple contingencies. All the simulations were performed on a Cluster Linux (running under Debian 4.0) equipped with eight Intel Xeon 2.33 GHz processors and 8 GB of main memory; however the procedure is still not parallelized and it runs on a single processor.

Among the randomly generated operation base cases, a realistic operation condition was selected, with active and reactive load power respectively equal to 30676.3 MW and 5976.6 MVAR; network losses amount to 366.7 MW. 656 transmission lines and 115 generation buses are in operation. Generation re-scheduling carried out by the procedure between a minimum and a maximum value for each generation bus is allowed in 72 power plants. Starting from this base case, a large number of contingencies was generated; among these, 2 significant and onerous test cases are described below:

Case C1 - Simultaneous outage of 2 lines in the North of Italy; the aggregate pre-fault power flow over the lines is 1316 MW. This causes 5 line overloads (the biggest overload is about

TABLE I
Execution Times for Near Optimal Solutions
(Test Network 'B')

Test case	Time [s]
Case 1	137
Case 2	228
Case 3	271

Fig. 3. 380 kV-50 Hz Italian transmission grid.

25%), while the post-contingency active power injection at the slack bus would exceed the plant rated power by 56 MW. Joule losses P_j in the network amount to 474 MW.

Case C2 - Loss of the whole generation at 4 buses, grouped together at the same busbar, in the South of Italy; the total loss of generation is 2440 MW. In this onerous case, it is supposed that the frequency stability is assured by the action of primary (due to the whole UCTE network) and secondary (only due to the Italian network) control. This contingency causes 6 line overloads, whereas the active power injection at the slack bus would exceed the plant rated power by 2718 MW; the Joule losses P_j in the network amount to 723 MW.

For each test case, the corrective actions carried out by the procedure, respectively for first acceptable solution (f.a.s.) and near optimal solution (n.o.s.), are listed from Table II to Table V, where power re-dispatching for each generation bus base case (b.c.) scheduling are reported. Lastly, Table VI and Table VII show the performance of the proposed procedure, in terms of number of load-flows, execution time and minimization of Joule losses, to reach the first acceptable and the near optimal solution.

TABLE II
Case C1 Re-scheduling for First Acceptable Solution

N°	Pgen,b.c. [MW]	Pgen,f.a.s. [MW]	N°	Pgen,b.c. [MW]	Pgen,f.a.s. [MW]
14	556.6	629.3	62	123.3	291
16	249.4	232	76	148.1	270.2
18	224.3	110	77	173.3	125
19	239.2	250	78	239.3	240
21	143.5	139.3	80	609.8	795
22	504.5	462	81	372.2	378.6
37	360.4	322.5	82	107.5	142
38	355.6	322.2	85	76.7	95.7
51	451.1	627.1	86	149.8	152.6
57	389	304.3	89	57.9	80.9
58	361.8	338.6	101	390.4	491
59	728.9	480	106	0.6	261.6
60	678.9	249.4	110	196.8	330

TABLE III
Case C1 Re-scheduling for Near Optimal Solution

N°	Pgen,b.c. [MW]	Pgen,n.o.s. [MW]	N°	Pgen,b.c. [MW]	Pgen,n.o.s. [MW]
14	556.6	629.3	62	123.3	291
18	224.3	110	76	148.1	162.4
19	239.2	250	77	173.3	175
21	143.5	139.3	81	372.2	378.6
22	504.5	462	82	107.5	142
37	360.4	322.5	84	290.4	222.9
51	451.1	627.1	85	76.7	152.9
59	728.9	780	86	149.8	152.9
60	678.9	374.1	101	390.4	491

V. Conclusions

The authors have proposed a methodology based on a μGA scheme coupled with an iterative power flow program, for the individuation of suitable system control actions aimed at recovering static adequacy during contingencies or in normal operation. Firstly, the proposed procedure has been checked on two test networks; it was subsequently applied to the resolution of single, double and triple contingencies in the Italian 380/220 kV transmission grid. Results show that the software provides fast and effective solutions. The first convergence of μGA (first acceptable solution) is generally reached in a few tens of seconds; the attendant solution (i.e., the proposed control actions) is able to drive the power system back towards an acceptable operation condition. At the end of the μGA evolution, (i.e., after a few hundreds of seconds), an optimized solution is reached which usually suppresses the abnormal operating states. The authors are currently working to improve the accuracy of the proposed procedure, to the implementation of economical constraints such as the ones introduced by operation costs and the electrical market, and to the reduction of the running time of the procedure, by parallelizing the μGA scheme.

TABLE IV
Case C2 Re-scheduling for First Acceptable Solution

N°	Pgen,b.c. [MW]	Pgen,f.a.s. [MW]	N°	Pgen,b.c. [MW]	Pgen,f.a.s. [MW]
2	20.8	38.6	66	137.5	86.6
16	249.4	125	68	358.9	310.4
22	504.5	858	71	17.5	23.5
23	370.9	446.3	75	382.5	386
29	0.3	140	76	148.1	281
32	76.5	41.5	79	357.9	445
34	540.3	471.7	80	609.8	795
35	280.8	380	82	107.5	71
36	356.7	380	83	12.7	56.4
37	360.4	363.6	85	76.7	110
40	86.1	100	87	240.1	279
42	149.1	127.2	90	57.9	100
49	92.8	131.4	93	52.4	36
50	242.1	316.3	95	530.4	754
52	18.8	25	104	24.6	36
53	34.4	38	106	0.6	166.5
54	32.9	19	107	636.8	956
56	389	270	108	650.8	958
61	322.2	402.9	112	89.5	120.7
62	123.3	276.5	114	2	21
63	0.1	33.4	115	18.2	380

TABLE V
CASE C2 RE-SCHEDULING FOR NEAR OPTIMAL SOLUTION

N°	Pgen,b.c. [MW]	Pgen,n.o.s. [MW]	N°	Pgen,b.c. [MW]	Pgen,n.o.s. [MW]
2	20.8	41.4	63	0.1	39.4
4	205	199.6	71	17.5	30.2
17	224.5	196.4	76	148.1	281
23	370.9	446.3	80	609.8	795
29	0.3	140	86	149.8	131.4
34	540.3	471.7	88	700.2	668.6
35	280.8	380	90	57.9	92.9
36	356.7	380	95	530.4	754
37	360.4	380	99	670.7	850
42	149.1	127.1	102	105.5	179.5
43	115.5	38.7	104	24.6	62
49	92.8	200	105	611.3	754.3
50	242.1	316.3	107	636.8	956
58	361.8	390	108	650.8	958
59	728.9	840	112	89.5	37.1
61	322.2	436.4	113	118.1	125
62	123.3	305.5	115	18.2	172.7

TABLE VI
BEHAVIOUR OF THE PROCEDURE FOR FIRST ACCEPTABLE SOLUTIONS

Test case	N° of Load-flow	P_j [MW]	Time [s]
Case C1	164	430	80.36
Case C2	71	495.3	36.21

TABLE VII
BEHAVIOUR OF THE PROCEDURE FOR NEAR OPTIMAL SOLUTIONS

Test case	N° of Load-flow	P_j [MW]	Time [s]
Case C1	184	418	90.16
Case C2	329	450.3	161.21

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