

THE ASSESSMENT OF POWER SYSTEM VULNERABILITY INDUCED BY LACK OF REACTIVE POWER RESOURCES FOLLOWING SEVERE CONTINGENCIES

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Abstract – The paper is concerned with the problem of power system vulnerability assessment following severe contingencies involving voltage degradation and reactive power unbalances which play a critical role in most major system disturbances. A procedure is designed for identifying critical contingencies aiming at discovering those situations which are likely to jeopardize system security with particular reference to voltage profiles. A model based on the linearized reactive balance equations is employed. The occurrence of possibly dangerous generator outages is simulated by means of binary variables reflecting the status (operating or outaged) of each generation unit. The model gives rise to a large-scale mixed (binary-continuous) linear programming problem which is solved by efficient branch-and-bound techniques included in the CPLEX optimization package. The procedure is applied to the analysis of the Italian EHV network with reference to a much stressed operation situation occurred in June 2003 and to foreseen scenarios relative to the year 2010.

Keywords: *System vulnerability, reactive power contingencies, mixed integer linear programming*

1 INTRODUCTION

Catastrophic failures occurred in large interconnected power systems in recent years [1] have contributed to give an ever increasing importance to the assessment of power system vulnerability. Based on the lessons learnt from these disturbances the Transmission System Operators (TSO) of large interconnected systems, as the UCTE in Europe, are jointly reviewing their operational criteria [5] with the aim of overshooting the traditional N-1 security criterion and extending the system defense plans beyond the control of regional disturbances.

After-the-fact analyses of blackouts have shown that in most cases a fault (or a combination of faults) acts as the initiating event of the cascading failure phenomenon; in particular, misoperation of the protection system and shortage of reserve margins in voltage and frequency control may contribute significantly to the system collapse [2-4]. However, a detailed analysis of the many different ways in which a system may collapse would require the exploration of a multi-level probabilistic tree of events [2,3] resulting in lengthy and cumbersome calculations which often make the vulnerability problem untreatable.

The computational effort could be remarkably reduced by the use of efficient screening procedures capable of identifying and ranking the most critical sequences of events endangering system security. This is the aim of the work undertaken by the authors.

The contingency set is partitioned according to the kind of effect that possible outages are expected to produce onto system operation. In this way the two subsets of the outages affecting the balance and routing of real power (line, transformer and generator outages) and those affecting the balance and routing of reactive power (generator outages) are considered.

In a previous work by the same authors [6], the outage of branches and/or generating units leading to the largest real power flow violations was considered.

In the present work, the aim is that of studying the electric energy system vulnerability induced by the deterioration of the voltage profile following the outage of reactive power resources.

The reactive power flow equations are linearized in correspondence to a power flow solution point; suitable binary variables are employed to describe the status (operating or outaged) of each generator as well as the attainment of the maximum reactive power generation limit. The problem is thus formulated as a mixed (real and binary) linear programming problem which is solved by means of efficient branch-and-bound techniques included in the CPLEX [7] optimization package.

To improve the accuracy of results, the nonlinearity of reactive power balance equations is taken into account by an approximated sequential linear programming procedure, which corrects possible linearization errors up to a pre-selected threshold. A full-fledged load flow solution is carried out anyway at the end of the procedure to ensure the correctness of the results and the actual voltage profile degradation used to gauge the system vulnerability.

The resulting Vulnrea (VULnerability REActive) procedure was successfully applied to the analysis of the Italian EHV network with reference to one of the most stressed operation points occurred in June 2003 and to some foreseen scenarios at the projection horizon of the year 2010.

2 REACTIVE POWER VULNERABILITY

2.1 Mathematical model

The consequences of the loss of the reactive power produced by a fixed number ng of synchronous generator outages are determined with the application of a linear perturbation approach to the reactive power flow equations. The set of outages having the largest impact on system vulnerability is obtained by maximizing the degradation in voltage profile. The effect of generator outages is considered by introducing a binary variable δ for each unit, which takes the value 1 or 0 according to the status (operating or outaged) of the corresponding generator.

The set of contingencies leading to the worst operation conditions is thus formulated as the following mixed integer linear-programming (MILP) problem:

$$\min \sum_{i=1, N} \Delta V_i \quad (1)$$

$$Q_i^0 \cdot \delta_i + \Delta Q_i = \sum_{j \in \alpha_i} \left(q_{ij}^0 + \frac{\partial q_{ij}}{\partial V_i} \Delta V_i + \frac{\partial q_{ij}}{\partial V_j} \Delta V_j \right) \quad (2)$$

$$-D_k = \sum_{j \in \alpha_k} \left(q_{kj}^0 + \frac{\partial q_{kj}}{\partial V_k} \Delta V_k + \frac{\partial q_{kj}}{\partial V_j} \Delta V_j \right) \quad (3)$$

$$0 \leq \Delta Q_i \leq \delta_i (\bar{Q}_i - Q_i^0) \quad (4)$$

$$\Delta Q_i \geq \sigma_i (\bar{Q}_i - Q_i^0) \quad (5)$$

$$-M(1 - \delta_i + \sigma_i) \leq \Delta V_i \leq M(1 - \delta_i + \sigma_i) \quad (6)$$

$$\sum_{i=1, n} (1 - \delta_i) \leq ng \quad (7)$$

In the model above, it is assumed that the n PV buses (to which the synchronous generators are connected) are numbered first in the network, while the remaining $N - n$ PQ buses are numbered from $n + 1$ onward.

The objective function in (1) consists in the sum of the voltage magnitude changes relative to all the nodes of the system, following a set of a-priori unknown generator outages. Since the ΔV_i are negative in sign, the objective function will have to be minimized to look for the contingency situation which determines the worst degradation of the voltage profile.

Constraint (2) is the linearization of the reactive power flow balance equation for generator bus i ; the right-hand side is the reactive power flow coming out of the bus. Similarly, constraint (3) contains the linearization of the reactive power balance equation for load bus k . More precisely, q_{ij}^0 and q_{kj}^0 are the reactive power flows through branches $i-j$ and $k-j$ in the pre contingency point, D_k is the reactive load at bus k and sets α_i and α_k contain the nodes connected to buses i and k respectively. The left-hand side of equation (2) is the value of the reactive power injected by an operating

($\delta_i = 1$), generator located in bus i assuming that Q_i^0 is the base case reactive generation and ΔQ_i is the post contingency reactive power change.

Constraints (4) and (5) take into account the mechanism of generation outage as well as PV to PQ node type switching. When a generator goes lost ($\delta_i = 0$), constraint (4) forces the reactive power generation change ΔQ_i to 0; in this case the left-hand side of equation (2) vanishes, thus zeroing the overall reactive power generation $Q_i^0 \cdot \delta_i + \Delta Q_i$ at the corresponding bus.

If generator i is operating ($\delta_i = 1$), the reactive power generation change following a unit outage, can assume positive values ranging from 0 to the upper bound $\bar{Q}_i - Q_i^0$, being \bar{Q}_i the Mvar rating of the unit.

The role of constraint (5) is that of enabling PV to PQ node type switching; indeed, to satisfy condition (5), the binary variable σ_i is forced to 0 if the reactive power change of the corresponding generator is less than $\bar{Q}_i - Q_i^0$. On the contrary, if the upper bound is reached, σ_i is forced to 1 in order to satisfy both constraints (4) and (5).

Constraint (6) sets suitable upper/lower bounds on the change in voltage magnitude for each generator. In particular, when a generator goes lost ($\delta_i = 0$) or when it is operating at the maximum reactive limit ($\delta_i = 1$ and $\sigma_i = 1$), the voltage magnitude at the bus connected to the generator is allowed to change. M is a large positive constant which has the role of freeing the voltage magnitude change ΔV_i when the corresponding generator is no longer able to carry out its voltage regulating function. Constant M should be taken large enough to allow the voltage magnitude change ΔV_i at a generator bus to take any reasonable value even when a serious degradation of the voltage profile is expected. In principle, if a generator reaches its upper Q limit, its voltage starts decreasing; hence the right inequality in (6) could be replaced by zero. The general double-sided expression was preferred to account for the possibility that the outage of an under-excited unit may result in a voltage increase at the bus where it is connected.

Finally, constraint (7) sets an upper limit, equal to ng , on the number of generator outages admitted for each study of reactive vulnerability.

2.2 Sequential linear programming approximation

The starting point of the procedure consists in a power flow solution pertinent to the base case loading conditions. The reactive power balance equations are linearized giving equations (2) and (3) of the model above. The ensuing MILP problem is then solved by the branch-and-bound method.

The accuracy of model (1)–(7) strictly depends on the acceptability of the linear approximations employed. This issue may become critical in view of the expected

changes in reactive power generation of surviving units and in voltage magnitudes throughout the system.

To improve accuracy, an approximated sequential linear programming strategy was implemented.

After each solution of the MILP problem, the reactive power balance equations (2) and (3) are checked, by using their exact nonlinear expressions, corresponding to the updated voltage profile and reactive generations. A balance error is computed and, if it is larger than a pre-selected tolerance (1 Mvar), the procedure goes through a re-formulation of problem (1)–(7) by a new linearization of constraints (2) and (3) corresponding to the updated solution.

This error compensating strategy is not completely equivalent to a genuine sequential linear programming approach since the control of the nonlinear balance equations only involves the reactive part of an AC power flow computation; the voltage phase angles are kept constant at their base case values. Practical experience has shown that the accuracy of the reactive vulnerability assessment procedure is greatly improved in this way. The severity of the worst cases, found solving the successive MILP problems, is verified anyway by a non-decoupled power flow calculation carried out at the end of the procedure.

An outline of the Vulnrea procedure is presented in the flowchart in Fig. 1.

3 IMPLEMENTATION ISSUES

The model described in the preceding Section and, in particular, the formulation of the PV-PQ node type switching through inequalities (4)–(6), is designed for the application of MILP methods based on branch-and-bound where the binary variables δ and σ take real values between 0 and 1 until the integer solution is found.

With reference to the model, it may be questioned about the possible role that the positive constant M in constraint (6), may have in the model and in the convergence of the solution algorithm. Since M does not appear in the objective functions, it must not be considered as a penalty parameter and, therefore, it does not affect either the optimal solution or the objective function. Anyway M should be taken large enough to allow the voltage magnitude change ΔV_i at a generator bus to take any reasonable value even when a serious degradation of the voltage profile is expected.

A value of $M = 100\text{kV}$ was adopted for all voltage levels.

With reference to the flow-chart in Fig. 1 it must be recalled that verifying the accuracy of the results obtained from the solution of the MILP problem (1)–(7) is a mandatory element of the overall computation. Indeed the nonlinearity of reactive power balance equations and the amount of expected changes in voltage magnitude and reactive generation may seriously impair the practical applicability of the results and lead to unphysical situations. For this reason, in addition to the base case power flow solution required for sensitivity evalua-

tion, a checkout power flow computation is included in the procedure. An industrial AC power flow code was used for this purpose. Although not explicitly intended for voltage collapse studies, it contains a complete set of solution checks and warnings which allow the user to easily identify the possible reasons for convergence failures, especially when saturation of reactive power generation limits occurs.

A user friendly interface of the proposed procedure was implemented in Microsoft Access to exploit the

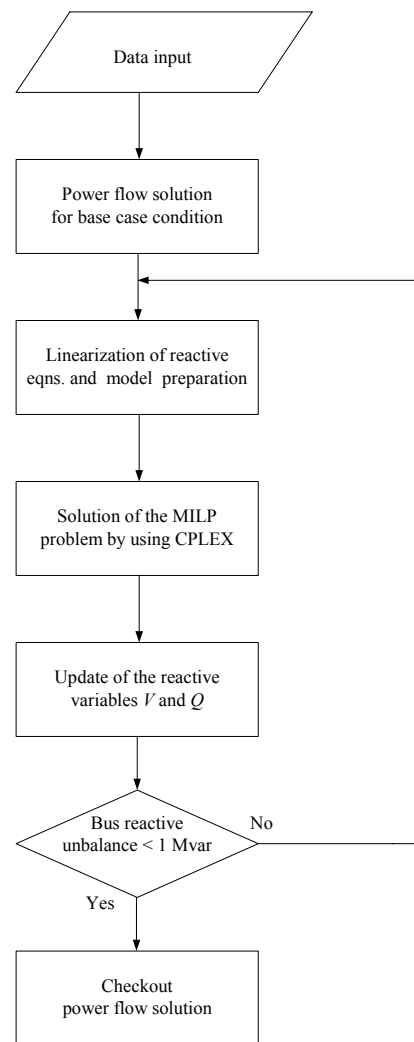


Figure 1 Flowchart of the Vulnrea procedure

data filtering facilities of the data base. This characteristic was found extremely useful in practice, since the powerful data base commands available allow an easy manipulation of branch and generator data. In most situations it is convenient to restrict the search for critical outages to one region of an electrical system at a time; this can be easily accomplished by using appropriate data base directives that enable opening of selected branches or generators in the network.

Another possibility offered by the data base interface is that of forcing the program to exclude certain generation units from outage simulation. This feature is particularly useful in screening contingencies according to

their potential danger. Indeed after examining the results of a given generator outage (possibly combined with other contingencies), it is sufficient to exclude it from outage to obtain a different set of potentially dangerous contingencies. By carefully exploiting this feature of the proposed program, a list of contingencies, ranked according to their potential risk, can be readily generated.

4 TESTS AND RESULTS

In the proposed implementation it was found expedient to exploit the efficient branch-and-bound techniques offered by the CPLEX solver.

Tests were performed with reference to the Italian system with over 800 buses. A Pentium IV 3.2 GHz personal computer, on which the CPLEX software had been uploaded, was employed for all the tests. Tests described in the sequel regard the Italian EHV network with reference to a stressed operating situation occurred in June 2003 and to some foreseen scenarios at the projection horizon of the year 2010.

4.1 The Italy 2003 test case

The summer of 2003 in Italy was characterized by extremely hot weather and consequent massive use of air conditioning, resulting in heavy loading of the grid. Moreover, in June 2003, some large thermal units had been put out of service for programmed maintenance, leading to a shortage in the reactive reserves.

Low voltage profiles were registered in that period even though this did not lead to a real black-out risk. Anyway this combined loading and grid situation is considered critical enough to deserve further study by means of the proposed reactive vulnerability procedure.

This test case features 851 nodes, 1187 branches (lines and transformers) and 223 generators. High loading conditions (about 1000 MW off from the peak load condition recorded for the same day) are considered for these tests.

The vulnerability assessment procedure was carried out, allowing an increasing number of generator outages ng to take place in the system.

With $ng = 1$, the optimization procedure shows that

Bus name	Vulnrea	Power flow	ΔV	ΔV error
P. TOLLE	382.06	382.77	-8.85	-0.7
ADRIA SUD	381.57	382.11	-6.78	-0.54
RAVENNA	382.29	382.73	-4.84	-0.44
P. CORSINI	384.56	385	-4.67	-0.43
DOLO	382.92	383.28	-4.48	-0.35
FUSINA	386.22	386.57	-4.45	-0.35
FORLI	376.35	376.72	-4.25	-0.37
VENEZIA	382.52	382.85	-4.14	-0.33
S.MARTINO	371.23	371.55	-3.73	-0.32
CAMIN	379.51	379.79	-3.64	-0.28

Table 1: Porto Tolle outage; voltage profile comparison

the worst post contingency situation is the one following the outage of the large thermal unit of Porto Tolle located in the Venice area. The loss of the 320 Mvar generation of the Porto Tolle power plant results in a consistent decay of the voltage profile in the area around the plant with far reaching effects involving all the Adriatic Sea coastal regions. The largest post-contingency voltage decrease is that found at the high voltage side of the Porto Tolle power plant bus; this voltage magnitude falls to 382 kV (starting from a pre-contingency value of 390 kV). The list of the system nodes which present the largest decrease in voltage profile is shown in Table 1.

As a result of reactive power shortage, as many as 18 power units are brought up to their upper reactive power generation limit in the effort to compensate the loss in reactive power generation.

The sequential linear programming procedure requires a total of 4 successive linearizations to reach the convergence.

The results obtained by the procedure were checked by the final AC power flow computation (see Fig. 1); the reactive generation of the Porto Tolle power unit was zeroed while leaving all the remaining data unchanged. Results are gathered in Table 1: the voltage magnitudes obtained via the proposed procedure can be compared with those of the checkout power flow. The voltage decrease ΔV corresponding to the power flow solution and the error between the voltages (ΔV error) are written in the last two columns. It can be easily realized that the solution provided by the Vulnrea procedure is actually very close to the exact nonlinear solution obtained via the AC power flow computation.

With $ng = 2$, the two power units of the Vado Ligure generation facility (in North-West Italy) are put out of service with an overall reactive power generation loss of 300 Mvar. The overall degradation of the voltage profile is a little worse than that obtained with $ng = 1$, as expected. The North-West Italy region is the one most deeply affected by this contingency.

It can be realized that the envisaged worst case double contingency no longer involves the Porto Tolle power plant considered when $ng = 1$ was assumed. This

Bus name	Pre-fault voltage (kV)	Vulnrea
P. TOLLE	390.05	375.26
ADRIA SUD	387.11	375.74
RAVENNA	386.52	377.91
P. CORSINI	388.71	380.24
DOLO	385.76	378.22
FUSINA	389.03	381.55
FORLI	379.89	372.45
VENEZIA	385.01	378.04
S.MARTINO	374.19	367.68
CAMIN	381.42	375.27

Table 2: Porto Tolle outage; voltage profile behaviour

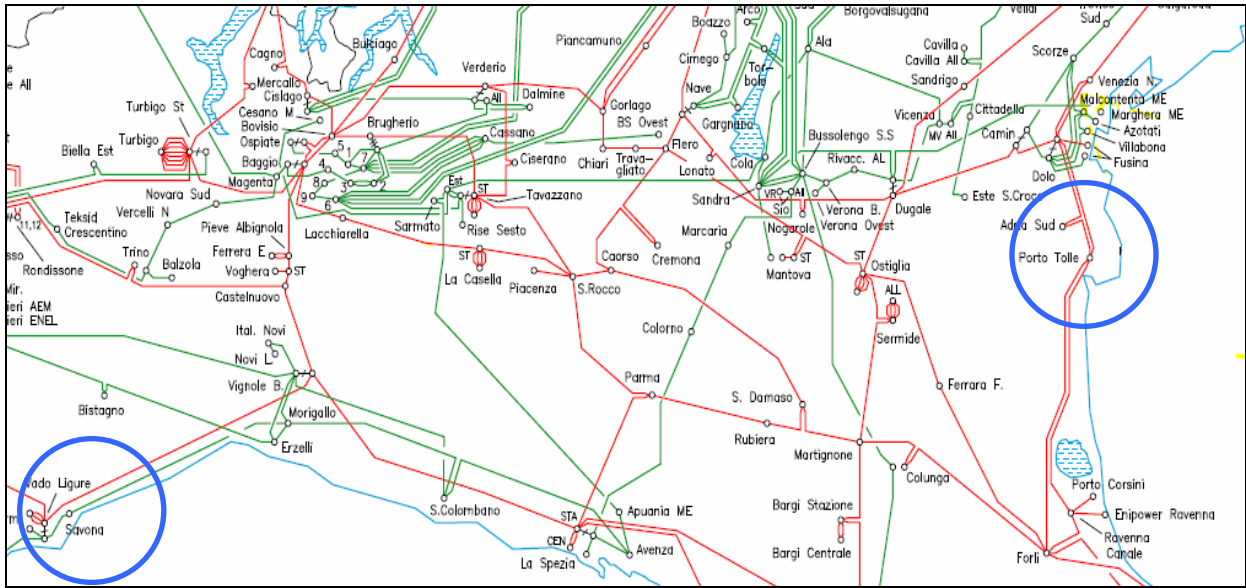


Figure 2: Layout of the Northern Italy system

result is not surprising bearing in mind that the worst double outage is not necessarily the combination of the two single contingencies that, taken individually, may produce the worst voltage degradation in the system.

Finally, with $ng = 3$, both the power unit in Porto Tolle and the two in Vado Ligure are outaged; this confirms that the locations of the worst power unit contingencies is anyway identified.

A sketch of the northern part of the Italian grid is shown in Fig.2 with the location of the generating facilities of Porto Tolle and Vado Ligure highlighted.

4.2 Heading for voltage collapse

Some further tests were carried out with reference to the actual June 2003 peak load conditions; the test cases with $ng = 1$, $ng = 2$ were executed again. Notably the vulnerability assessment procedure provides the same results of Section 4.1 as far as the identification of the worst case contingencies is concerned; the Porto Tolle power unit is still the worst single outage contingency while the two Vado Ligure units are involved in the most critical double contingency case.

However the degradation in voltage profile obtained by Vulnrea is remarkably worse. Table 2 shows the post-contingency voltage magnitudes obtained by the vulnerability assessment procedure in comparison with the corresponding base case situation.

In this case, however, it was found that the AC power flow failed to converge within the usual 1 MW – 1 Mvar convergence threshold. A careful examination of the iterations report revealed that the AC the power flow actually led a larger number of power units to saturate their reactive generation limits than according to the sequential linear programming procedure. A voltage collapse eventually occurred when all the reactive power generation margin was exhausted.

Such a result confirms the effectiveness of the proposed reactive vulnerability procedure in identifying

outage situations that may be dangerous for the power system. On the other hand it is apparent that, when the system is brought to operate close to voltage collapse by a given contingency condition, the linear model assumption adopted becomes troublesome and this might lead to an underestimation of the risk involved. For this reason it is so important that an AC checkout power flow solution is included as the final step of the procedure.

When $ng = 2$ the two Vado Ligure power units are put out of service with a large degradation of the voltage profile. Also in this case, the AC power flow successive to the end of the last iteration MILP problem fails to converge and, once again, voltage collapse results due to the lack of reactive power generation margins.

4.3 The Italy 2010 test case

A provisional Italian system relative to the year 2010 was also considered. In comparison with the Italy 2003 test case previously considered, the effects of some reinforcements both in the grid (commissioning and operation of new overhead lines in North-West and Southern Italy, new DC cable from mainland Italy to Sardinia) and in the generation facilities deriving from new power plants and re-powering (up to about 9000 MW) were taken into account. Peak load conditions are considered also with reference to this test case.

A first test case was carried out with reference to a rather unrealistic situation where the island of Sicily was importing power from mainland Italy. This kind of operation is banned from actual operating policy for reasons of security and stability.

The Vulnrea procedure (with $ng = 1$) identifies the outage of the Termini Imerese power unit, (Tyrrhenian coast of Sicily) as the most dangerous single contingency. The loss of 139 Mvar of the Termini Imerese plant causes a consistent although non-impressive decay

Bus name	Pre-fault voltage (kV)	Vulnrea
TERMINI	218.92	208.49
CARACOLI 220	218.69	208.43
CIMINNA' 220	215.8	206.37
B.ELLOLAMPO 220	218.28	209.61
PARTINICO	218.2	210.16
CARACOLI 150	151.12	144
CIMINNA' 150	144.34	137.96
PARTANNA	218.48	212.61
BELLOLAMPO 150	150.51	144.77
FAVARA	219.65	215.53

Table 3: Termini Imerese outage; voltage profile behaviour

of voltage profile of the 220 kV and of the 150 kV sub-grid results from the simulation; the voltage magnitudes of the nodes more deeply affected by this outage are reported in Table 3.

Rather surprisingly, the checkout AC power flow failed to converge in this case showing the occurrence of voltage collapse due to insufficient voltage support of the 150 kV sub-transmission system. It must be recalled, however, that, if a more realistic situation, implementing the actual loading and generation policies, were tested, this voltage collapse phenomenon would likely not show up.

Further tests were carried out with reference to the Italy 2010 system looking for other dangerous contingencies. In this phase the Sicilian subsystem was excluded from the possible occurrence of reactive generation outages by suitable database directives.

With $ng = 2$, Vulnrea selects the two power units of the Sparanise power plant (total reactive generation of 307 Mvar) as candidates for the worst contingency situation. The nodes showing the largest voltage decay are listed in the second column of Table 4. This test case is particularly significant since the checkout power flow converges to a solution, partially shown in the third column of the Table, only after many iterations. It is believed that this double contingency brings the system to a condition extremely close to voltage collapse, although still on the safe side. This fact is also confirmed by the maximum voltage decrease exceeding 11 kV and by the amount of the error in voltage changes evaluated by the Vulnrea procedure and by the AC power flow. Indeed, by comparing the last column of Table 4 with the corresponding column of Table 1, relative to a less stressed contingency event, it is apparent that errors are now 3 to 4 times larger in absolute value.

4.4 Computation efficiency and CPU times

A nice feature of the proposed procedure is that, despite of the computational complexity involved in the solution of the successive MILP problems, the CPU

Bus name	Vulnrea	Power flow	ΔV	ΔV error
SPARANISE	382.75	379.67	-11.3	3.09
S.SOFIA	383.5	380.5	-9.95	2.99
PATRIA	380.42	377.26	-10.0	3.16
S.MARIA	384.1	381.09	-9.36	3.01
S.VEROLA	384.59	381.58	-9.33	3.01
STRIANO	383.14	380.24	-8.76	2.9
BENEVEN.	387.63	385.15	-7.76	2.48
GARIGL.	385.24	382.62	-7.62	2.63
M.CORVINO	388.15	385.62	-7.04	2.53
CEPRANO	385.09	382.6	-6.63	2.49

Table 4: Sparanise double contingency; voltage profile comparison

time required for a complete reactive security assessment study remains limited within a few tens of seconds even in the most severe situations.

The number of successive linearizations required generally increases with the severity of the contingency study, ranging from 2 to 4 on the average. The CPU times similarly ranges from a few seconds to about 20 s for the more stressed cases. The CPU time required to carry out the initial and the checkout AC power flow is negligible (always less than 1 s) in comparison to the time needed to perform the MILP optimization by means of the CPLEX package.

The reduced CPU time burden of the Vulnrea procedure makes it valuable to system operators as well. Indeed Vulnrea could be employed as a tool for the identification of critical single or multiple reactive outages in a quasi real-time environment.

It is interesting to compare the timing results obtained with those of a contingency simulation approach based on direct enumeration of the different possible cases. For a 223 generator system (Italy 2003) a complete N-2 study requires 24753 load flows while a N-3 study needs more than $1.8 \cdot 10^6$ single case evaluations. Only under very stressed conditions, it happens that the enumeration approach becomes competitive with the proposed Vulnrea procedure.

5 FUTURE WORK

As previously mentioned, the present contribution is a part of an ongoing research on power system vulnerability which already produced a work [6] on the identification of critical line outages. The aim is that of combining the procedure described there with the one developed for the present work to obtain a full-fledged vulnerability assessment tool based on the real reactive decoupling principle. The envisaged procedure should be capable of dealing both with the real and the reactive effects of outages as well as with multiple contingency cases involving the loss of lines and generator units at the same time.

6 CONCLUSIONS

Detailed analysis of black-outs has shown that outages are often the initiating event leading to dramatic failures in which hidden failures in the protection system often play an important role. Following previous work by the same Authors, the strategy of finding the worst combination of possible contingencies has been pursued. The aim is that of providing planners and protection engineers with an indication of the weakest part of their system, i.e. the one where an initial outage has the highest probability of evolving in a cascading failure.

The perspective of reactive power unbalance and voltage profile degradation is the one considered in this work. The problem of identifying the most critical sequence of generator outages which is likely to endanger the system security is formulated here as a linear model with mixed (real and binary) variables. The objective function of the ensuing MILP problem is the most severe degradation in the voltage profile. To correct the errors introduced by linearization of the reactive power flow equations, an approximated sequential linear programming strategy is adopted which greatly improves the accuracy of results.

Up-to-date branch-and-bound and cutting plane techniques included in the CPLEX optimization package are employed for its solution. The proposed Vulnrea procedure proved to be effective in the identification of severe single or multiple contingency cases with reference to the Italian system. Indeed, with reference to some high load, extremely stressed situations, Vulnrea was capable of finding outages leading to voltage collapse.

The reduced computation burden and CPU time requirement make Vulnrea a valuable tool for reactive vulnerability studies either for the planner and for the system operator.

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