Interruptible Load as a Competitor to Local Generation for Preserving Voltage Security

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Abstract: This presentation focuses on voltage security analysis in a deregulated power market. The alternative methods to alleviate congestion using generator rescheduling and/or interruptible load rejection are compared. Quantitative results showing this comparison in the Hellenic Interconnected System are presented.
Keywords: Interruptible Load, Voltage security assessment (VSA), loadability limits, generation rescheduling,

I. INTRODUCTION

A. Interruptible Load as Generator Competitor

Deregulation of the electric power industry is in full effect worldwide and consists of the progressive unbundling of generation, transmission and distribution, in order to create market conditions allowing competition among electric energy producers. One key assumption, on which the deregulation process is based, is that increased competition will eventually result in lower energy prices for the consumers. However, it has been reported on various occasions that at periods of increased demand energy prices went increasing unreasonably.

A common factor in many of these incidents is the reduced capability of the transmission network to import power in the affected regions. In general, network limitations can create a distorted power market situation, where local generators have a decisive advantage due to the reduced competition. This is sometimes referred to as "market power" [1].

To overcome this problem without resorting to regulatory measures, one has to introduce more competition in the affected region. However, it is not always easy to build new generating stations in the such areas due to various difficulties, such as expensive land prices, difficulties of importing fuel, environmental constraints, etc.

The introduction of interruptible loads offers an attractive alternative to local generation in such cases. Interruptible load is made up of customers who agree to be interrupted when the security of the system is at stake, and are compensated by paying a reduced tariff. For instance such loads may be:

- industrial customers that either rely too much on electricity to have their own back-up generation.
- Industrial customers that can easily reschedule their production scheme in case of a power outage.
- residential customers who want to save on their electricity bill.

B. System Security and Network Congestion

Transmission constraints are encountered particularly in systems having weak connections among areas leading to transmission system congestion. Network limitations are of various types. For most developed power systems the limitations do not refer to the nominal operating state of the system (i.e. with all components available), but are rather security limitations. In other words the concern is that the system should continue to operate without problems for all single contingencies (usually referred to as N-1 security) and even for a number of "credible" double contingencies.

Power system security is divided into static and dynamic security. Static security deals with line flow limits and acceptable voltage levels. Dynamic security involves transient stability assessment (TSA) and Voltage Security Assessment (VSA). In [2] the case of voltage security constrained transmission systems in an open power market was discussed.

By introducing the concept of interruptible load, every time that the generation scheme resulting from the operation of the market meets a security constraint, the system operator has two alternatives:

- generation rescheduling (introducing out-of-merit local generation in the place of more efficient generation that is far away, or
- keep the generation schedule resulting from the bidding process and rely upon interruptible load disconnection in case of a dangerous contingency

The purpose of this presentation is to illustrate how a voltage security constraint can be alleviated using generator rescheduling and/or interruptible load. This is done using a realistic scenario based on the Hellenic Interconnected System, but using hypothetical bids.

II. CONGESTION MANAGEMENT

A. Overview of market operation

The market structure involves an Independent Transmission System Operator (TSO), who is responsible for meeting the load demand and establishing the price at which the market will be settled for each hour of the day. The method with which the market is cleared is transparent to all players. Here we will assume that the market is cleared by establishing an order of merit for the generator units using the bids made by the different electrical energy suppliers, so that the load is met at the lowest cost.

More specifically the suppliers submit to the TSO quantities and prices (bids), that are normally based on their variable cost, for each hour of the day, one day ahead. The bids are sorted by the TSO and a merit order for generators is obtained. The projected load demand of the hour is satisfied by the generator bids in increasing order of cost. The System Marginal Price (SMP) is thus defined by the last (most expensive) generator whose bid was accepted. The SMP is the cost of electrical energy for the specific hour of the day and all generators are remunerated at this price [3]. This procedure is then repeated for every hour of the day.

The TSO is also responsible to obtain a reasonable pre-specified reserve for each hour and it is assumed that this is achieved also by running a parallel market of the so-called "ancillary services". In this presentation we do not consider a separate reactive power market.

The generation schedule obtained through the order of merit is the "unconstrained" generator dispatch. This will subsequently be checked to verify that it allows sufficient security margins. If the security check is passed, then the schedule is finalized. If, however, the generation schedule fails to meet the network security requirements due to line overload, transient stability, or voltage stability considerations, the generation schedule cannot be accepted and network *congestion* results.

B. Transmission Network Congestion

Congestion can be defined as the inability of the transmission system to accommodate the energy flows arising from an unconstrained generator dispatch [4]. It may be considered as an *externality* that has to be internalized in the dispatch process.

Congestion due to static security (mostly line overloading) is the main transmission constraint analyzed so far. It can be detected by using simplified load flow models (usually DC load flow). By repeatedly running a linearized (DC) load flow for various load and generator patterns, the Available Transfer Capability (ATC) between two areas in a system can be defined.

When congestion appears, the system is divided into areas separated by the congested transmission corridors. Several schemes for congestion management have been proposed and applied.

Using the *zonal pricing* model, the system is divided into bid areas separated by the corridors, for which different bids are submitted [5]. The spot market is first resolved as an uncongested one and if transfer between areas exceeds limits, then each is area separately settled using only the bids for that particular area. Bid areas with different prices after market settlement are called *price areas*. Clearly in this case all the generators in the congested area have a market advantage.

Alternatively, the following scheme can be adopted: congestion is corrected by including in the dispatch schedule the generator in the congested area with the lowest unsuccessful bid (constrained-in, or must-run generator) and removing from the dispatch list the most expensive of the generators outside the congested area (constrained-out generator). The SMP remains as in the unconstrained dispatch, but both the constrained-in and the constrained-out generators receive additional compensation that forms the *uplift cost*, which is subsequently shared by all the participants.

The uplift cost of the constrained-in generator is determined by the difference between its bid and the SMP. For the constrained-out generator the uplift cost consists of its compensation for expected profit lost, i.e. the difference between the SMP and its successful bid. This scheme reduces the effect of the congestion on market players, since the SMP is unchanged, but it may be seen as unfair by the other generators in the affected area that receive less payment for the same service, and are thus penalized for being economical. Thus one may expect them to increase their bids as well.

C. Interruptible Load for Congestion management

The problem associated with the above schemes of congestion management is that they introduce the risk of increasing electricity prices due to the market power of local generators in the congested area.

One alternative to the above schemes is the management of congestion through load disconnection, instead of generation rescheduling. This requires that some load should be assigned as interruptible. The interruptible load will have a special tariff depending on the maximum number of interruptions (or the total interruption time per year). The load rejection relays will be armed by the TSO for the projected hour of day, where the system is expected to be insecure and will give a trip signal in case any of the foreseen critical contingencies will occur.

Under this scheme, the amount of price reduction offered to loads that choose to be interruptible will be decided based upon the expected uplift cost of generation rescheduling during the critical periods of the year, basically Summer and Winter peaks.

As long as the TSO has available interruptible load, this is the first to be scheduled for interruption, in case of an insecure operating state. If the resulting security margin is still insufficient after the load disconnection, then the out-of-merit local generation will be included in the dispatch, as discussed above.

Alternatively, an auction similar to that of generators could be introduced, with loads offering bids for power reduction at the same time with generator bids.

The introduction of interruptible loads provides a competitor to local generators, which will no longer be in a position to increase their bids. Thus the congested area power market is stabilized.

III. VOLTAGE SECURITY ANALYSIS

Power system security is usually defined as the absence of risk of system operation disruption. In other words it is the ability of the system to withstand, without serious consequences, any one of a list of "credible incidents".

Congestion due to voltage security is the main issue analyzed in this presentation. It arises when there is insufficient local real and reactive power production within an area with heavy consumption. In voltage insecure cases there exist credible contingencies that induce long-term voltage instability. This in turn may lead to excessive low voltages, as well as severe short-term instabilities.

Voltage security is a complex problem involving highly nonlinear phenomena and can not be assessed using approximate linear methods, which is a common practice for market analysis purposes. Thus VSA should be performed using AC load flow and, preferably, specialized voltage stability programs. Since many factors influence the outcome of voltage security studies, such as direction of system stress, generator participation in load pick-up, type of overexcitation protection of generators, etc., it is relatively more difficult to establish ATC values beforehand for VSA. The VSA is thus assumed to be executed after the unconstrained dispatch has been determined.

In the sequel we will use the well-known criterion of N-1 security, according to which a system must be able to withstand any single transmission or generation outage without entering an emergency state. In particular we will require that the system is able to withstand all single contingencies followed by a 6% increase of load demand (considered as constant admittance for medium voltage loads behind LTC transformers and constant current for high voltage customers) distributed proportionally among all buses in the system. During this load pick-up it is required that the precontingency load consumption will be restored in every major area of the power system.

The last requirement is introduced (as it will be seen in the case study) in order to guard against a case where voltage instability is hidden in the simulation because the LTCs have reached their range limits, thus stopping the load restoration process. In such a case it is likely that load will be restored downstream of the LTC by increased demand, or distribution system voltage regulators. Thus our criterion is a positive post-contingency loadability limit. The concept of post-contingency loadability limits is illustrated in Fig. 1 using PV curves.

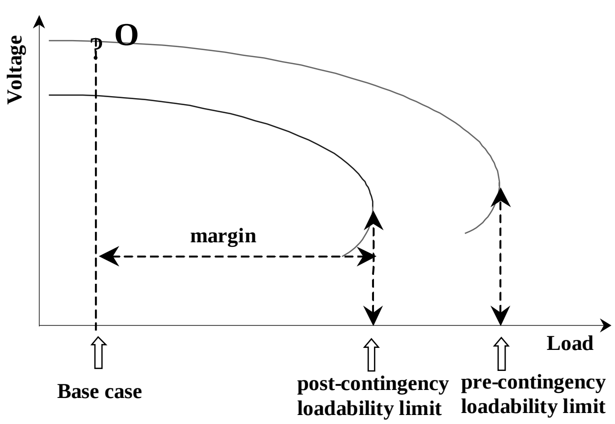

Fig. 1. : Post-contingency loadability limits evaluation

For the purpose of contingency evaluation a long-term simulation program (WPSTAB), which has been developed at NTUA is used [6]. WPSTAB relies upon the Quasi Steady State (QSS) approach [7,8] based upon the time-scale decomposition of power system dynamics and a simplified representation of short-term dynamics, when focusing on long-term phenomena. This program is presently used by PPC during system planning for off-line contingency evaluation and the classification of countermeasures against voltage instability and collapse. It is foreseen to be installed in the Control Center of the future HTSO together with other security analysis software, for contingency evaluation and in-depth analysis purposes.

IV. CASE STUDY

A. The Hellenic Interconnected System - Description

The electricity market in Greece is expected to open on February 2001. Eligible large customers represent 26% of the total demand. An organized day-ahead market for electric energy, as the one described in section IIA, is expected to be established under the responsibility of the Hellenic Transmission System Operator (HTSO). HTSO is also responsible for the secure operation of the Hellenic Interconnected System. All market players will operate under the rules established by the Grid Code.

Fig. 2 shows a single line diagram of the Hellenic Interconnected System. The main production center is in the north of Greece in the vicinity of the lignite rich area of Ptolemais. Thermal power plants in this area generate about 70% of the total electricity in the Greek mainland. Significant hydro generation exists also in the north and the northwest of the country. There is also significant lignite power generation in the southern peninsula of Peloponnese; natural gas and oil-fired generation exists near Athens metropolitan region. All international interconnections, with the neighboring systems of Albania (with 150kV and 400kV lines), Bulgaria (one 400kV line) and former Yugoslavia (150kV and 400kV lines), are also in the North.

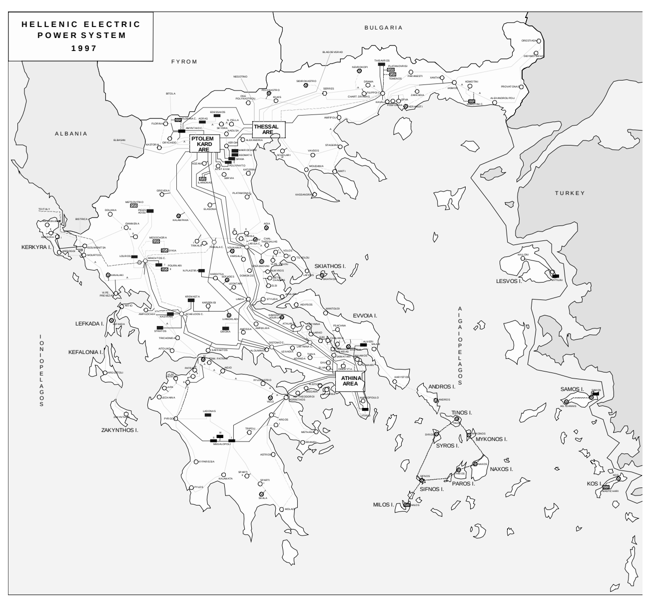

Fig. 2. : The Interconnected System of Greece

Two parallel transmission networks, operating at 400kV and 150kV respectively are in operation. The 400kV transmission network has a dominant presence in the northern and central part of the system, playing the primary role in the power transmission to Athens. There is no 400kV transmission in the peninsula of Peloponnese, served exclusively by the 150kV transmission network, including a weak submarine cable to Western Greece. The 150kV network covers the secondary transmission needs as well as radial distribution needs in the metropolitan area of Athens.

The peninsula of Peloponnese has a local generating plant located in Megalopolis with a significant total generation capacity of 800 MW. However, in case of local unit unavailability during peak hours this area is heavily importing power. During the Summer peak of 1996 severe voltage stability problems have been experienced in the Southern part of the system, namely in the Athens area and in Peloponnese, that were due to the reduced generation availability in this area [9]. Following this incident the Athens area was reinforced in a variety of ways. New local combined cycle and natural gas generation was added, more capacitor banks were installed. Also, the 400kV transmission is operated at higher voltages during summer peak hours. As a result of these and other system upgrades, the Athens region is now relatively secure with respect to voltage stability. However, as is the rule in such cases, the corresponding instability mode has moved further South, so that Peloponnese is currently the area vulnerable to voltage security risks.

B. Voltage security assessment of the Greek Power System

Table 1 depicts an assumed order of merit of the available units in the South part of Greece, ordered according to their hypothetically submitted bids. It should be made clear at this point that the entire scenario studied is not based upon actual cost data for the units, which are not (and should not be) available to anyone but the Regulator. Thus the assumed order of merit is completely random.

Table 1: Units sorted according to their hypothetical bids

Unit	Load (MW)	Area
⋮		⋮
AHSAG 8	160	Metropolitan Athens
⋮		⋮
LAURIO 1	150	Metropolitan Athens
LAURIO 2	300	Metropolitan Athens
LAURSC	550	Metropolitan Athens
MEGALOPOLI 3	250	Peloponnese
PTOLEMAIS 2	125	Northern Greece
PTOLEMAIS 3	125	Northern Greece
MEGALOPOLI 4	300	Peloponnese
⋮		⋮
AHSAG 9	200	Metropolitan Athens
MEGALOPOLI 2	125	Peloponnese
MEGALOPOLI 1	125	Peloponnese

The units up to the double lines were successful at the unconstrained clearing of the market. As seen in the Table, two units of the power station of Megalopolis in Peloponnese are assumed to have been driven out by the market. Note also that a small hydro power plant in Peloponnese of an installed capacity of 60 MW has been assumed unavailable.

Voltage Security Assessment performed for the unconstrained generation scheme of Table I shows a severe voltage instability after the tripping of Megalopolis 4 generating unit. The instability leads to voltage collapse ending up to a loss of synchronism. The eigenanalysis and sensitivity analysis performed shows that Peloponnese is the critical area for this instability.

Clearly a voltage security congestion problem is encountered that has to be removed either by generation rescheduling, or by interruptible load rejection as discussed in Section IIC.

C. Interruptible load vs. generation rescheduling

Assuming at first that there is no interruptible load, generation rescheduling is performed by committing local generation units with unsuccessful bids instead of remote ones. As discussed above, the voltage instability is localized in the area of Peloponnese, therefore units in the metropolitan area of Athens (like AHSAG 9) are not effective in managing the congestion.

The unit Megalopolis 2 is first dispatched in the place of the unit Ptoleamais 3 in Northern Greece, that was assumed in Table I to be the most expensive outside the congested area. The result is a much milder instability, with transmission voltages in Peloponnese as low as 78%, but without voltage collapse. The load in the area of Peloponnese cannot be restored to its predisturbance value, leaving a negative margin of -1.4%.

Consequently the unit Megalopolis 1 must also be included in the redispatch, in the place of Ptolemais 2 in Northern Greece. With both units Megalopolis 1 and 2 in service the system remains stable after the loss of Megalopolis 4 with all load restored and a positive security margin of 2.6%. Voltages of transmission buses in Peloponnese are still low after the contingency and the load ramp, but are all above 0.85 pu and thus the system with all Megalopolis units in service is considered secure.

The uplift cost UC in this case is:

$$UC = (B_{M1} - SMP)x125MW + (B_{M2} - SMP)x125MW + (SMP - C_1)x125MW + (SMP - C_2)x125MW$$

where B_{M1} and B_{M2} are the bids of units Megalopolis 1 and 2, and C_1 and C_2 are the successful bids of the constrained-out generators.

Consider now that a large industrial customer in the area of Peloponnese with a load of 25 MW, 12.1 MVar is assigned as an interruptible load. A simulation run with the unconstrained dispatch and this load disconnected at the time of the contingency (loss of Megalopolis 4) shows that the system is still voltage unstable, although the collapse is avoided. The load in Peloponnese is not restored leaving a large negative margin of –6.5% and the transmission voltages in Peloponnese drop below 70%. Thus the interruptible load is not sufficient to restore voltage security by itself.

The next step is to reschedule unit Megalopolis 1 instead of Ptolemais 3, as well as disconnect the interruptible load following the contingency. In this case there is a marginal load restoration after the contingency and the voltages after the load ramp are above 82%. Thus the operating scheme with the interruptible load and only one unit redispatched is considered marginally secure.

It is thus concluded that the interruption of a 25 MW load is an alternative to rescheduling of 125 MW in order to preserve voltage security.

Using load rejection the uplift cost of generator rescheduling is reduced by al least 50%, but the cost of interruptible load has also to be considered.

VII. CONCLUDING REMARKS

The problem of congestion due to voltage security, or other network limitations, is always present in systems having weak areas, or overstressed corridors. The problem of the dominant market position of generators in these areas that may lead to unreasonably high prices, can be solved by including interruptible loads as competitors to expensive local generation.

In the example case studied, a voltage security limited system was studied with hypothetical bids and it was found that an interruptible load of 25MW with a 0.9 power factor is roughly equivalent in terms of restoring voltage security to the redispatching of 125 MW of generation. Careful auditing of the actual costs in such a case, will provide a reasonable compensation for the interruptible load, which will in turn discourage unreasonable bids by local generators during hours of foreseen congestion.

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BIOGRAPHY

Costas D. Vournas received the Diploma of Electrical and Mechanical Engineering from NTUA in 1970, the MSc in Electrical Engineering from the University of Saskatchewan in 1976 and the Doctor of Engineering again from NTUA in 1986. He is currently Professor in the Electrical Energy Systems Lab of the Dept of Electrical and Computer Engineering of NTUA. His research interests include voltage stability analysis, as well as power system control.