AN INTERRUPTIBLE LOAD MANAGEMENT METHOD WITH CONSIDERING VOLTAGE STABILITY IN A RESTRUCTURED POWER SYSTEM: AN OPF APPROACH

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INTRODUCTION

A common standpoint shared by nearly all restructured electricity market is designation of a system operator that is responsible for reliable real time control and secure operation of the transmission system. This enables efficient operation of competitive electricity and ancillary services markets. Reactive power and voltage support are among those services that should be provided efficiently for preventing occurrence of voltage instability in a power system. Common experiences of power system operation under restructuring environment in different countries, reveal that Independent System Operator (ISO) should pay attention to recognition of power stability margin more precisely than before. In this new era all rivals compete for higher profit margin in trading of electricity as much as possible. This strategy might endanger some parts of power system. Therefore it is vital for ISO to procure different kinds of ancillary services necessary for harness of power system instability. Generally voltage magnitudes at load buses are regulated with injection or absorption of determined amounts of reactive power at voltage control buses where reactive power can be provided by special devices such as generators, fixed capacitors, static VAR compensator and etc. Besides procurement ISO will attempt to use reactive power resources to keep away from voltage instability points such as saddle node Bifurcation (SNB) or Limit Induced Bifurcation (LIB) points as far as possible [1]. Prominent characteristic of reactive power strongly requests that it should be provided locally rather than transferring from long distances. In these areas where reactive power encounters with shortage in resources ISO can take advantage of interruptible loads to overcome the problems.

Interruptible loads can be exploited for different purposes, for instance increasing active / reactive power reserves, promoting stability conditions, congestion management and etc in a deregulated power system. The benefits of using interruptible loads are debated in [2-4] with all the specifics. [5] Demonstrates the advantage of interruptible loads to increasing active power reserve while [6] investigates the profits gained at using them for improving of introduced static voltage stability index.

In this paper appose to [6] we use voltage stability margin index as a main constraints of an OPF based structure proposed for managing interruptible loads in a restructured power system. Other constraints of this optimisation problem consist of limits pertain to magnitudes of bus voltages, magnitudes of transmission line currents and constraints related to resource’s limits. The model is then implemented by introducing a new OPF method through Particle Swarm Optimisation algorithm. Case study on the IEEE 14 bus test system is reported to illustrate the proposed method.

A COMPETETIVE MARKET STRUCTURE FOR INTERRUPTIBLE LOADS

In general, two different kinds of market structure can be considered to promote competition among interruptible loads. These are referred to simultaneous and sequential markets. ISO is in charge of secure operation and management of the system in both cases. In simultaneous market structure, participants, generating and loads, are required to offer both their base generation and consumptions along with their adjustable parts at the same time. In contrast to simultaneous market, sequential one, participants first compete to trade electricity in power free market and then they are allowed readjusting their required power in a regulation market. In this stage apart from the structure of power market (power pool market or bilateral contracts) every market player can offer some portion of his financial transactions to market operator or system operator depends on market structure. In this paper we consider the regulating market is operated independently and after clearing of energy market that is performed by ISO or MO. Hence it is assumed that after clearing of electricity market, some participants decide to sell a limited portion of their power to regulation market before the transaction are to be executed physically on the network. Winners are distinguished by ISO depend on their offers and also their influences on technical characteristics of power system at each moment. For getting better accomplishment, regulation market is operated about 1 hour before trading market is finished. It is evidence that, in this structure the player should know power system network restrictions for making a better decision. In brief, ISO declare the results of regulation market arranged on hour K-1 for the next hour – K- serially. Figurer 1 depicts the interval times of proposed regulation market.

BID STRUCTURE OF MARKET PLAYER

One of the main proposes of ISO is to take advantage of interruptible loads for increasing of voltage stability margin where enough reactive power resources is not available use. In view of the fact that in our proposed market structure, any distinguishable market for reactive power does not exist. We assume that its costs will also be cleared in regulating market. Therefore loads are requested to participate in regulating market by specifying their offer consist of two components, one part is related to their adjustable power in MW and the other is pertain to their suggesting prices in ($/MW).
Reactive power prices provided by static compensators such as fixed or variable capacitors, SVC... are modelled by their investment and operational costs in ($/MVAR) [7]. Power generators are inherently capable to produce or absorb reactive power at buses they are connected. Exact determination of generator reactive power cost, if it is not possible, is very hard. In such a case reactive power cost is usually divided into two parts: explicit and implicit. [8, 9] have demonstrated the cost incurred by a generator due to generation or absorption of reactive power. Investigations show that usually operational reactive power cost of a generator is very small comparison with its loss opportunity cost. When a generator is compelled to reduce its active power output for more generation of reactive power, based on its capability curve, it should be compensated in some how that does not feel any change in its profit. This payment that cause profit of a generator to be the same at different situations is called opportunity cost and can be modelled as below [10].

\[
C_{gpi} = k_{g} C_{ggi}(S_{gimax}) - C_{ggi}\left(\sqrt{S_{gimax}^2 - Q_{ggi}^2}\right)
\]  

In this equation \( Q_{ggi} \) and \( S_{gimax} \) is referred to reactive power and maximum apparent power of generator \( g \) and \( C_{ggi} \) represents the cost incurred by active power generation that can be evaluated as \( C_{ggi} = aP_{ggi}^2 + bP_{ggi} + C \). In above equation, \( k_{g} \) pertains to profit rate of active power generation and usually is considered between 0.05 - 0.1.

**ISO's POINTS OF VIEW IN INTERRUPTIBLE LOAD SELECTION**

Interruptible loads can release active and reactive loading capacity of the network at the same time. However their incurred costs are very high in comparison with using reactive power capability of compensators installed at loads area buses. Therefore ISO should be minimize the cost of reactive power procurement from generators, static VAR compensators along with the cost may be appear due to purchasing of curtail able loads. In this strategy, technical condition should be complied simultaneously. Voltage stability margin can be distinguished as an index identifies how much current operating point of power system is far from to instability point. In fact voltage stability margin is equal to amounts of power that can be added to every loads and generation connected to power system before system goes to instability region. This margin is illustrated graphically in fig.2.

This criterion can be modelled as following:

\[
VSM = P_{MAX} - P_{o} \quad \text{Where:} \quad (2)
\]

**VSM**: Voltage stability margin.

\( P_{MAX} \): Maximum feasible loading capacity of the power system.

\( P_{o} \): Current operating point.

**PARTICLE SWARM OPTIMIZATION ALGORITHM**

Particle swarm optimization algorithm (PSO) is a new evolutionary computation technique motivated by simulation of social behavior [11-13]. This method is well developed for optimization of continuous nonlinear functions. PSO is similar to Genetic Algorithm in that the system is initialized with a population of random solutions. In PSO agents share their best information of previous experiences of searching feasible solution space to the other ones to help neighbors for finding global optimum point. Referring to fig 3 one can pursue PSO’s algorithm as following:

**Step1** - a number of agents as initial population is positioned in searching space of the problem. Their initial velocity is also assigned to them. Populations are categorized into different classes on their geometric distance from each other.

**Step2** - objective function is evaluated for each agent. Then the best point of separated groups is determined by sorting of cost value in descending order. This point can be considered as relative global point in each group.

**Step3** – In this stage the best point among all searching group will be distinguished. Moreover the best point experienced by each agent is also saved in memory of particles. The first information is referred to global optimum point of each group while the second can be referred to local optimum information. According to these data, particles are motivated to move toward following direction:
\[
V_{i}^{t+1} = V_i^t + \alpha (P_{gi} - X_i) + \beta (P_{e_j} - X_j) \\
X_{i}^{t+1} = X_i^t + V_{i}^{t+1}
\]

Where:

- \( V_i \) and \( X_i \) are current velocity and position vectors while index \( t+1 \) is referred to next direction and position of particles. \( \alpha \) and \( \beta \) are random numbers in the range \([0,1]\). \( P_{gi} \) is global position in each group and \( P_{e_j} \) is local optimum point found by agent \( i \).

**MATHEMATICAL FORMULATION**

IEEE 14 - bus test system is considered as a network for implementation of OPF based model of following presented regulating market structure. One line diagram of this network is shown in fig 4. All detail information of this system is presented in [1]. Bus No.1 is assigned to slack generator where active or reactive power mismatches is provided from. Reactive power outputs of other generators are adjusted by varying their voltage magnitudes. In other words output voltage of generators form a part of control variables. One SVC is placed at bus no 19 with maximum capacity of 0.19 p.u based on 100MVA. This variable along with all consumption loads form remain parts of control variables. In this study it is assumed loads vary at constant power factor direction. Based upon above assumptions one can use following mathematical market model to determine optimal solution of available resources in different situations.

\[
\text{Min} \sum_{j=1}^{3} \text{cost}_j \\
\text{s.t:} \\
P_{Gi} - P_{Di} + \Delta P_{Di} = \sum_{j, j \neq \text{slack}} \left| V_j \right| \left| V_i \right| \cos(\theta_i - \theta_j - \phi_j) \\
Q_{Gi} - Q_{Di} + \Delta Q_{Di} = \sum_{j, j \neq \text{slack}} \left| V_j \right| \left| V_i \right| \sin(\theta_i - \theta_j - \phi_j) \\
MVA_{j \text{min}} \leq MVA_{j \text{max}} \\
V_{j \text{min}} \leq V_i \leq V_{j \text{max}} \\
Q_{j \text{min}} \leq Q_{j} \leq Q_{j \text{max}} \\
0 \leq \Delta P_{Di} \leq P_{Di \text{max}} \\
VSM \geq VSM_{\text{Desired}}
\]

Where:

- Cost1: is interruptible load procurement cost.
- Cost2: is SVC reactive power cost.
- Cost3: is generator reactive power opportunity cost.
- Other symbols used here are standard in this literature.

**SIMULATION AND RESULTS**

Case1 – In this case voltage generators are fixed at their nominal values and it is assumed that ISO will use only interruptible loads for increasing voltage stability margin. Reactive power output of generator 2 is about 45.184 MVAR. This value is very close to its maximum capability. VSM of the system in normal case is calculated 0.057 pu. This value refers to limit induced bifurcation and is calculated using CPFLOW method [14, 15]. Decreasing 10% consumption loads will increase VSM to 2 pu. This indicates load reduction have a proper effect on improving this index. Figures 5–7 show generators reactive power outputs and interruptible load management related to VSM while increasing from 0.05 pu to 0.27 pu. Costs of interruption load are listed in table 1.
Figure 5 indicates that load reduction will also increase reactive power reserves of the system.

**Case II-** In this case voltage of generators as well as interruptible loads is assumed to be controllable. This means ISO can use both of them to operate the system in a safe manner. Results of simulations are presented in figures 8~11. It can be clearly seen, interruptible loads are not exploited until voltage stability index reach to 0.27 pu. As a matter of facts, OPF formulation prefers to use reactive power resources instead of using expensive curtail able loads reasonably. At this stage if ISO decide to increase VSM more than 0.27 pu. OPF formulation pursues load reduction to enhance voltage stability margin. Figures 8 and 9 depict generators voltage profile and reactive power outputs respectively. Referring to these figures one can find that generators reactive power outputs vary slightly before VSM reaching to 0.27 pu. One reason of this behavior may akin to inherent characteristics of the power transmission line network. These figures also show that when interruptible loads are utilized to alleviate power system, reactive power produced by generators will decrease similar to results obtained in previous case study.
CONCLUSION

In this paper an OPF based structure is presented suitable for managing of interruptible loads in a deregulated power system. The equations of the model is so arranged to well represent the proposed sequential market structure. Particle swarm optimisation is used to determine optimal interruption loads with respect to technical and economical aspects. Financial proposes is considered to be as main objective function while technical indices are modelled as soft constraints within the problem. Different case studies are implemented on IEEE 14 bus test system. It is shown that it is possible to use interruption loads for increasing of voltage stability margin of the network, however it may cost more than using static or dynamic reactive power resources.

REFERENCES