CONSTRAINT ANALYSIS TECHNIQUES FOR ACTIVE NETWORKS

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ABSTRACT

The adoption of active network management can mean that generators are offered "non-firm" connections to constrained networks. Constraint analysis provides estimations of the frequency and magnitude of constraint conditions experienced by non-firm generators, and the resultant curtailment of export in response to the constraints. In this paper, the key stages of the constraint analysis process are introduced; at each stage a variety of techniques are available. These techniques are discussed and mapped to the typical problem characteristics to which they are best suited.

INTRODUCTION

Network constraints on congested distribution networks present a barrier to the integration of further growth in distributed generation (DG). Various types of constraint may prohibit the connection of DG, with the traditional solution of network reinforcement often resulting in long time delays and the cost of connection becoming uneconomical. Provision of a "non-firm" network connection, enabled via Active Network Management (ANM), provides an alternative method of accommodating DG with less network reinforcement. Smarter Grid Solutions Ltd is responsible for the successful delivery of ANM systems [1], facilitating the non-firm connection of DG onto congested networks previously considered at full capacity.

ANM enables the non-firm connection of DG via the real-time control of energy export or other variables, maintaining network parameters at constraint locations within operating limits. On occasions when network parameters are at risk of breaching limits, control actions are exerted on participating generators, most commonly in the form of curtailment of energy export. Assessing non-firm DG connections requires the estimation of the frequency and magnitude of control actions required from non-firm DG under constraint conditions. Such estimations are calculated through investigation into the constraints which occur and the energy curtailment required from non-firm generators. The non-firm network capacity at constraint locations is a dynamic parameter, dependent on variable factors such as the level of demand and generation export behind the constraint location. Constraint analysis must model these variations in order to investigate the dynamic nature of constraints and resultant curtailment.

The primary aim of constraint analysis is to provide information on the frequency and magnitude of constraints which may arise, and model the resultant implementation of control actions across participating non-firm DGs. The most instructive output from constraint analysis is the estimate of curtailment enforced on non-firm DG connections across a typical annual period. This can provide an estimate for annual constrained energy export, which when compared to its unconstrained equivalent energy export, can illustrate the impact of accepting a non-firm connection.

Different types of constraint can exist, and may result in the implementation of other control actions with non-generator devices. Within this study, however, examples of constraints relate to thermal power-flow constraints, with resultant control actions in the form of DG export curtailment. For other types of constraint and control action, similar approaches to that described in this paper would be applied.

MODELLING VARIABLE NETWORK PARAMETERS

Constraint analysis must take account of the variation in generator export and demands on the network, as these parameters define the amount of non-firm capacity available to non-firm DG. In addition to the dynamic nature of non-firm network capacity, the non-firm DG under study may have an intermittent export profile, for example from wind turbines. The combination of intermittent non-firm DG export and the dynamic constraining non-firm network capacity must be modelled together to form an estimation of curtailment the non-firm DG will experience. If other flexible parameters, such as dynamic line ratings exist, these should be modelled alongside demand and intermittent generation. The two primary approaches to modelling variation are time-series data profiles or probabilistic distribution functions.

Modelling of variable parameters via time-series data profiles presents the variation in level at uniform intervals across a set period. Such profiles often reflect observed measurements from devices on the network. If sufficient correlation is expected between parameters, for instance different load locations on a section of network, a data profile may be normalised and re-scaled to represent the variation in the other parameter. When used sensitively, this technique can be applied to model variation in network parameters for which data is not available. If no profiles are available for some network parameters, and re-scaling is unrepresentative of the parameters, the process for creating time-series profiles from scratch can be extremely complex.

For cases where no time-series profiles are available, variable network parameters may be modelled using a representative probability distribution function (**PDF**). If knowledge exists about the behaviour of the parameter, generic **PDF**s can be manipulated to model the parameter. The probability distribution reflects the probability of a parameter being a specific value at any point in time. If variation in parameter behaviour is expected, for example demand across seasons, a **PDF** can be generated for each individual season. It is also possible to convert time-series data profiles into an equivalent probability distribution. Regardless of the manner in which the variable network parameters are modelled, there must be confidence that the modelling represent the stochastic characteristics of the parameter to a reasonable degree. The results presented from constraint analysis studies are heavily influenced by the variable input parameters, therefore for the constraint analysis to provide a realistic representation of the network, the modelled parameters must reflect their real-life equivalent.

STAGES OF ANALYSIS

The constraint analysis process can be divided into three fundamental stages, described in the following sub-sections:

- Preparation of Input Data
- Curtailment Calculation
- Output Analysis

At each stage there are different of techniques which can be applied. The variety of techniques available provide flexibility, allowing constraint analysis to be performed under circumstances of varying data availability, required precision, modelling and calculation platform, and output requirements.

Constraint analysis may be performed for a set of scenarios, each studying the network under different characteristics such as: network topology, connected generation, or different input profiles representing variable parameters. This allows the analysis to cater for uncertainty in future developments, such as the growth in DG or changes in demand.

Preparation of Input Data

Curtailment calculations are performed across a range of network conditions, each representing the network under a specific realisation of the variable parameters, such as DG export and local demand. Sources of input data include time-series data profiles and probability distribution functions to describe the variable parameters. The manner in which these sources of data are manipulated for use within the study depends on factors such as the initial source of data, the length of period it represents, and format of results to be presented. The available techniques in which to prepare suitable input data profiles are described as follows.

Deterministic time-series data profiles can be directly implemented in the constraint analysis process, representing the variation in network parameters in a sequential, temporal manner. For such profiles to be used as a direct input to the analysis, all variable parameters must be represented by a time-series profile, complete across the entire study period. If inter-dependency exists between parameters, it is necessary for all profiles to be concurrent; i.e. correspond to the same period of time.

Monte-Carlo Sampling (MCS) can be applied to probability distribution functions, creating profiles of random samples for each variable network parameter [2]. Unlike the application of time-series profiles, the profiles generated via MCS have no inter-dependencies between entries, each sample is independent of the previous one. If correlation exists between different parameters, this must be accounted for in the sampling process. MCS is best applied in studies that contain multiple variable parameters represented by probability distributions. For some techniques of presenting results, MCS is a pre-requisite input technique. The number of samples which must be generated for each variable parameter will depend on the chosen treatment of the outputs from the study.

Discrete evaluation of probability distributions can be implemented to studies with suitable input characteristics. This technique involves the conversion of continuous probability distribution functions into discrete equivalents; each discrete value has a probability of occurrence. Assuming that all variable parameters are independent of each other, each potential combination of discrete realisations can be studied, and assigned a probability of occurrence. When a small number of variable parameters exist, this is a relatively quick way to perform constraint analysis, however if discretization is performed to a high resolution, or a high number of variables exist, the number of studies required to evaluate all potential operating conditions grows at a high rate.

Curtailment Calculation

At this stage of the analysis process, a simulation of network operation is performed for each instance of fixed input variables. This stage requires the modelling of the network under study to a sufficient degree to represent the constraint behaviour. Following network simulation, active constraints are identified, and in the case that such constraints exist, control actions are derived and implemented to eliminate the constraint. The manner in which the network is modelled and simulated will depend on factors such as available analysis platforms, complexity of the network under study, and number of discrete network states to be studied. The two basic approaches for performing curtailment calculation are simple calculation-based modelling methods, and power systems analysis software-based modelling methods.

Calculation based modelling methods provide a quick and uncomplicated approach to modelling and studying network constraints. Such methods approximate the power flow at each constraint location by aggregating the generation export and local demand behind the constraint location. Upon identification of active constraints and the magnitude of the overload, required curtailment can be determined and executed at ANM-participating non-firm generators. Application of this method requires the modelling of the network in terms of the constraints, mapping all generators and system demands to their respective constraint locations. The key benefit of this approach is the speed with which a large number of network states can be studied, and the relatively simple modelling process.

The estimation of power flow at each constraint location is a simplified approximation, and does not take account of factors such as voltage, losses or reactive power flows. Margins may be applied to the limits at the constraint locations to account for such factors.

Calculation-based modelling methods are best applied to studies with radial or simple meshed network topologies. For cases with radial topologies, it is possible to assume a 1:1 relationship between generator export/demand and the level of power flow at the constraint location. Under cases with meshed network topologies, this assumption will not hold, and sensitivity factors must be determined and applied to represent the relationship between generator export/demand and level of power flow at the constraint location.

Power systems analysis software based modelling methods provide a detailed representation of the study network and accurately simulate operational behaviour. This approach models the study network within standard power systems analysis software and performs load-flow simulations to identify network operating conditions. Performing load-flow simulations ensures that losses, reactive power flows and system voltages are taken into consideration, and provides an accurate indication of power flows on the network. Following identification of active constraints, suggested curtailment actions are implemented via the use of sensitivity factors, and another load-flow simulation performed. This process continues iteratively until all active constraints are eliminated.

It may take several iterations of load-flow simulations and subsequent control actions before all constraints are eliminated under a single network state instance; therefore this method is significantly more time-consuming than the simplified calculation method. However, the software-based modelling approach has the advantage of modelling complex power flow relationships in meshed networks, and accounting for losses and reactive power flows.

Under both calculation-based and software-based modelling techniques, it is essential to ensure that control actions are implemented in an order that reflects the "principles of access". If nested constraints exist, where one constraint location sits behind another, care must be taken regarding the order in which constraint locations are assessed. The most-nested inner, constraint must be eliminated prior to any outer constrains, as the updated, curtailed export from generators behind the initial constraint will modify power flow at the outer constraint location.

Output Analysis

Once the curtailment calculation process has been performed for all data within the input profiles, a large amount of information is available regarding network operating points and curtailment volumes under each network state. The next stage is to analyse this information and extract the key findings from the results. The manner in which the calculation outcomes are prepared as results depends on the manner in which the input data was collated.

Single-point estimates provide the most straightforward manner to present outputs from the constraint analysis; as individual estimations of expected curtailment across the planning period. Single-point estimates can be calculated finding the average observed from the array of calculation outputs and scaling the average up across the duration of the planning period, most likely to be a year. Single-point estimates of constrained DG export are best considered in the context of their unconstrained equivalent, therefore estimates are extracted from both the input data profiles and the outcomes from the curtailment calculation process.

If time-series profiles are directly applied as input data, single-point estimates can be limited in that they only provide an illustration of curtailment across the period covered by the data profile. In the case of MCS generated input profiles, the number of samples generated must be sufficiently high that the sample average of study outputs converges to an adequate level of accuracy.

Probabilistic estimates [3] can be extracted when studies use input profiles that take account of long-term, multi-year, variation in behaviour. The results are split or sampled into sub-sections of uniform size. A single-point estimate of results is created for each sub-section from its sample average. This creates a series of approximations for annual constrained non-firm DG export, which can be represented as a probability distribution function. Statistical analysis of this distribution can be performed to provide parameters such as the exceedance probability values for curtailed export, the P90 and P50 values. The P90 value is the approximate export which DG is expected to reach 9 years out of 10, or 90% of the time. Similarly, the P50 value presents the approximate median energy export from DGs. This information is familiar to wind farm developers and their lenders, and provides a more detailed illustration of curtailed export estimates than a single-point estimate.

Two examples of typical outputs plots from constraint analysis are provided in Figure 1. The first presents the results from a constraint analysis study which determines a single-point estimate of annual constraint export, compared to its unconstrained equivalent. The second presents a probabilistic distribution of multiple annual approximations, based upon MCS. It is clear that providing a probabilistic distribution of annual constrained export presents more information. To perform such analysis, however, input data must be representative of parameter variation across a period greater than two or three years, ensuring that long-term variability is taken into account.

MAPPING SOLUTION TECHNIQUES TO PROBLEM CHARACTERISTICS

Table 1 and Table 2 map typical problem characteristics to the most appropriate techniques to implement at the respective stage of analysis. Table 1 maps the available data regarding variable parameters to the potential techniques for preparing study scenarios for the curtailment calculation stage. Table 2 maps typical problem characteristics to the most appropriate network modelling technique to be applied at the curtailment calculation stage.

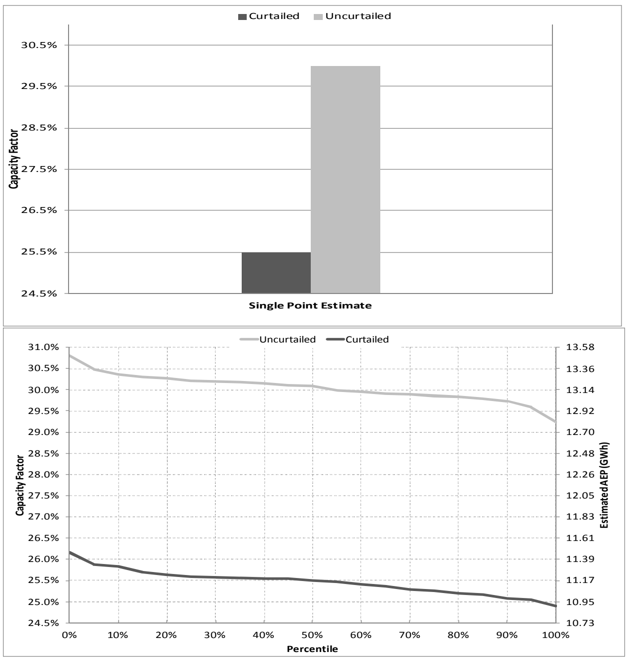

Figure 1: Constraint Analysis output plots

Available variable parameter models	Concurrent Time-series Profiles	Probabilistic Functions with MCS	Discrete Evaluation of Probabilistic Functions
Concurrent time-series data profiles	✓	✓	✓
No available time-series data profiles		✓	✓
Partial time-series data available		✓	✓

Table 1: Mapping data availability to scenario modelling technique

Problem Characteristics	Calculation based modelling	Load-flow based modelling
Radial network topology	✓	✓
Simple meshed network topology	✓	✓
Complex meshed network topology		✓
Requirement to model reactive flows or voltage		✓
Studying large number (>10000) of data points	✓	

Table 2: Mapping problem characteristics to network modelling technique

CONCLUSIONS

Constraint analysis provides a valuable illustration of the impact of providing non-firm connections to distributed generators via ANM. Through modelling the dynamic nature of non-firm capacity at constraint locations and intermittent DG export, it is possible to approximate the volume of energy curtailment expected by DG with a non-firm connection. This paper has introduced the key stages of constraint analysis, describing the various techniques available, and the circumstances under which they would be implemented. The list of techniques described in this paper is not exhaustive, but although different techniques can be applied at different points in the analysis process, the general methodology remains consistent.

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