AUTOMATED CAPACITY ANALYSIS OF DISTRIBUTION SYSTEMS

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ABSTRACT

Distribution businesses need to forecast potential system developments several years in advance. This activity facilitates efficient system investment so that a secure and reliable service can be provided at the lowest possible cost.

This paper describes the development of an automated software tool to calculate the network capacity during normal system and N-1 running conditions. By including forecast annual load change and an accurate representation of switching it has been possible to identify system bottlenecks both in terms of their severity and the sequence in which they occur. The commercially available IPSA+ fast decoupled load flow engine has been utilised as the core calculation method with a higher level program providing a simple user interface.

INTRODUCTION

This paper details the approach taken during the development of a capacity analysis calculation tool.

The typical long-term system planning horizon for the major British licensed distribution businesses is five to fifteen years. The system planning requirements include a requirement that voltages are maintained within statutory limits and that supply security complies with Engineering Recommendation P2/6 [1]. Ensuring that power flows are maintained within circuit and transformer ratings is critical to meeting the P2/6 recommendations. At 11kV and above the limiting condition will generally be under single circuit (N-1) outage conditions.

In contrast with the majority of distribution systems, the SP Manweb distribution system in Merseyside and North Wales is largely operated as a meshed system at all voltage levels. This makes analysis of capacity ‘headroom’ complex due to the large number of circuits that need to be included in contingency analysis. For example the identification of the spare capacity available at a substation is based on the capacity from infeeding higher voltage levels plus all possible interconnections with adjacent substations. In order to apply P2/6 recommendations, the capacity analysis is normally performed on the meshed network that forms a network group.

The long-term system reinforcement plan is developed taking into account the headroom within each group along with the forecast load change and other considerations such as the lead-time and the availability of resources to complete the reinforcement works.

A requirement was therefore identified to automate the network studies in order that the available capacity could be quickly and accurately calculated, thereby providing a faster and simplified method of undertaking regular reviews of the long-term reinforcement plan.

CAPACITY ANALYSIS TOOL DESIGN

Design Requirements

There were several principal requirements of the capacity analysis tool. The first requirement was the ability to perform system normal and contingency analysis incorporating a forecast annual load change. This would report all circuits and transformers that would become overloaded due to the annual load growth, contingency conditions or both.

The underlying load flow calculation methodology should ideally be identical to the power system software currently in use by SP EnergyNetworks . This would allow engineers to study individual cases in more detail by ensuring that the results from the tool could be easily replicated using normal load flow studies. Validation and debugging of the tool would also be simplified.

The tool would also need to use the existing network model files that were in regular use. This would eliminate the overhead of maintaining a separate power system model and also allow the model to be edited and updated according to the normal company procedures.

Solution Overview

SP EnergyNetworks use a number of network analysis packages, including the commercially available IPSA+ power system software for network studies. IPSA+ uses a Fast Decoupled Newton Raphson (FDNR) load flow calculation technique which is also available as a standalone engine for integration into other software applications [2].

This load flow engine can be used with C, C++, C#, Fortran and Visual Basic (VB). The ability to call the engine from
VB allows the tool to be integrated within a Microsoft Excel spreadsheet. This allows the user interface to be quickly and easily created using the standard VB editor supplied with Excel.

The decision was therefore taken at an early stage to develop the tool using VB and embed it within a conventional spreadsheet. This would allow rapid development as well as straightforward deployment.

The tool itself was designed as a set of separate code classes handling aspects such as the user interface, file operations and analysis operations. The load flow engine contains only the FDNR calculation code therefore all other operations, such as file reading and writing, must be coded separately. Figure 1 shows the high level block diagram of the tool, principal elements of which are described further.

Two principal analysis modes were included in the tool. Both modes carry out N-1 contingency studies on a selected sub-network. Options for the first analysis mode allow the contingency studies to be repeated including a percentage load change for a number of years. The second analysis mode identifies the spare capacity available before the first overload occurs. Either analysis mode can be undertaken by applying the load growth to busbars individually or across a group of busbars simultaneously.

ANALYSIS METHODOLOGY

Based on the various analysis modes and the block diagram in Figure 1 the software was developed in line with the flow chart summarised in Figure 2. This shows a generic method for all analysis modes. Selection of different modes is achieved through the use of different group load scaling factors, selection of the planning horizon or application of the load scaling to different busbars.

Figure 2 – High Level Flow Chart

Generic Solution Methodology

The basic methodology is the same for all analysis modes. The network is first loaded into the engine and a load flow undertaken to ensure that the base case network converges. A predefined load scaling factor, positive or negative, is then applied to selected loads to represent the annual load growth or reduction respectively. The N-1 contingency analysis is then undertaken on all the circuits in the selected subsystem. Switching data for each circuit is obtained from the network file to identify and switch multi-ended circuits correctly. After each switching event a load flow is performed and, if solved, circuit ratings and voltage levels examined to identify exceptions.

The network with scaled loads is then restored in the load flow engine, essentially restoring the pre-switching network. This ensures that load flow initial conditions are identical.
for each switching study. Analysis then progresses by switching out the next circuit in the subsystem.

Once all N-1 switching studies have been processed a new load scaling factor is calculated. Applying a uniform load scaling factor allows any number of years of load growth to be analysed whilst recording all thermal and voltage exceptions.

**Capacity Calculation Method**

An alternative analysis mode allows the load scaling factor to be adjusted in order to identify the first network exception. This enables the spare capacity or headroom to be calculated for a specific part of the network.

The load scaling factor is calculated by analysing the sensitivity of the maximum circuit flows obtained during the N-1 studies. Two sets of N-1 studies are performed with different load factors $I_n$ and $I_m$. The scaling factor $I_n$ defaults to an initial value of 1% with a fixed difference between $I_n$ and $I_m$ of 0.1% of the individual loads.

The circuit headroom $S_h$ at each end of the circuits under consideration is calculated from the circuit rating $S_r$ and power flow results, $S_n$ for the first load factor $I_n$ as in (1).

$$S_h = S_r - S_n$$

A sensitivity factor $F_n$ is calculated for each circuit end based on the circuit headroom and power flow results, $S_n$ and $S_m$ for each load factor as in (2).

$$F_n = \frac{(S_n - S_m)}{S_h}$$

The highest sensitivity factor $F_{\text{max}}$ is then obtained from the individual circuit factors (3). The resultant $F_{\text{max}}$ then represents the circuit whose change of flow with respect to remaining capacity is largest and therefore most liable to overload. This is used to determine a new load factor $I_{n+1}$ based on the remaining headroom for that circuit (4).

$$F_{\text{max}} = \max[|F_1| \ldots |F_n|]$$

$$I_{n+1} = \frac{\alpha(I_n - I_{\text{threshold}})}{F_{\text{max}}}$$

The dependence of $F_{\text{max}}$ on the circuit headroom together with additional convergence logic ensures that the final two sets of N-1 studies represent the limiting condition. That is the lower load factor ($I_n$) results in a network with no overloads whilst the higher load factor ($I_m$) gives a network with at least one circuit overload.

Figure 3 shows the convergence of the load scaling factor ($I_n$) for the calculation of available capacity on a single 33kV subsystem on a 1700 busbar network. This indicates that for this 33kV subsystem a 5.7% increase in general load growth would result in a circuit overload during N-1 conditions. Convergence was achieved in five iterations using an acceleration factor $\alpha = 1.4$. Validation tests determined that this value was not network dependent and affected only the number of iterations required to achieve convergence.

**Additional Analysis Functionality**

Network loads are typically modelled at 11kV or 33kV in the networks used by the DNOs. No special measures were taken regarding the redispatch of generation. The majority of generation was modelled at 275kV and above and so accurate redispatch was not considered necessary. The additional load was assigned to slack generators automatically by the FDNR load flow engine.

Details of all exceptions are recorded and copied to the analysis spreadsheet on completion. The results presented allow the user to identify each exception, the associated N-1 switching event, load factor applied and summarised load flow results.

The operation of on-load tap changers can be inhibited during the N-1 studies to simulate the transient post fault loading and voltage profiles.

**SOFTWARE VALIDATION**

All validation tests were undertaken using special
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debugging code built into the capacity analysis tool. This allowed the load flow results of the various automated studies to be examined and compared with those obtained using normal, manual IPSA+ network load flow analysis. This enabled the operation of the tool to be optimised for different network configurations.

RESULTS

The results obtained proved to be sufficiently accurate when compared with manual power flow studies as detailed in Table 1. The overloaded branch flows were generally accurate to within 0.1MVA, the preset convergence tolerance for the capacity headroom. This details the results obtained from the analysis tool together with the results obtained using manual analysis (bracketed).

<table>
<thead>
<tr>
<th>Year</th>
<th>Demand Increase</th>
<th>Group Demand MVA</th>
<th>Overloaded Branch</th>
<th>Branch MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0%</td>
<td>178.9</td>
<td>Cadk - Mons</td>
<td>21.95 [21.94]</td>
</tr>
<tr>
<td>0</td>
<td>0.0%</td>
<td>178.9</td>
<td>Osws E2 - Maes</td>
<td>18.56 [18.47]</td>
</tr>
<tr>
<td>0</td>
<td>0.0%</td>
<td>178.9</td>
<td>Cadk - Osws E2</td>
<td>17.87 [17.92]</td>
</tr>
<tr>
<td>0</td>
<td>0.0%</td>
<td>178.9</td>
<td>Lega E2 - Ruab</td>
<td>20.86 [20.89]</td>
</tr>
<tr>
<td>6</td>
<td>6.15%</td>
<td>189.9</td>
<td>Mons – Lega E2</td>
<td>22.95 [23.03]</td>
</tr>
<tr>
<td>7</td>
<td>7.21%</td>
<td>191.8</td>
<td>Butt - Wepo E1</td>
<td>23.14 [22.63]</td>
</tr>
<tr>
<td>11</td>
<td>11.57%</td>
<td>199.6</td>
<td>Osws E1 - Cadk</td>
<td>17.79 [17.84]</td>
</tr>
<tr>
<td>12</td>
<td>12.68%</td>
<td>201.6</td>
<td>Lega E2 - Johs</td>
<td>22.71 [22.53]</td>
</tr>
</tbody>
</table>

The table also details the order, or year, of each overload and the N-1 outages which cause each overload (not shown). This essentially ranks the overloads in chronological order allowing future reinforcements to be ranked in terms of both severity and order of occurrence. Long term planning of network reinforcements can then be undertaken on the ranked set of overloads produced.

CONCLUSIONS

A capacity analysis tool has been successfully developed within an Excel spreadsheet and validated against manual power flow studies. Both main analysis methods were found to be sufficiently accurate for long term planning studies converging to the required tolerance within a small number of iterations.

The final version of the tool was then deployed in two separate major licensed distribution businesses where it was utilised successfully for long term planning studies. Capacity analysis studies were undertaken for the full distribution systems and the results ranked in order in which overloads were predicted to occur.

The tool used existing power system networks without modification thereby reducing the overhead in using and maintaining the tool.

REFERENCES


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AUTHORS BIOGRAPHY

Mr Stephen Ingram holds the position of Senior Consultant at TNEI Services Ltd. He obtained his B.Eng at the University of Salford in 1992 and his MSc from the University of Bath in 2001. His experience includes an extensive power system studies background including the development of Python, C++ and VBA software for power system analysis and applications.

Dr. Bathurst obtained his Bachelors and PhD at the University of Canterbury in New Zealand in 1996 and 1999 respectively. He spent some time with Siemens in Germany before moving to the United Kingdom to work with UMIST and Regenesys on the value and application of energy storage technology. In 2003 he joined TNEI to provide technical input to the development of IPSA as well as develop the power engineering consultancy business. Graeme is currently the Technical Director of TNEI and heads up the Power System and Technology group.

Christopher Berry has over 25 years experience in the UK electricity industry. Currently he is responsible for design standards for the SP Manweb distribution system at all voltage levels and leads a team of professional engineers responsible for the design and development of the 132kV and 33kV networks. He received his BSc (Hons) in Electrical and Electronic Engineering from the University of Manchester Institute of Science and Technology (UMIST) in 1985 and his MBA (Distinction) from the Edinburgh Business School in 2002. He is a fellow of the Institution of Engineering and Technology (FIET).