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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

NETWORK-ORIENTED APPROACH TO DISTRIBUTED GENERATION PLANNING

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The main objective of the paper is to present an innovative complex approach to distributed generation planning and show the advantages over existing methods. The approach will be most suitable for DNOs and authorities and has specific calculation targets to support the decision-making process. The method can be used for complex distribution networks with different arrangement and legal base.

Keywords: *power system management, power system planning, power system analysis computing*

1. INTRODUCTION

The past power systems (PSs) were dominated by a conventional, load-following generation that injected large amounts of power into an extra high voltage transmission network built during the middle of the last century. Today, a large number of generators are connected and much more planned to be connected at every level of the distribution network and integration of these new resources into all aspects of the power system will be the key to ensuring the evolution of an economically efficient and effective system based on sustainable generation sources. However, the existing system has been optimised for the requirements of conventional generation and it is clear that facilitating the integration of DG (Distributed Generation) into the existing system will require redevelopment of the regulatory, technical and commercial arrangements that underpin the current system.

There are well-known existing methods of modelling of distribution power systems and their components – overhead lines, cables, transformers etc. However, power systems are facing a stage of rapid development due to innovations in the sector, integration of new technologies and new legislation base. Existing power system modelling tools do not solve topical issues and do not offer a complex approach to a model for power system long-term development planning.

2. ANALYSIS OF EXISTING POWER SYSTEMS ANALYSIS SOFTWARE AND APPROACHES TO DG PLANNING

2.1 Analysis of Existing PS Analysis Software

The model presented in the paper is proposed to be used in existing or new power system analysis software, offering some new features, e.g., new models and complex approach to DG planning. There is plenty of power system analysis software available on the market, incorporating standard and unique features, but none of them is capable of complete DG planning due to the complexity of the task. The most popular power system analysis software packages were analysed within the research, highlighting their advantages and downsides. Special attention is devoted to DG planning capabilities.

The most common standard functions of the existing power system modelling tools are as follows:

- Steady state analysis (power flow analysis, OPF);
- Transient analysis (short circuit, transient stability, harmonic analysis);
- Protection setting analysis.

Using these tools, an engineer would be able to build a power system model and study a single steady state or transient up to several seconds. However, these tools lack or have very limited capabilities for planning, which would involve option to automatically study multiple steady states and build time dependent models (a power station output during the year, not only for a single steady state). Therefore, the existing modelling tools are only partly used by an engineer for planning purposes.

2.2 The Existing Economic Approach

The economic approach aims at studying an economic effect of DG penetration. At the moment DG is not profitable enough without subsidies; therefore, this approach is more suitable for developers, as there is no direct monetary profit for government from DG. This approach allows studying costs and benefits of installing a particular DG in a particular location. Selection of location of DG is not the aim of this approach; therefore, distribution network parameters, like voltage and thermal loading are not considered. Generally, it cannot be used for long-term planning with many uncertainties. This approach is described in detail in [1].

2.3.The Exisitng Scientific Approach

Most of the proposed scientific approaches are based on the selection of a site location and DG size by optimisation of a single or multi-objective function under certain operating constraints. Usually, the objectives are the following:

- Minimisation of line losses;
- Maximisation of DG capacity;
- Social welfare and profit maximisation;
- Multi-objective.

The main problem of this approach is that it does not take into account practical aspects of DG business and difference between DNO and developer roles. This approach would be suitable if a DNO developed its own DG. However, in reality developers select location and size of DG based on legal, economical and geographical criteria, and then apply for connection to DNO. This approach would be appropriate if the task were to advise best locations and sizes of DG in a particular network. This approach is described in detail in [2] and [3].

2.4 The Exisitng Practical Approach

The existing approach applied to DG planning by existing DNOs is not based on optimisation or long-term planning method.

Developers seek for best locations of DG, usually based on availability of cheap land and/or landowners' willingness to develop DG on their land. Developers then apply to DNO for a connection offer that would define how expensive it is to connect the proposed DG to the network. Connection costs are based on location, size of the plant, type of the plant, connection voltage, required network reinforcement works etc.

To define required network reinforcement in order to connect the proposed DG, usually the following studies are carried out:

1. Load flow study. This study is required in order to investigate potential thermal overload issues of cables and transformers. The planned generator adds power flow to the existing power flow, which results in a higher power flow in the network and at DNO substation transformer. If the cable or the transformer thermal limits are exceeded, they will require replacement.
2. Voltage rise. This study is required to investigate if a voltage rise caused by connection of a new generator is within statutory limits. If a planned generator causes voltage to rise to 1.07 p.u. at the point of connection, this is unacceptable by most DNOs (see Fig. 1). However, there is a number of possible solutions that can be proposed: increasing the cable size from the proposed generator to the existing network, reinforcement of further cable section, decreasing the proposed generator capacity, installation of reactive power compensators, which force the proposed generator to operate in a leading power factor mode (absorb reactive power).

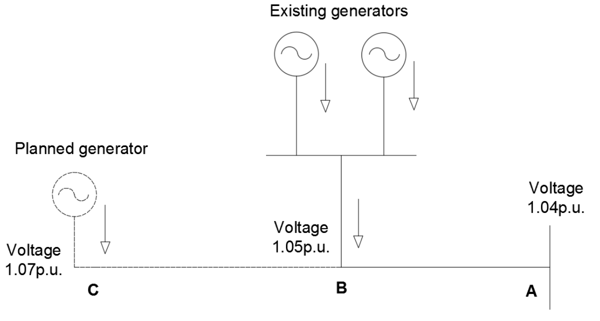

Fig. 1. Voltage rise caused by a planned generator.

3. Voltage step change. This study is required to investigate if a step change caused by sudden connection/disconnection of a new generator does not exceed statutory limits and complies with Voltage Fluctuations recommendations. This is usually the case when voltage rise limits are exceeded.
4. Fault level study. This study is required to assess the effect of a new generator on the total fault level in the distribution system. New fault levels in the system are compared against equipment specifications to make sure limits are not exceeded. This is specifically a problem for big DG based on synchronous generators.

If there is a constraint in the network that does not allow connecting DG without reinforcement, a developer has to pay for the reinforcement works or cancel the project.

In fact, there is no planning as such since there is not enough incentive for DNOs to reinforce their network and there is no government support for such reinforcements (unlike reinforcements for load, which are usually subsidised by the government). This approach does not allow forecasting network behaviour in future and is very limited in terms of predicting available capacity and other essential network parameters in future.

Nevertheless, this approach gives a clear indication of essential network parameters that need to be studied in order to assess a possibility of a new generator connection to a distribution network. These parameters will be considered in the methodology described in the paper.

3. THE PROPOSED METHODOLOGY

3.1 Calculation Targets

Models are usually created for a specific task. In case of power system models, the target of the calculations usually is a set of system parameters, such as voltages, power flows etc. Since the methodology created within the present research is meant to support distributed generation planning, there is a set of specific calculation targets. There are two main target options for the calculations, which were created under assumption of main interests of potential users of the methodology:

1. Target costs for DG development

How much money is required to install defined capacity of DG (the Capacity Target)? Obvious example is EU Directive “20-20-20”, which defines the target for renewable energy by 2020. In this case, the capacity target would be 20 % of the total generation and the result of the model calculations would be the amount of investments required to accommodate this capacity on a distribution network. It is important that investments do not include any costs associated with development of the DG (planning, commissioning etc.), only network reinforcement.

2. Target for future DG capacity

What DG capacity is possible to install having a defined budget (the Costs Target)? This is the most important issue for decision making on a government level to understand the outcome of particular investments.

Other calculation targets are technical, but unique and not considered in other power system models. In order to calculate both Cost and Capacity Targets, it is required to perform simulations of various operational states and network conditions. The model will then identify network issues and report the proposed reinforcements. This will be explained in more detail in the next section.

3.2.Simulation Types

Distributed generation planning, like any planning activity, involves prediction of future network conditions, e.g., generation and load. Since these parameters are uncertain for future, especially for a few years, it is required to develop an approach to how they are selected, how many operational states to consider, what format of results to use and how to analyse the results.

To study the effect of DG implementation in the distribution network, two approaches are proposed – Specific Operational State Simulation (SOSS) and Realistic Full Simulation (RFS). It is proposed that both of these approaches are used in parallel and results compared for a more balanced decision.

In case of the SOSS, calculation is performed only for certain selected operational states to assess if a certain DG is acceptable on the network. It is proposed to study the following operational states in order to consider the most common scenarios, including the worst case scenario:

- Power flow study – maximal load + maximal generation; minimal load + maximal generation;
- Fault level study – maximal load + maximal generation.

The specific features of this approach are low risk (the worst case scenario is studied), unrealistic (probability of the worst case scenario is low), low coverage (only certain operational states are studied).

To overcome some downsides of Specific Operational State Simulation, it is proposed to use Realistic Full Simulation (RFS) type in parallel. This is the most natural way of modelling the future uncertainty. In this approach, generation and load parameters are modelled as realistic forecasted values for a defined period of time in future. It is a more complicated approach since it requires precise models and calculation of multiple operational states. Models developed by the authors and described in [4] and [5] can be used for this purpose.

3.3 Conventional and Constrained Connections

Constrained (controllable) connections become extremely popular and will be even more popular in future. This is explained by a number of benefits, the main being lower cost of connection. In certain situations, a generation plant becomes unacceptable on the network only under certain very rare conditions, e.g., during very low demand hours. As an alternative to network reinforcement, it is possible to install Active Network Management (ANM) equipment at the generation plant and restrict its operation under certain conditions. Since DG rarely generates constantly at 100 %, it is possible that certain ANM controlled generation plants will never be constrained. This is usually attractive to developers, as allows saving up to 90 % of project costs.

However, if annual constrain time is above a certain threshold, ANM connections are not economically viable. Based on feasibility studies from [6], the proposed threshold is 70 %. It means that ANM connection is considered to be viable, if forecasted annual availability is >70 % and forecasted constrain time is <30 %.

It will be required to calculate forecasted constraint time and decide if a particular DG can have ANM connection. Since each operational state is 1h, a number of operational states with issues can then be divided by a number of hours in the year to get the constraint time. Availability can be calculated as follows:

$$A = 1 - (h/8760)100\ \% \qquad (1)$$

If annual constraint time <30 %, ANM connection is enabled for the power station. If constraint time >30 %, it is assumed that it will not be economically viable for developers to accept this connection and network reinforcement is triggered. It is proposed to consider ANM as a second option in the following order: Conventional connection → ANM connection → Network reinforcement.

3.4 The Main Algorithm

The main algorithm of the model is presented in Fig. 2. The main idea of the algorithm is to add DGs one by one to the existing network until the target is reached. For each new DG the model will calculate the size, preferable location, connection type, required network reinforcement and check how each new DG behaves in the existing network. This involves multiple sub-algorithms, which will be described in the full paper.

The required model input parameters include (each will be further explained below):

1. The existing distribution network parameters: lines, transformers (including ratings), DG, load (including motors to consider fault level contribution), fault level ratings for each node (switchboard), transmission network infeed and other distribution network infeed;
2. Target costs or target capacity;
3. Reinforcement costs – capital investments required for replacement of 1km OHL/cable and different size transformers;
4. DG size limits for each voltage level;
5. Statutory voltage limits;
6. Optional: mean wind speed in the area, mean solar irradiance in the area, forecasted annual load growth;
7. Optional: future distribution of DG types;
8. Optional: future distribution of DG sizes;
9. Optional: protection modification costs (€ per site).

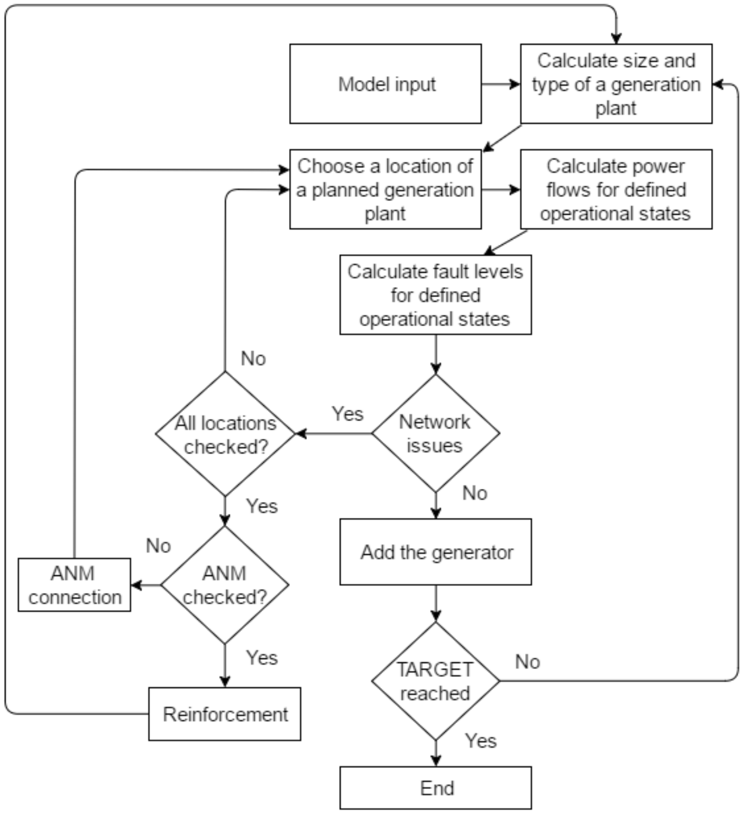

Fig. 2. The calculation algorithm of the model.

3.5 Selection of Size and Type of a Planned DG Plant

Each new DG in the algorithm is considered as a connection application from a developer. It is possible to predict a capacity range that will be popular for each technology time and period. However, this range is usually quite wide, e.g., solar generation plants can be as small as rooftop solar and up to 50 MW large, when developers apply, for example, for Contract for Difference. Therefore, it is not possible to accurately predict the capacity of the next DG that application will be received for. For DG size selection it is proposed to use the following function in the following sequence: 3 x Random(1-10); 6 x Random(10-35), 1 x Random(35-50). For more detailed selection, a different size range can be applied to each technology type and it is subject to a study for each specific area separately.

3.6 Selection of Point of Connection (POC)

General awareness of developers about amount of free capacity in different areas of the network is quite poor. For this reason, it is assumed that DG applications come for random locations. The only physical limitation is available space (e.g., solar farm cannot be built in a city centre), so it is proposed to assume that 70 % of DG will be in a rural area and 30 % in an urban area. This can be achieved by adding a *Type* parameter to each node.

3.7 Power Flow and Fault Level

Any power flow calculation method can be used to obtain the following parameters essential for the model: node voltages, active power flows and reactive power flows. The connection of a planned DG is not possible if thermal ratings of lines or statutory voltage limits are exceeded in any operational state. Normally, it is required to analyse the system under N-1 conditions or an action from a control centre will be necessary.

Fault level calculation is another important study required for complete planning since medium voltage connected DG significantly contributes to it [7]. It is required to calculate 10 ms peak and 100 ms RMS three-phase fault level values at all nodes of the network and compare them with the ratings. Usually it is sufficient to check switchgear ratings only. The connection is not possible if the rating is exceeded. For the purposes of the study, it is assumed that network re-configuration (splitting) or other means to reduce the fault level (except network reinforcement) are not available.

3.8 Reinforcement

Reinforcement is the least favourable measure that can be taken in order to connect a planned DG to the network since usually it requires considerable investments.

Planner should input costs of reinforcing 1 km of overhead line (OHL), 1 km of cable, transformers for two voltage levels – one below the studied network level and one above. For example, if the object of study is 33 kV network, it is required to input costs for 33/11 kV and 132/33 kV transformers. It is proposed to input two possible transformer size options for each voltage level to make reinforcement in steps, e.g., replace 45 MVA transformer with 60 MVA, then with 90 MVA transformer. If there are two transformers in parallel, both need to be replaced.

If reinforcement is insufficient and there are still network issues which cannot be solved (maximum transformer size or maximum cable size is installed), the current DG should be terminated. The algorithm will then select the new POC for the next DG. In real life, DNOs are obligated to provide connection options, but in this case connection costs will not be reasonable (e.g., next level voltage connection, new major substation).

3.9 Protection

DGs significantly affect power flows in the system and have their own protection, which needs to be graded with DNO protection. In some cases, it is possible to simply adjust the settings to achieve discrimination. However, protection used in modern distribution systems is not always modern digital protection. In fact, most protection schemes, including protection relays, were produced in 1950s–1960s. If maintained regularly, these schemes work well, but sometimes are not flexible enough and additional relays are required, for example, to delay the tripping time beyond the relay capability. Sometimes, even complete scheme replacement is necessary.

In each case, a protection study needs to be performed to determine the requirement for modification or replacement. Due to its complexity and number of input parameters required, it is not covered within the research. It is proposed that additional costs are added on top of total reinforcement costs to allow for protection studies and modifications (€ 10,000 for schemes connected at voltage below 100 kV and € 100,000 for schemes connected at voltage above 100 kV). It is based on the assumption that distance protection is used on higher voltage levels by DNOs. It cannot be effectively graded with DG private network protection since the first stage of distance protection is usually instantaneous. Hence, the whole scheme will need to be replaced with unit protection, which is expensive due to the need in long-distance communication channels.

4. CONCLUSIONS

This paper presents an approach for DG planning based on sets of models and interaction algorithms. The approach is complete and can be used for different network arrangements, voltage levels and development scenarios. It is possible to carry out all calculations manually or using simplified calculation tools, e.g., MS Excel. However, even the power flow alone is extremely hard to calculate manually for large systems, but considering a number of equations and algorithms involved, it will be practically impossible to implement the approach. Since this is a unique approach and there is no existing software tool that would be capable of doing the required calculations, a new software tool is required in order to use the approach in an efficient manner. Due to complexity and different specifics of software development, it is not part of the research.

Another research development direction is implementation of calculation for benefits gained from DG contribution to security of supply. Effectively, this would reduce total capital investments required for distribution system development. On the one hand, DGs require investments in network infrastructure; on the other hand, it potentially reduces requirement for investments related to security of supply, by generating electricity closer to the load. Even though this option is possible, it is not always utilized since there are special requirements for DG contributing to security of supply, e.g., protection, stability earthing etc. A majority of modern DGs operate in parallel only with a healthy network and automatically disconnect from a faulted/islanded network.

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TĪKLU ORIENTĒTA PIEEJA IZKLIEDĒTAS ĢENERĀCIJAS PLĀNOŠANAI

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K o p s a v i l k u m s

Raksta galvenais mērķis ir piedāvāt inovatīvu, kompleksu pieeju izkliedētas ģenerācijas plānošanai un parādīt tās priekšrocības salīdzinājumā ar esošajām metodēm. Šī pieeja būs vispiemērotākā Sadales Tīklu Operatoriem un valsts iestādēm, kuriem ir svarīgi uzdot īpašus aprēķina mērķus, lai palīdzētu lēmumu pieņemšanas procesā. Šo metodi var izmantot sarežģītiem sadales tīkliem ar dažādu topoloģiju un juridisko bāzi.

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