

DISTRIBUTED ENERGY RESOURCES AND POWER SYSTEM STABILITY

IZKLIEDĒTAS ĢENERĀCIJAS AVOTI UN ENERĢOSISTĒMAS STABILITĀTE

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Keywords: *distributed energy resources, islanding, power system stability*

Introduction

The tendency towards increasing efficiency of the use of primary energy resources and extensive introduction of renewable energy sources have given rise to interest in the investigation into the possibility of wide use of distributed generation or distributed energy resources, i.e., electric energy sources with a relatively small capacity located near the consumers.

The design and production of generators that use steam/gas technologies, wind and solar power, and fuel cells are progressing rapidly. Such sources can cover – fully or almost fully – the ever increasing demand for electric energy, which is a promising direction of power systems' evolution. The use of alternative sources will make it possible to limit the power transmitted via high voltage and super-high voltage networks (thus saving investments into their development), to improve the viability of power systems, and to increase the reliability of power supply to customers.

The paper presents the results of the investigation into the FPS that contain a considerable volume of DER. One of the main requirements for the system development and operation is the existence of a sufficient dynamic stability reserve [1], which ensures the system viability and prevents large-scale incidents.

Another problem that has recently become actual is the possibility to continue operation of DER following an unintended islanding of a distributed grid and the automatic subsequent reconnection with the high-voltage part. The authors consider an approach to this problem that differs from previous ones [2].

Answers to the following questions are sought for:

1. How will the transmission grid stability be influenced by a DER introduction?
2. What should a suitable automatization of simulation methods?
3. What should technical requirements be for a distribution grid with the DER?

The use of industrial software for simulation of transients in FPS

Stability reserves are determined simulating transient processes in the systems with preset structure and parameters [3, 4].

Digital simulation of transient processes generally involves a number of steps.

First, a load flow data set defines the active generation, consumptions and topology of the grid under study. To the load flow equations appropriate numerical solution techniques [5] are applied. The results include reactive generation and node voltages, power flows and losses, which together with the initial data bring into complete solutions.

It is the starting point for further transient simulations. The differential equations presented describe the dynamic response of equipment (generators, machines, protection and control, etc.) to the events occurring in a system.

At this point, a researcher should select between very detailed equipment models (supported by a full set of coefficients) or a reduced approach. Reduction of equipment models (equations) is a common practice based on neglecting less important internal processes and not involving coefficients of unknown value.

A range of numerical techniques exist for differential equations' solutions [6], whose results for network elements include voltage, current, and power variations in time. Figure 1. a) overviews the mentioned steps.

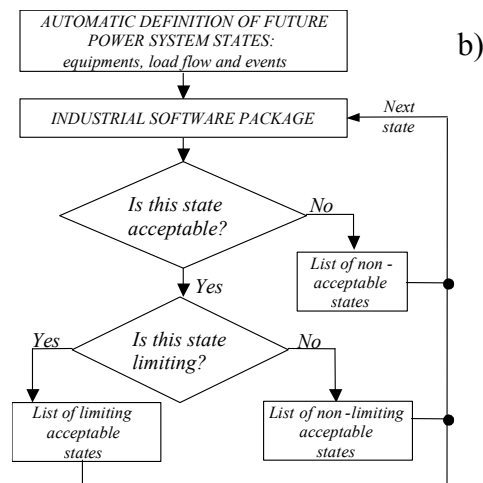
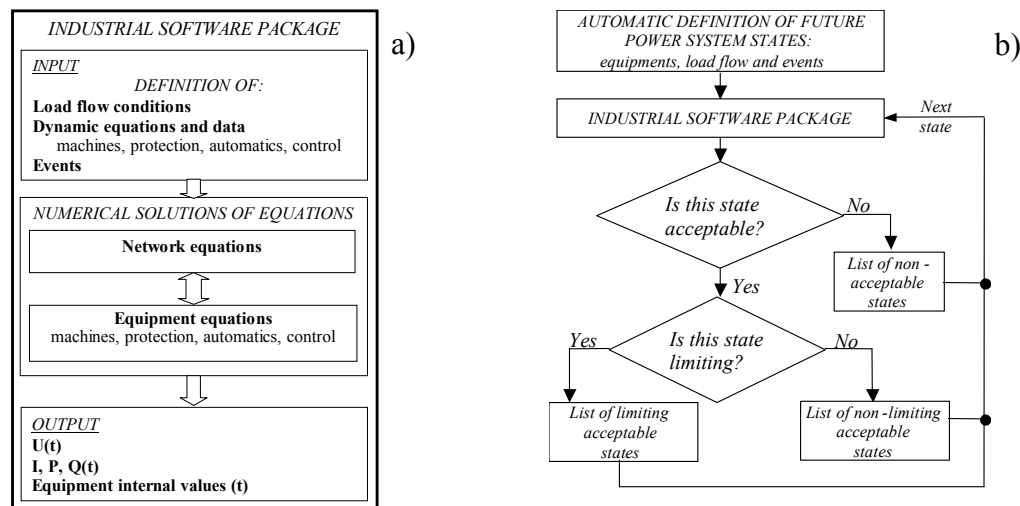


Figure 1. a) Transient simulation steps using industrial software packages; b) Extended blocks for estimation of dynamics restrictions in FPS

For FPS it is not easy to make *a priori* clear assumptions about the network development and generation planning at the DER level.

It is impossible to predict exactly the structure, composition, and parameters of such systems. For this, it is necessary to perform calculations that would correspond to various combinations of the types of DERs used, their connection places, and disturbances that may cause a loss of dynamic stability.

To do this, we propose to use industrial software that simulates the electromechanical transient processes in the systems containing both traditional and DER generators complimented with:

- a block (procedure) that automatically predicts possible future states of FPS, including load-flow conditions, dynamic description of equipment and events;
- a block (procedure) that estimates states as acceptable or non-acceptable from the angle stability point of view.

Figure 1. b) shows the links connecting the introduced blocks with the industrial transient simulation software.

Next sections present the methods involved in realisation of the blocks.

Methods for modelling fps states

Methods used in system planning

The future states of FPS are unknown resulting in uncertainty in their definition. Large-scale power system planning and design tasks face it extensively [7], using a number of uncertainty modelling techniques. They include [8]:

Scenario approach. It is actively involved in practical tasks in a hope that a set of scenarios collectively would represent a wide range of future situations that might occur.

Bayesian's theory. It describes mathematically a combination of expert estimations with the probability theory.

Monte-Carlo approach is based on the probability theory. The probability is taken into account by specifying the ranges and distribution laws of random.

Possibility theory extends a fuzzy logic approach and may be employed to estimate the boundary conditions to be used in Monte-Carlo's method.

Structural analysis of the FPS

While estimating the DER impact on the angle stability of FPS, one can find the difference between this task and those of system planning. The algorithm considered in this paper is aimed at classifying all possible states of FPS as acceptable or non-acceptable from the angle stability point of view. More precisely the limit states are found posing additionally a sub-task as shown below. The mentioned difference deals with boundaries for a wide scope of development plans (mostly unknown) and not with an optimal development plan.

Selection of the most suitable uncertainty modelling method should be based on the whole system's analysis. Structural analysis of FPS shows four groups that differ in the uncertainty level:

1. Future states of transmission parts that are generally known, since there exist development and extension plans. Expert estimation or scenario approach methods suit for modelling this part using the proposed algorithm.
2. Future states of distribution grids with connected DER that are not known exactly. We can only estimate or hypothesise possible ranges and distribution laws of characteristic values. This makes the Monte-Carlo approach the most suitable for uncertainty modelling in this part.
3. Events, or disturbances, that are the most severe from the angle stability point of view. This group is mainly unknown.
4. Future total system consumption accepted as known.

The uncertainty level for the second and third groups is very high and requires special methods to deal with considered further.

Monte-Carlo-based automatic distribution grid modelling

The automatic construction of the DER-related model data is based on Monte-Carlo's approach.

The modelling of future states requires that there be pre-defined formulations of the variation ranges and distribution laws for the parameters. The following hypotheses were accepted:

1. DER share varies up to 40% of the total generation in a system.
2. DER sources are evenly located among the network nodes (by the uniform distribution law generating random values).
3. The rated power of one DER unit is in the range from 3 to 6 MW.
4. The proportion between different types of generators (synchronous, asynchronous, and connected via invertors) is variable.
5. The total consumption increase is compensated by DER installations.

Based on the above hypotheses, data sets were formed that describe FPS structure and parameters. The next step is the Monte-Carlo-based search of disturbances that cause most severe transients in a power system.

Search for the most severe disturbances

An automatic Monte-Carlo procedure is intended for search of the locations and types of the most severe disturbances in the systems with the preset structure and parameters.

Three sub-steps are included here:

1. A list of possible faults is automatically formed (3-phase faults, element tripping - loss of a generating unit, loss of a bus-bar, loss of a double-circuit line, miss-operation of special protection schemes) in the system.
2. From the complete list the events are excluded that do not entail significant changes in the rotor angle and other parameters. In this work, such an exclusion was made by expert estimation.
3. Selection among the events was made by Monte-Carlo procedure. The list of selected events is translated into the simulation software format for the estimation of their severity index (degree). As a result, the events are automatically arranged in the danger degree.

The methods presented in this section allow us to form the FPS states as a list of exactly defined conditions, which are used by the industrial software. The analysis and classification of transients are given in the next section.

Classification of FPS states

Classification of FPS states as acceptable or non-acceptable is based on the sufficiency of stability reserve for a transmission grid. As the sufficiency criterion, the allowable limit for short-circuit critical clearing time (CCT) has been assumed. CCT is defined as the maximum duration of a fault which will not lead to the loss of synchronism of one or more generators [9]. The minimum value of CCT (CCT limit) is limited by operation times of the relay protection and circuit-breakers. As acceptable, there are assumed states at which the CCT value exceeds that of CCT limit. Non-acceptable states are the states at which the CCT is below the CCT limit. Our maximum DER share concept looks as follows. The group of acceptable FPS states is additionally divided into limiting and non-limiting. The limiting state group is denoted as DER_{max} range, which corresponds to the CCT values close to the CCT limit (see Figure 3). The presented approaches for modelling and classification of FPS states were used to study a system based on the existing interconnection of power systems of the Baltics (Estonia, Latvia, and Lithuania) with the Northwest of Russia and Belarus.

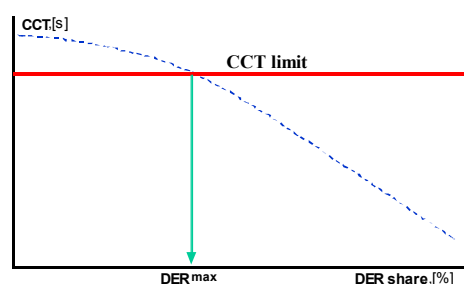


Figure 2. Definition of the maximum DER share concept

Selected results

Model description

The electricity networks of Estonia, Latvia, Lithuania, as well as neighbouring electricity networks of Russia and Belarus, form an electric Ring, consisting of 330 and 750 kV lines [10]. The 750 kV network in the integrated power system under consideration is not loop-closed.

In the defined system the most dangerous disturbance from the stability point of view is a sudden loss of the 750 kV line that connects the Leningradskaya s/st and the Kalinin NPP.

When the 750 kV line is disconnected, the power that was transmitted through this line under pre-emergency condition is immediately redistributed among other elements of the network, including lines of lower voltage. The 330 kV network does not possess the stability level high enough to transmit the emergency increase in power (in addition to the power of pre-emergency condition). The emergency switching off of an element of the 750 kV network may result in a loss of stability in the 330 kV network.

For the Monte-Carlo simulation, we prepared a list of 110 kV nodes where grids with DER may be connected in the future. Possible nodes for additional distribution grids with DER are located in Estonia, Latvia, Lithuania, Belarus, and the Pskov region of Russia, total approx. 130 nodes.

Results

The interaction of transient processes in transmission and distribution networks can affect both positively and negatively the transmission system's stability. Tripping of DER generators can increase - or decrease as well - the power flows in a transmission thus leading to the stabilisation or destabilisation of the angle position.

In the positive case when DER are located mainly at the importing side of a transmission corridor. Figure 3. a) illustrates this case with two different power exchange values over the transmission corridor.

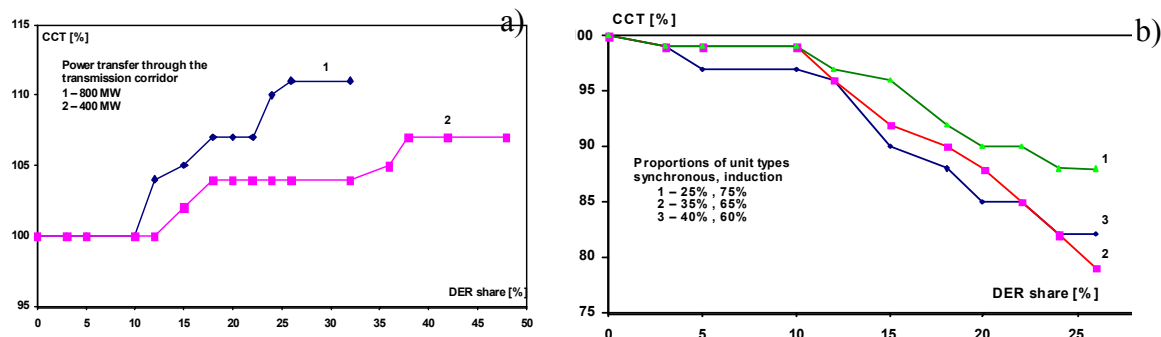


Figure 3. a) CCT increasing with DER volume, b) CCT decreasing effect

The negative effect of CCT decreasing was found in other our simulations in the frame of this work. This happens in two cases: when DER are located mainly at the exporting side of a transmission corridor, and when they are evenly distributed in the whole system. Figure 3 b) shows the mentioned decreasing effect.

To comment this, one should consider the dynamic behaviour of DER synchronous generators following a fault in the transmission part.

DER units are very sensitive to the faults originated in transmission. Two types of DER response exist affecting the CCT values:

- Tripping of DER by their own protection following repeated voltage falls (swings) in the high-voltage part, and
- DER generators have lost synchronism after large and sudden changes of the operating conditions in transmission networks. In this case, large generators keep synchronism.

To this end, all synchronous generators of DER in our simulations were supplied with protection automatics for asynchronous operating conditions.

The limit for the acceptable states was estimated to be $DER_{max} \approx 25\%$ of the total generation in FPS. This reduces the CCT value down to 79% (with 100% for production without DER). Figure 6 illustrates the trends found, differing by proportions between the synchronous and induction units.

A boundary between acceptable and non-acceptable states may be extended introducing one or several of the following:

- implementation of more fast acting relay protections and circuit-breakers in the transmission grid;
- application of new requirements for keeping the DER in operation under decreased and increased voltage and frequency conditions.

The last point also provides a basis for maintenance of the operational integrity of a distribution network when it is separated from the transmission network.

Surviving after unintended islanding

Overview

Surviving after an unintended islanding is quite a new approach, which is to replace the tripping-of-units approach following the “loss-of mains” event. For comparison, approaches given in [11] could be considered.

New requirements mean that the customer is kept under supply and the generators operate under the conditions close to normal. In this case, re-synchronization and complete restoration of the normal conditions is needed.

In this paper, surviving strategy requires that DER units are kept in operation as long as possible, with supplying as much customers as possible when an unintended islanding (loss-of-mains) happens.

The experience of operation of major interconnections can be helpful as to the restoration of normal functioning after a severe disturbance (blackout). A review of restoration strategies based on actual blackout experience is presented in [12]. Its main points are as follows:

1. “Bottom Up” is the only method of restoration with no outside assistance available.
 - “Multiple island” method of restoration, with multiple areas to be restored in parallel.
 - “Core island” method of restoration is based on formation of a larger and more stable island with greater generation, but if such an island blacks out the process must be restarted.
2. “Top Down” approach may be used if outside assistance is available for restoring an underlying system.
3. “Combination approach” combines two previous ones.

Generally, continuation and restoration plans for a distribution grid with DER should be started applying “Bottom Up” approach, since in this case external support is unavailable. After reconnection, other approaches may also be effective.

In a distribution system with DER, the restoration steps to be taken depend very much on the pre-fault conditions. High active and reactive power imbalance (exchange) means that more active actions should be taken in the islanded system.

Highly active power export will cause significant and fast control actions in order to reduce production [13]. The next sections of this paper focus on the transient processes following separation in the high-import case.

High-volume power import: frequency and voltage transients

The study discussed here starts with frequency and voltage transient simulations, and continues with requirements to be satisfied by control actions.

The 10 kV distribution grid model represents an urban network under extension consisting of approx. 100 nodes, a transformer connection with 110 kV and 400 kV parts and the total consumption of 44 MW. The model diagram is illustrated in Figure 4.

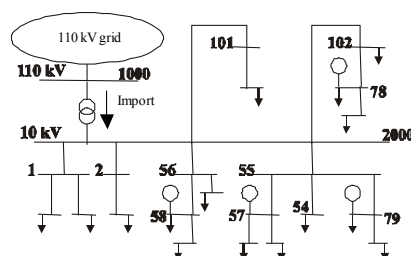


Figure 4. The 10 kV distribution grid model

In the simulations, the synchronous generators were equipped with a voltage regulator.

Multiple transients are modelled with the following assumptions:

- power imports before islanding cover from 20 up to 85% of the internal load depending on the number of DER units in operation and their outputs;
- DER units can have variable rated values (unit size, inertia, etc.);
- types and characteristics of loads (static, rotating, etc.) can be different.

Figures 5.a), 5.b), 6 shows frequency and voltage variations in time, with 0 sec corresponding to the islanding instant. The time range covers two seconds that follow islanding.

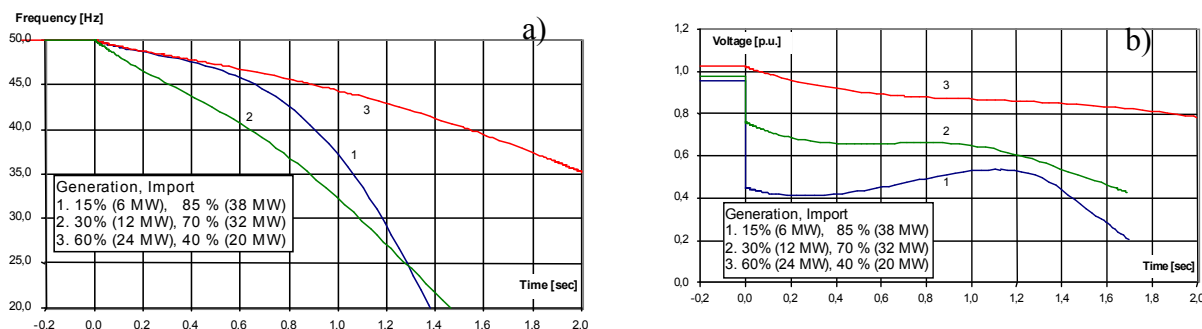


Figure 5. a) frequency diagram, b) voltage diagram

Deep fall in the frequency (below 20 Hz) and voltage (below 0.5 p.u.) is a normal phenomenon under high-volume import separation conditions [14].

The results of investigation into the transients form a basis for further development of suitable operational algorithms and adjustment of a special load shedding system operating inside the island.

Availability of such a system is mandatory for a system to survive. The requirements to be imposed on its design are as follows:

1. Load removal actions should be based both on the frequency and voltage decrease indications.
2. Load shedding for a tens-of-MW-scale system must be coordinated with the existing relays that operate in the same island and originally support a thousands-of-MW- scale system.

Operational algorithm of control actions and their adjustment approaches should be based on recent developments with the rate of frequency change application so as to increase its efficiency. Figure 6 shows calculated values that differ enough to use this in control.

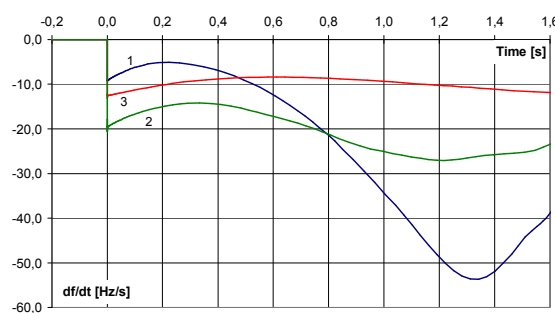


Figure 6. Rate of change of frequency diagram

Design of algorithms should be part of future activities.

The philosophy of reconnection of the islanded part is based on additional support that may be provided and minimisation of restoration time.

Reconnection

In the simulations, reconnection transients were modelled for two grids, with determination of the maximal frequency and voltage differences that still permit coupling.

The distribution system was described in the previous section. The high-voltage model comprises three generation areas, connected by ten 400 kV lines, and the total consumption 3000 MW.

The reconnection conditions were estimated as acceptable or non-acceptable depending on post-reconnection transients.

Frequency differences Δf immediately before coupling that were tested equalled 0.3 Hz, 0.65 Hz, and 1.0 Hz.

For each frequency difference, the range of voltage angle differences $\Delta\phi$ was checked, starting from 20° and finishing with 60° .

Simulation output was checked from electrical and mechanical points of view. Figures 7 a), 7b), 8 shows an example with Δf equal 0.65 Hz and $\Delta\phi$ as 52° .

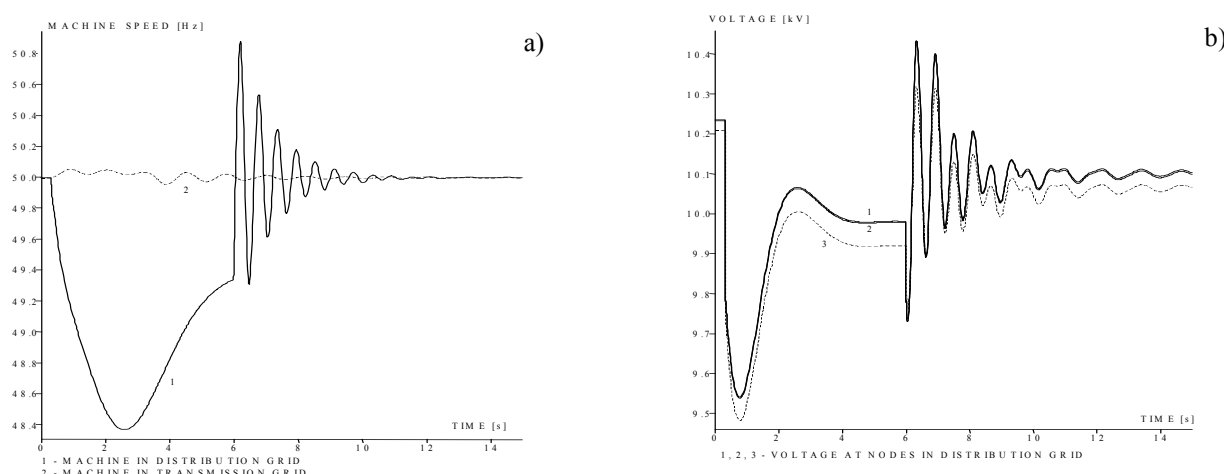


Figure 7. a) Machine speed (frequency) diagram, b) Voltage diagram

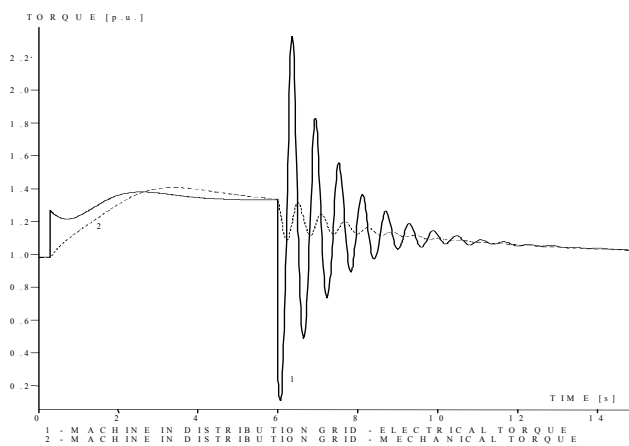


Figure 8. Electrical and mechanical torques diagram

Summarising electrical transients (frequency, voltage and power values), reconnection is possible with the frequency difference up to 1.0 Hz and voltage angle difference up to 60°.

However, mechanical and electrical torques' imbalance is quite dangerous for small generators (see Figure 8). This may reduce live time of generating unit shaft.

Reconnection requirements should be extended as torque restriction to be considered properly.

Conclusion

The automation procedures have been developed for stability reserve estimation in the FPSs that contain a considerable volume of DER. The set of methods model uncertainty that characterises FPS states so as acceptable and non-acceptable estimated.

Considering unintended islanding, surviving strategy requires operation of DER is prolonged with supplying customers when loss-of-mains happens. Technical requirements include automatic load shedding and subsequent reconnection with the high-voltage part. Mechanical and electrical mechanical and electrical torques imbalance is quite dangerous for small generators.

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Sauhats A., Svalova I., Svalovs A., Kucajevs J. Izklidētas ģenerācijas avoti un energosistēmas stabilitāte

Šis zinātniskais darbs veltīts Nākotnes enerģētiskās sistēmas (NES) pētīšanai. NES sastāvēs no ievērojama skaita izklidētas ģenerācijas avotiem. Precīzu priekšstatu par tādās sistēmas struktūru, sastāvu un parametriem nav iespējams radīt. Tāpēc ir jāveic atbilstoši aprēķini, izmantojot dažādus enerģijas avotu tipus, to pieslēgšanas vietas tīklam, darba traucējumus, kas var radīt dinamiskās stabilitātes zudumus. Viens no galvenajiem šo sistēmu attīstības un ekspluatācijas noteikumiem ir pietiekama dinamiskā stabilitāte. Šādu sistēmu darbības režīmi nākotnē nav zināmi, un ir nepieciešamas atbilstošas modelēšanas metodikas. Tika izstrādātas automatizācijas procedūras NES ar lielu izklidētas ģenerācijas avotu skaitu stabilitātes novērtējumam. Aplūkojot izklidētas ģenerācijas avotu pēkšņu atdalīšanos no tīkla, darbaspējas saglabāšanas stratēģija prasa turpināt apgādāt patērētāju ar elektroenerģiju, ja pazūd saikne ar pamata energosistēmu. Šajā publikācijā ir apskatītas tehniskās prasības sadales tīklu saglabāšanai un atkārtotai pieslēgšanai. Papildu automatikai jāresinhronizē sadales tīkls pēc pēkšņas atslēgšanās no tīkla pārraides daļas.

Sauhats A., Svalova I., Svalovs A., Kucajevs J. Distributed Energy Resources and Power System Stability

This paper is dedicated on investigation of the Future power systems(FPS). FPS will contain a considerable volume of distributed energy resources. The present study is dedicated to the investigation of the future power systems (FPS) that contain a considerable amount of DG. Exact prediction of the structure, composition, and parameters of such systems is impossible. It makes necessary to perform calculations that correspond to various combinations of the types of DGs used, their connection places, disturbances that may cause a loss of dynamic stability. One of the main requirements for the system development and operation is the existence of a sufficient dynamic stability reserve. The future states of FPS are unknown with need in appropriate modelling techniques. The automation procedures have been developed for stability reserve estimation in the FPSs that contain a considerable volume of DER. Considering unintended islanding, surviving strategy requires operation of DER is prolonged with supplying customers when loss-of-mains happens. Technical requirements for distribution grid surviving and reconnection are considered in the paper. Additional automation shall resynchronize the distribution network after its emergency disconnection from the transmission part.

Саухатс А., Свалова И., Свалов А., Куцаев Е. Распределённые генерационные источники и стабильность энергосистемы

Данная научная работа посвящена исследованию Энергетических систем будущего (ЭСБ). ЭСБ будут состоять из значительного числа распределённых источников электроэнергии. Точное представление структуры, состава и параметров таких систем невозможно. Поэтому необходимо выполнение соответствующих расчётов при использовании различных типов источников электроэнергии, их места подключения к сети, нарушения в работе, которые могут привести к потере динамической стабильности. Одно из главных требований для развития и эксплуатации этих систем - это существование достаточного резерва динамической стабильности. Режимы работы в будущем таких систем неизвестны, необходимы соответствующие методики моделирования. Разработаны процедуры автоматизации оценки резерва стабильности для ЭСБ, которые будут содержать большое число распределённых источников электроэнергии. Рассматривая внезапные отключения этих источников электроэнергии от сети, стратегия сохранения работоспособности требует продолжения успешного снабжения потребителей электрической энергией при потере связи с основной энергосистемой. Технические требования сохранения распределительной сети и повторного включения рассмотрены в этой статье. Дополнительная автоматика должна ресинхронизировать распределительную сеть после внезапного отключения от передающей части сети.