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Stability Investigation of the Virtual Power Plants Electrical Systems

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Abstract

Distributed energy becomes the key direction of the electric power industry in developed countries. Concept of virtual power plant (VPP) has become increasingly important. The main objective is the effective integration of distributed energy resources in the centralized electricity grid. In the design of VPPs electrical systems considerable attention should be paid to ensure their stable operation. Incorrect choice of elements or operating mode may lead to loss of stability of the system and, as a result, to power interruption.

The paper deals with investigating the stability of VPPs electrical systems on the example of wind-diesel hybrid power systems (WDHPS). The relevance of research due to the fact that stability issues of electrical systems with a large share of distributed energy resources are poorly understood. The paper considers a mode when the VPP disconnected from the centralized electricity grid and operate autonomously, i.e. load powered only by WDHPS.

Criteria for assessing the stability of electrical system "wind electric plant (WEP)-diesel generator set (DGS)-load" are formulated. The author points out five main criteria: the WEP stability, the absence of the generator's asynchronous running, the absence of circulating currents in the system, the absence of reverse power flow in the DGS, preserving the stability of the load node. All mentioned stability criteria are studied under different operating modes of WDHPSs electrical system using developed Matlab/Simulink computer model.

The studies allow to define the unstable operating modes of the VPPs electrical system with WDHPS and to take measures for increase the stability of the system.

Keywords: Virtual Power Plant, Wind-Diesel Hybrid Power System, Stability Criteria, Algorithm, Simulation Modeling.

Introduction

Increasing share of distributed energy resources in electricity generation is typical for modern electric power industry in many developed countries, and it makes urgent creation of a "virtual power plants" [1, 2]. Virtual Power Plant (VPP) is a single entity that integrates distributed energy resources, energy storages, controlled load and adaptive control system. VPP can be integrated into the centralized electricity grid or operate autonomously.

VPP connected to the centralized electricity grid are an effective tool for reducing the peak demand, energy losses and loading on grid. Integrating of single distributed energy resources in VPP increases their efficiency by allowing to small power sources take participation in the electricity market.

Design of VPP requires the solution of optimization and technical issues such as the choice of the topology and types of power sources, provision of the required power quality, the creation of effective control and protection systems and others. An important problem is to ensure the stable operation of diverse electrical systems of VPP. Unlike large electrical grids, questions of the stability of electrical systems with a high content of distributed generation are not sufficiently studied. In Russia, there are no regulations and guidance documents for the calculation and assessment the stability of electric power systems with renewable energy resources.

The article describes methodology and results of the studies of stability of the separate components of the autonomous VPP on the example of wind-diesel hybrid power systems (WDHPS).

Literature review

The two main schemes of WDHPS are shown on a fig. 1: combining of wind electric plant (WEP) and diesel generator (DGS) on alternating current (AC) bus (fig.1, a) and direct current (DC) bus (fig.1, b).

The electrical battery B in AC bus WDHPS provides an economical operation of the diesel engine DE [3]. The main problem of the AC bus scheme is the parallel operation of two or more electric generators with different power and load sharing between them [4]. The synchronous generator SG operates with a fixed rotation frequency of output shaft at any load that is necessary to maintain the utility frequency of 50 Hz on the AC bus [5]. WEP can operate with a variable rotation frequency of the wind turbine WT shaft, thus output of permanent magnet synchronous generator PMSG is connected to the electrical load L through a rectifier R and power inverter I.

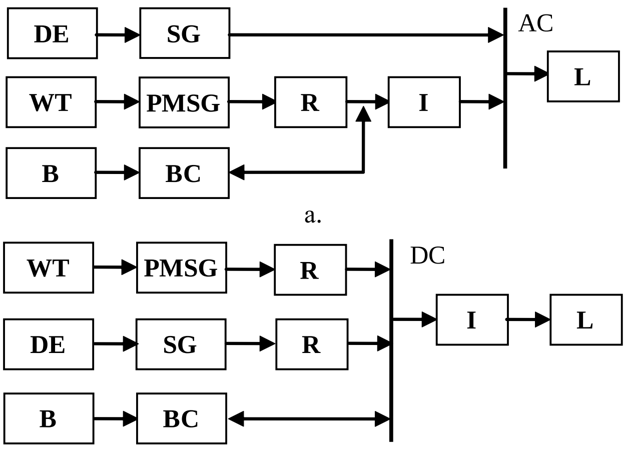


Fig.1. WDHPSs structural scheme: a-AC bus; b-DC bus; B-electrical battery; BC-bidirectional converter; DE-diesel engine; I-inverter; L-load; PMSG-permanent magnet synchronous generator; R-rectifier; SG-synchronous generator; WT-wind turbine

In the case of DC bus WDHPS there is no need to coordinate with each other operation of sources. It allows controlling the operation of units using optimality criteria [6]. There is no need to maintain on the generator output the equal and constant values of voltage and frequency of the grid. It is possible to use WEP and DGS generators with variable rotation speed of shaft, and therefore the variable generated power. There is an opportunity to maximize the utilization of wind energy using the wind turbine WT and reduce DGSs fuel consumption. However, DC bus scheme is more complicated and expensive than the AC bus scheme.

In AC bus WDHPS required utility frequency and voltage are determined respectively by the implementation of the balance of the active and reactive power on AC bus. Because of the discrepancy between reactive power production and consumption in an isolated system voltage fluctuations occur, which reduces system stability and power quality [7]. Thus, the control system should monitor each time the balance between electric power generation and consumption in the system. To maintain the reactive power balance in WDHPS, the authors [8, 9] suggest the use of a static synchronous compensator (STATCOM) for automatic reactive power control. This method is relevant for inductions WEP, when it requires a reactive power source for its operation.

To control the operation of DC bus WDHPS it is proposed [10] to use a balance of instantaneous currents. Importantly, it is necessary to stabilize the voltage on the DC bus, controlled by the DGSs excitation system. Energy storage device performs a function of providing the energy balance of production and consumption on DC bus. The control signals are generated in real time based on the power sources and energy consumption characteristics.

Maintaining the powers balance is primary to ensure the WDHPSs stable operation. However, this approach does not account an electromechanical characteristics and interaction features of the individual elements in the system. Therefore, for better understanding of the causes of stability violation of the power supply system with WDHPS requires identification and study of stability criteria, universal for all connection schemes of sources.

Materials and methods

An algorithm for determining the stability of WDHPS was developed (fig.2). It includes two stages: 1) an assessment of the power systems balance reliability; 2) a stability determination of the WDHPSs main units using stability criteria.

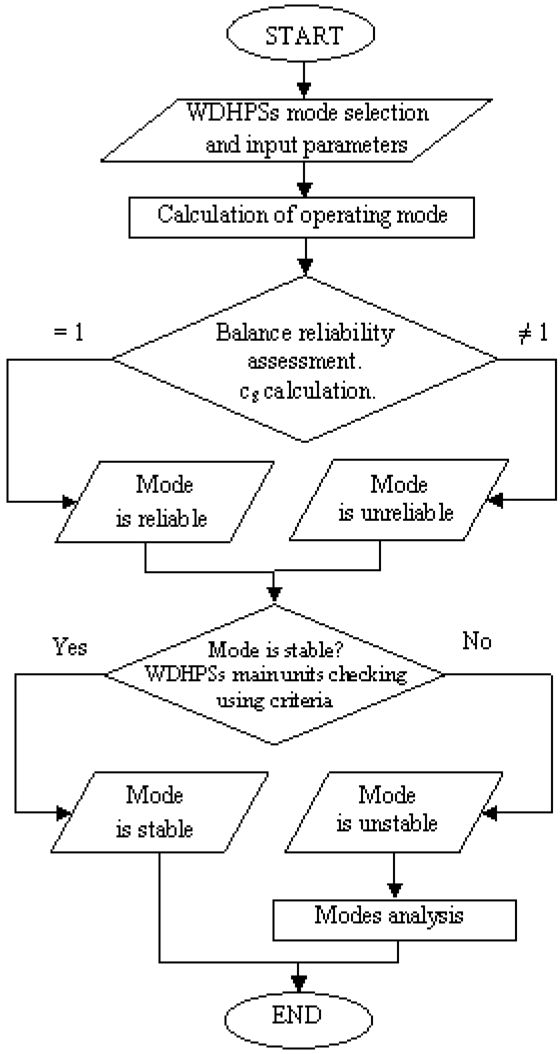


Fig.2. An algorithm for determining the stability of WDHPS

WDHPS operation mode, power supply system parameters, wind speed graph and load profile of the autonomous consumers set on the initial stage.

Power systems balance reliability assessment performed by verifying compliance the balance of the active P and reactive Q power in the system [11]:

$c_s = (P_{WEP\,i} + P_{DG\,i} \pm P_{B\,i} - P_{BR\,i}) / P_{L\,i} = 1$ (1)

$(Q_{WEP\,i} + Q_{DG\,i} \pm Q_{B\,i}) / Q_{L\,i} = 1$ (2)

P_i and Q_i-active [W] and reactive [var] power in the i-th mode; indices: B-battery, BR-ballast resistance, L-load.

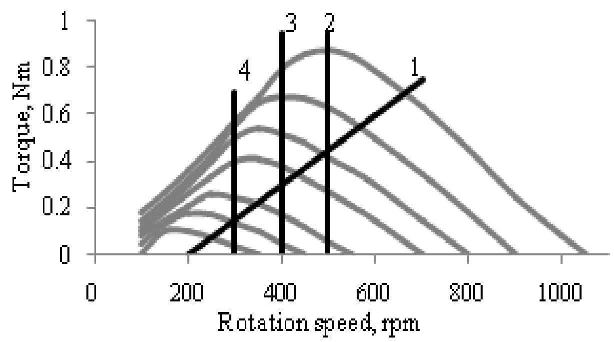
Operating mode is reliable when a (1) and (2) holds. Then proceed to the stability estimation of the WDHPSs main units. The authors suggest five stability criteria [12, 13]:

1) the stability of the WEP (coordination of the wind turbine and the generator);
2) the absence of the generator's asynchronous running;
3) the absence of circulating currents in the system (entering electromotive force (EMF) opposite-phase with the concurrent running WEP and DGS);
4) the absence of reverse power flow in the DGS;
5) preserving the stability of the load node.

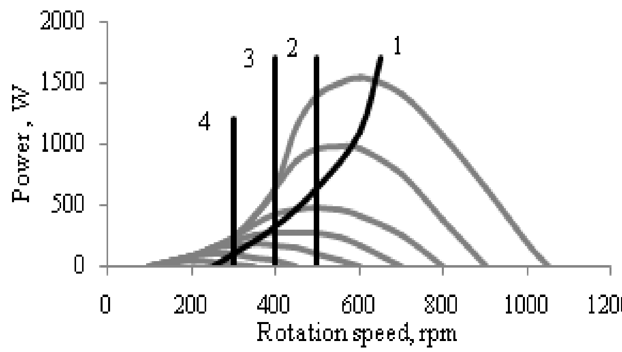
These criteria allow determining the stability of the WDHPSs main units. Mode is unstable in case of violation of at least one of criteria. These modes make the area of the WDHPSs unstable modes. They are subject to further analysis, during which identifies the causes of stability violations and generate recommendations to eliminate the recurrence of violations.

A more detailed description of each criterion can be found below.

WEP stability



a



b

Fig.3. WEPs performance characteristics at different wind speeds: a-torque characteristics; b-power rating

The WEP converts kinetic energy from the wind flow into mechanical energy of the rotor rotation and after that transforms it into electrical energy. WEPs performance characteristics are the torque characteristics T = f (n) and the power rating P = f (n). Operating point is determined by the crossing of the performance characteristics of the wind turbine and generator (fig. 3) [14].

Characteristics (fig.3) should be given to the same shaft rotational speed, e.g. the generator output shaft. The system is statically stable, if under a small perturbation in the system the resultant moment strives to return the system back to its original position. This condition is expressed by the inequality [15]:

$d T_G / d n > d T_T / d n$ (3)

T_G-generator torque [Nm]; T_T-wind turbine torque [Nm]; n-generator output shaft speed [rpm].

The absence of the generator's asynchronous running

Violation of generators static stability is a loss of synchronism, which is accompanied by the passage of high currents in the stator winding.

The condition of operation of the synchronous generator is equal rotation speeds of the rotor n_1 and the resulting magnetic field n_2. It is determined by the expression [16]:

$n_1 = n_2$ (4)

Synchronous machine static stability is the ability to maintain synchronous rotation (4), when changes an external torque or braking torque, applied to its shaft [16]. The condition of static stability is given by:

$\theta < \pi / 2$ (5)

θ-load angle of the machine [°].

The smaller the load angle θ, the greater the stability margin of the synchronous machine. Increasing excitation current leads to decrease of the load angle, thus stability increasing.

Failure to comply (5) may cause a loss of stability. For example, in the presence of a large proportion is capacitive load in the grid. In this case, the generator will operate in underexcitation mode to maintain stable voltage, i.e. excitation current drops, and the angle θ increases. Another reason for the loss of stability may be a reduction in the wind speed, and consequently reduction the torque and excitation current.

The absence of circulating currents in the system

The load is variable, and the wind speed is changed during the day. Thus the working conditions of the WEP and DGS generators are different in all modes. In WEP and DGS parallel operation the output voltages are different.

In the DC bus WDHPS this would lead to the electric potential difference Δ*U* on DC bus:

$\Delta U = | U_{R1} - U_{R2} |$ (6)

U_{R1} and U_{R2}-the output voltages of the first and second rectifiers [V].

Under the influence of ΔU circulating current I_C appears on DC bus according to Kirchhoff's current law:

$I_C = I_{R1} + I_{R2} - I_{INV}$ (7)

I_{R1} and I_{R2}-the output currents of the first and second rectifiers [A]; I_{INV}-the input current of the inverter [A].

Circulating current causes an additional energy losses, leads to false positives of the WDHPSs control system (false connection of the ballast load, improper operation of the battery charger controller), DC bus additional heating (rapid aging of conductors or breaking). Thus, the task of the WDHPSs control system is to prevent the appearance of circulating currents in the system.

The absence of reverse power flow in DGS

The condition for the generators stable operation is the (5). If the load angle becomes negative, the synchronous machine from the generator mode goes into motor mode. This leads to disruption of power supply of consumers and the stability of the whole system.

In the DC bus WDHPS cause of violation may serve as the breakdown of the rectifier. The breakdown of the rectifier diodes can occur due to the voltage rise above the norm, overheating of high current passing through the diode, and mechanical damage. The destroyed diode resistance to the current is practically zero in both directions, leading to a phase short-circuit in the stator windings and generator failure. As the result this reduces the generators voltage, and the electrical battery is not charged. The battery begins to discharge through the stator winding, which causes destruction of the winding insulation and the battery discharge rapidly. To eliminate the breakdown of the rectifier, it is necessary to satisfy the condition:

$$U_{REV} / U_{PRV} < 1 \qquad (8)$$

U_{REV}-the voltage applied to the rectifier in the reverse direction; U_{PRV}-the peak reverse voltage.

Preserving the stability of the load node

Voltage collapse occurs in the system while reducing the voltage at the load node to a critical value U_{cr}. This effect leads to power supply disruption of this node consumers.

To determine the stability margin in normal and postaccident modes, and test the stability of the load calculated voltage margin coefficient [17]:

$$K_U = (U_0 - U_{CR})\ 100\ \% / U_0 \qquad (9)$$

U_0-nominal rated voltage of the system [V]; U_{CR}-critical voltage value corresponding to the static stability boundaries of the system [V].

To determine the critical voltage value and load stability margin it is necessary to carry out the weighting of an initial normal mode. Weighted mode is a operation mode of the system at coincidence repairs of main equipment of electric grid at maximum or minimum load. Load stability increases with an increase in the voltage margin coefficient.

Practical methods of the stability calculation may simplify calculations without reducing their accuracy.

The most common practical criterion is [17]:

$$d\,\Delta Q / d\,U < 0 \qquad (10)$$

ΔQ-the imbalance in the node between the power generated by the generator $Q_G(U)$ [var] and consumed load $Q_L(U)$ [var]; U-voltage in the node [V].

Unbalance of reactive power ΔQ causes a change in the EMF of the generator E [V]:

$$d\,E / d\,U > 0. \qquad (11)$$

The choice of criterion is determined by the simplicity and ease of analysis.

If the load static stability calculations are made for the total static load characteristics of the node $P_L(U)$ and $Q_L(U)$ on practical criteria, the stability violation means a violation of the stability of the entire node, not taking into account individual consumers of the node. But in most cases, the stability violation of the individual consumers takes place before the whole load node. To study the stability of any element, it must be isolated with its own characteristics.

Experimental results

The WDHPSs stability investigation have been conducted by developed algorithm (fig.2) using a simulation modeling. The object of the study is DC bus WDHPS (fig.1, b).

The part of the VPP with WDHPSs computer model was developed in Matlab 7.11.0.584 (Simulink) [18, 19]. Computer model consist of four units: the WDHPS, distribution electrical grid, the load node and a measuring devices (fig.4).

WDHPSs unit consists of three model of the power sources (WEP, DGS, and B) that are connected on a side of the rectified voltage across the DC bus. The input data of the model are a wind profile and a battery state of charge at the initial time of simulation. The output is a three-phase voltage of 380 V and 50 Hz. The model simulates the WDHPSs operating modes when changing load rated power from 0 to 100 kW and the wind speed from 0 to 10 m/s.

View of the VPP with DC bus WDHPSs computer model without measuring devices is shown in fig.5.

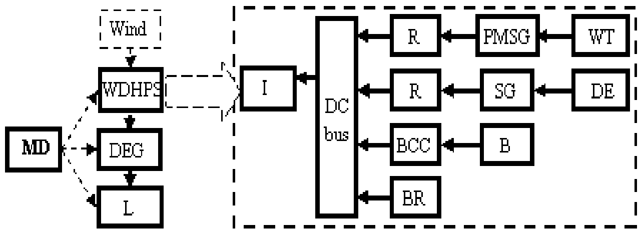


Fig.4. Structure scheme of the VPP with WDHPS computer model: B-electrical battery; BCC-battery charger controller; BR-ballast resistance; DC bus-direct current bus; DE-diesel engine; DEG-distribution electrical grid; I-inverter; L-load; MD-measuring devices; PMSG-permanent magnet synchronous generator; R-rectifier; SG-synchronous generator; WT-wind turbine

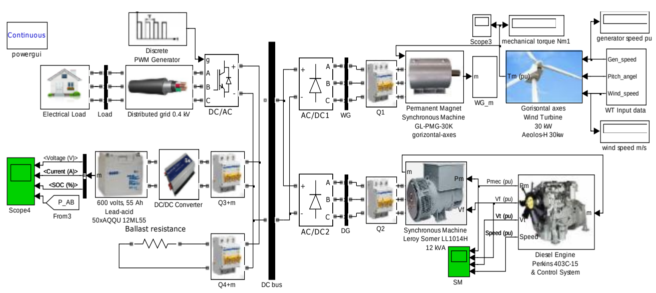


Fig.5. VPP with DC bus WDHPSs computer model

Output data are presented in the form of oscillograms, timing diagrams and the instantaneous values of the measured values. According to the readings of voltmeters, ammeters, wattmeters and frequency counters are carried out monitoring parameters of power sources, load and DC bus.
The modeling results of the WDHPSs operating modes are shown on fig.6-9.

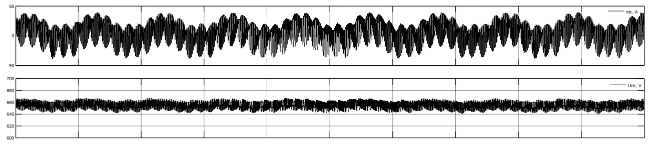


Fig.6. Current and voltage on the DC bus

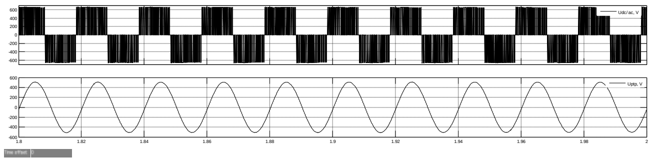


Fig.7. Phase-to-phase voltage at the output of the inverter

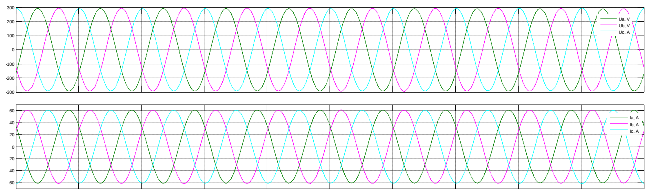


Fig.8. Phase-to-ground voltages and currents in the load grid

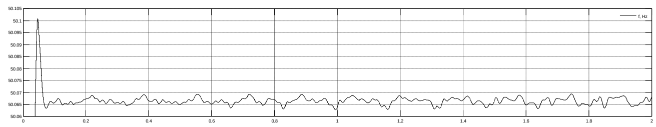


Fig.9. Frequency of alternating current in the load grid

Discussions

The developed methodology allows to determine the stability of diverse electrical systems of VPP. The conducted research of the DC bus WDHPS revealed its high stability. In the DC bus WDHPS does not require generators synchronization of the sources connected to DC bus, and algorithms [10] allow the use of the battery as a controlled current source and control the balance of generation and consumption in the system. Connecting on DC (fig. 6) enables the use of energy-efficient WEP and DGS generators without worrying about the stochastic nature of the wind and power quality in a consumers grid. The ideal sine wave of voltage and current (fig.7 and 8) in the load grid allows to achieve the use of the inverter. Frequency of alternating current in the load grid in the operating range of the wind speed (fig.9) is within permissible bounds [20].
A correction of the WEP and DGS output parameters can be carried out using a controlled thyristor rectifier [21]. Control signals are current and voltage feedback signals. Thus it is possible to maintain a required WDHPSs output voltage (fig.8) at the equal loading parallel operating generators of a various power. This avoids the occurrence of circulating currents on the DC bus eliminating possible causes of stability violation of the studied system.

Conclusion

Considered stability criteria allow to determine stable and unstable operating modes of the WDHPS. With the simultaneous implementation of all five criteria the operating mode is stable.
Developed VPP with DC bus WDHPS computer model allows to study operating modes of the WDHPS. The findings will form the basis for developing the Project of guidelines to improve the stability of the WDHPSs electrical systems.

Acknowledgsment

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