Analysis of electricity supply systems flexibility and problems to be investigated

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Abstract. The problem of electric power systems (EPS) flexibility is discussed, definition of EPS flexibility is given. Causes of EPS flexibility degradation and measures for flexibility enhancement are analyzed based on the review of publications. Urgent problems of EPS flexibility studies are identified and directions of further studies of the electricity supply systems are grounded.

Key words: electric power systems; electricity supply systems; flexibility; causes of flexibility degradation; measures for flexibility enhancement; directions of studies.

Introduction

Electric power systems (EPS) flexibility in recent years has been in focus of studies that is evidenced by the list of references to this paper. Meanwhile, the problem of flexibility as applied to complex technological systems was stated as early as in 2002 [54]. Generalizing a number of definitions of 'EPS flexibility' term, Ref. [46] offers the EPS flexibility to be defined as ability of a system to maintain normal operating conditions (regimes) under the impact of internal (sudden changes in generating sources, fluctuations in loads and line flows) and external (sudden external impacts of different origin) random (uncertain) factors. The factors mentioned were systematized and measures for EPS flexibility enhancement were briefly discussed in [46, 55]. Detailed review of measures on EPS flexibility enhancement in Ref. [23] is also worth mentioning (393 cited papers). Generalizations proposed in [23] were taken account of in this paper without referring to the papers cited there.

Objective of the present study is to give a detailed comparative analysis of papers published in recent years with focus on the causes of EPS flexibility degradation and measures for its enhancement. The analysis forms the base for statement of the considered problem.

Analysis of EPS flexibility degradation problems

Let us first formulate some obvious conclusions on the base of the analysis of papers listed further as regards the causes of EPS flexibility degradation.

a) In the majority of cases (73%) the main cause of EPS flexibility degradation is assumed to be fluctuations in power generation by wind power plants (WPP) and photovoltaic modules (PVM), wind power plants prevailing. It is not surprising as authors of appropriate studies are from countries with high share of WPP in the installed capacity. It is obvious that it is those studies that actualized the EPS flexibility problem.

b) Works that consider uncertainty of active consumers' loads as the cause of flexibility degradation come second (20%). It is also understandable as in the conditions of random fluctuations of electricity prices at the spot market an active consumer makes on-line decision on the volume of electricity to be purchased, and this volume is random for a dispatcher.

c) Publications that consider reduction of regulating effect of load in terms of voltage and frequency, and frequency characteristics of generation as causes of EPS flexibility degradation come third (15%). This problem was first stated in [56]; it is related to large-scale use of frequency control of electric motors of consumers and to connection of wind mills, high-speed gas-turbines and some other generating units to EPS via reversible converters.

d) Connection of generators via reversible converters and low inertia constants of rotors of small generating units connected directly to the system reduce the inertia and, hence, EPS flexibility.

e) Impact of external disturbances as a factor of EPS flexibility degradation was directly studied in few papers. An obvious more or less higher indirect impact of this factor in combination with other factors, e.g., with reduction of EPS inertia, reduction of regulating effects of load and generation and some others is also worth mentioning.

Let us now briefly comment on measures for enhancing the EPS flexibility.

Analysis of publications listed evidences that active load control (66% of cases), provision of power balance, as a rule, at the expense of emergency load shedding, active power reserve (55% of cases) and use of energy storage devices (37% of cases) are the most popular measures of EPS flexibility enhancement. Technological

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and market control (25% of cases) and reconfiguration of the electric grid (12% of cases) deserve lesser attention.

Analysis made allows us to make an obvious conclusion that peculiarity of EPS flexibility problem is mainly conditioned by specific features of the studied systems. As to flexibility enhancement measures, complex use of two and more measures prevails (72% of cases).

Validation of directions in EPS flexibility studies

Since urgency of EPS flexibility studies is conditioned by specific features of the studied systems, let us consider this specificity as applied to Russian conditions. In this respect the following factors should be mentioned.

Should power generation by wind mills and PVM be considered as the main cause of flexibility degradation, then, in the conditions of centralized power supply in Russia, despite governmental incentives, the share of generation by renewable energy sources (RES) in the future will hardly be high, with some local exceptions, e.g., South Interconnected EPS where RES share by 2025 is expected to be as high as 30% [63]. Islanded remote electricity supply systems (PSS) hold a unique position as RES there are competitive with fueled power plants and can make a considerable share in the total installed generating capacity.

Thus, summing up the initial conditions, the object of studies may be an islanded PSS that in the most general case includes a conventional fueled power plant, a wind mill, a power storage device, a car charging station that along with car charging may supply power to PSS, and active consumers that keep control of their power consumption. All those units are connected to a distribution network of PSS. It is necessary to determine the required capacity and electric capacity of the power storage device subject to availability of the given parameters of the remaining devices, structure and parameters of the distribution network.

Difficulty of studying the presented object lies in the fact that operating conditions of the wind mill, charging station, power storage device and behavior of active consumers are subjected to the impact of random factors. Let us start with the active load that, along with conventional irregular fluctuations, has a random component determined by independent choice of a consumer to control his electricity consumption depending on the state of the spot market. Then, as it has already been noted, power generation by a wind mill is of random nature. Charging/discharging of the power storage device is also a random process. A random process of a car charging station has the most complicated nature. Random factors here include: a mix of cars at the charging station at every time moment; time of arrival and departure of each car; degree of charging/discharging of accumulators of every car at every time moment.

Each of these random factors shall be assigned probability distribution laws. Monte-Carlo method allows identification of random state for each random

factor at a given time moment. A mix of those random states forms random state of a power supply system for which the optimum power flow in the distribution network is determined using the criterion of minimum electric losses subject to account of constraints on the voltage levels in the nodes and currents in the branches. The result is determination of the size of capacity required at a given time moment for the power storage, keeping in mind that the node to which the power storage is connected is balancing one. Since the required electric capacity of the electricity storage shall be determined along with its power, the considered simulating procedure is repeated for multiple time moments within the specified time interval (e.g., a year) in conformity with load curves of consumers.

The problem of losses minimization in a power supply system has the form:

$$\min P_{loss} \tag{1}$$

$$\left[\dot{Y}\right]\left[\dot{U}\right]=\left[\dot{I}\right]=\left[\hat{S}\right]/\left[\hat{U}\right] \tag{2}$$

$$\hat{S}_i = \hat{S}_{gi} + \hat{S}_{wi} + \hat{S}_{zi} - \hat{S}_{li} \tag{3}$$

$$0 \le P_{gi} \le P_{gi}^{\max} \tag{4}$$

$$0 \le P_{wi} \le P_{wi}^{\max} \tag{5}$$

$$0 \le P_{si} \le P_{si}^{\max} \tag{6}$$

$$E_{si}^{k-1} + \Delta P_{si}^k \Delta t \le E_{si}^{\max} \tag{7}$$

$$U_i^{\min} \le U_i \le U_i^{\max} \tag{8}$$

$$U_i = \sqrt{U_{re_i}^2 + U_{im_i}^2} \tag{9}$$

$$I_{ij} \le I_{ij}^{\max} \tag{10}$$

$$\dot{I}_{ij} = (\dot{U}_i - \dot{U}_j)\dot{Y}_{ij} \tag{11}$$

$$I_{ij} = \sqrt{I_{re_i}^2 + I_{im_i}^2} \tag{12}$$

Where k is the number of time interval, Δt; i, j are numbers of PSS nodes; a system of equations (2) with account of (3) describes power flow in the PSS network, each iteration being controlled by constraints on the voltage levels in nodes (8) and currents in branches (10), and by generated active power of a conventional generator (4), by a wind mill (5) and by the power storage device (6); expression (8) forms charging mode limitations in the energy storage operation. Relations (6) and (7) represent both the stationary electricity storage, and a car charging station.

Conclusion

Analysis of recent studies on the EPS flexibility revealed causes of flexibility degradation due to random fluctuations in power generation by renewable energy sources and allowed one to give recommendations on measures for flexibility enhancement. This analysis with account of conditions in Russia allowed us to state the problems of PSS flexibility studies. Consideration was given to the main statements of a simulation algorithm for determination of required power and electric capacity of the energy storage device to balance irregularities of power production by wind mills subject to account of the main random affecting factors.

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