The analysis of power system steady-state aperiodic stability with electronic generation

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Abstract. One of the main directions of electric power industry development all over the world is the use of distributed small generation, both based on carbon fuel resources with synchronous communication between sources when they are connected to electric networks, and renewable energy sources working in the electric network through frequency-converting devices (electronic generation). The latter leads to the inevitable mass use of inverters in existing AC electric networks. The objectives of this investigation are to study the impact of electronic generation on the modes and stability of existing electric networks and power systems, the formation of requirements for the characteristics of electronic generation control, which minimize the coordination of relay protection and automation with electronic generation in the electric network, as well as increase the reliability of the general electrical mode. The article presents the results study of the steady-state aperiodic stability of the power system with electronic generation, the requirements for their steady-state characteristics and control in the power system.

1. Introduction
Currently Smart Grid based technologies are being developed differently than in Europe, USA and other countries. Small scale distribution generation abroad is based mainly on renewable energy sources (RES) operating in electric grid alone or through converters. Up to date Russia considering its climate and geographic features is mainly developing for cogeneration plants of small scale fuel distribution generation [1, 2]. Power-generating units synchronized with electric grid of power system, based on smart automated control system allows to fully use system effects from large scale concentrated and small scale distribution generation. However operation in an AC network is associated with a using of inverters in the form of current or frequency converters for most generators using RES [3].

A new concept of “Electronic Generation” has been introduced for such power sources.

Electronic generation (EG) – electrical energy sources supplying the load based on alternate or direct current via converters. One kind of electronic generation is a virtual synchronous machine.

The positive environmental effect of the using of RES is accompanied by many negative technical consequences due to the fundamental features of inverters when converting DC to AC and the lack of requirements for the characteristics of EG from electrical networks [4].
2. **Inverters in the composition of electronic generation**

Inverters in composition of EG perform the following main functions:

- Conversion of direct current to alternating current.
- Synchronization in frequency, voltage and angle with the power system.
- Stabilization of the output voltage.
- Limitation of current overloads in case of short circuit [5].

The Figure 1 shows typical connection schemes of inverter transformer substation (TS) to main switchgear. Radial connection schemes of inverter transformer substation to main switchgear are applied for low capacity power plants which used RES (2-3 MW) (Figure 1a). For power plants with a capacity of 4–8 MW, a reliable and inexpensive scheme is a circuit, where each feeder contains one or two pass-through inverter transformer substations and one dead-end (Figure 1b). For power plants with a capacity above 9 MW, the most suitable scheme is in the form of open ring sections (one ring for every 8–12 MW), where all inverter transformer substations are through-feed (Figure 1c).

![Figure 1](image-url)  
*Figure 1. Typical connection schemes of inverter transformer substation to main switchgear.*

Inverters operate either in Slave mode or Master mode.

The frequency and voltage are regulated depending on the power in Master mode (voltage source). In this mode it is possible to maintain a given voltage and adjust the voltage and frequency with statism (Figure 2a).

The output current is regulated depending on the voltage at the point of connection of the inverter to the network in Slave mode (current source). In this mode it is possible to stabilize the output current and adjust the output power (Figure 2b) [6].
Figure 2. Connection scheme of electronic generation in the mode: a) Master (voltage source); b) Slave (current source).

Modern converters allow creating a variety of electrical network architectures. The MicroGrid architecture, shown in Figure 3, makes it possible to connect consumers into a unified system, powered by different types of currents from power plants with different natural energy sources (sun, wind, fuel).

Figure 3. MicroGrid network architecture with different types of generation and consumers.
For systems with a high proportion of energy cells (Mini- and MicroGrid) and distributed RES, which have unguaranteed generation of power in their composition, it is advisable to introduce an additional concept of stability of the power system mode:

The systemically stable mode of the power system, which includes energy cells and sources of unguaranteed generation of power, is the mode of the power system in which small or large disturbances, as well as disturbances of the overall balance, the stability of the mode in the system is maintained as a whole. But stability disturbances can occur in cells division from the general network in which disturbances arose, without their propagation to other parts of the power system.

3. The modes and characteristics of EG influencing the steady-state aperiodic stability of power system

The limits of the steady-state aperiodic stability of power system are significantly dependent on the steady-state characteristics of the loads and generation, as well as electronic generation.

It is considering the basic modes and primary characteristics of EG inverters.

3.1. The mode A1
The inverter of EG operates in the Slave mode with the EG in the Master mode with synchronous generation or with synchronous electric network. The control system maintains a constant output current.

Steady-state characteristics for mode A1 are defined:

\[
\begin{align*}
I &= \text{const}, \text{ if } |I| \leq I_{\text{permissible}} \text{ and } |U| < U_{\text{max}} \\
I &= 0, \text{ if } |U| \geq U_{\text{max}}
\end{align*}
\]

Figures 4 and 5 show the dependence of currents on voltage at the connection point of EG and dependence of power on voltage, where \(U_{\text{loss synch}}\)—voltage below which the inverter can lose synchronization.

**Figure 4.** Characteristics of dependence of currents on voltage, \(I = \text{const}\), the mode A1.

**Figure 5.** Characteristics of dependence of active and reactive powers on voltage, \(I = \text{const}\), the mode A1.
3.2. The Mode А2

The inverter of EG operates with synchronous generation or with synchronous electric network similar to mode A1. But the control system maintains the constancy of the issued active and reactive powers in this mode.

Steady-state characteristics in the mode A2 are defined:

$$\begin{align*}
|S| &= \text{const}, \text{ if } |I| \leq I_{\text{permissible}} \text{ and } |U| < U_{\text{max}} \\
S &= I_{\text{permissible}} \cdot U, \text{ if } |I| \geq I_{\text{permissible}} \text{ and } |U| < U_{\text{max}} \\
S &= 0, \text{ if } |U| \geq U_{\text{max}}
\end{align*}$$

Figure 6 shows the dependences of the active and reactive power on the voltage with changes in the behaviour of the inverter at critical points ($U_{\text{min}} = S/I_{\text{permissible}}, |U| = U_{\text{max}}$).

3.3. The Mode B

In the mode B, the inverter of EG operates in the Master mode. This inverter is possible to work in parallel with other electronic generation(s), but provided that other electronic generation(s) operates in A1 or A2 mode (Slave mode). The control system automatically maintains constant frequency, phase and module of the output voltage.

Steady-state characteristics in mode B are defined:

$$\begin{align*}
|U| &= \text{const, } (U, \delta, f) = \text{const, if } U < U_{\text{max}} \\
U &= 0, \text{ if } U \geq U_{\text{max}}
\end{align*}$$

Figure 7 shows the dependence of voltage on inverter current.
3.4. Steady-state characteristics of the inverter as a virtual synchronous machine (generator)

A virtual synchronous machine (generator) means electric power source connected to an alternating current electrical network through an inverter simulating dynamic characteristics, voltage and frequency statism of a traditional electric generator [6, 7]. The inverter as a virtual generator operates in mode A2. Moreover the active power set point changes depending on the frequency and reactive power set point changes depending on the voltage. The steady-state characteristic for active power is defined as $P_{\text{steady}} = P_0 - k \cdot \Delta f$ with the following limitations:

- $P_{\text{steady}} = P_{\text{max}}$, if $P_{\text{steady}} > P_{\text{max}}$
- $P_{\text{steady}} = P_{\text{min}}$, if $P_{\text{steady}} < P_{\text{min}}$
- $P = 0$, if $f > f_{\text{max}}$ or $f < f_{\text{min}}$ (simulation of disconnecting the generator from the network)

Figure 8 shows the dependence of active power on the frequency of the current.

![Figure 8. Characteristics of dependence of active power on the frequency of the current.](image)

The steady-state characteristic for reactive power is defined as $Q_{\text{steady}} = Q_0 - k \cdot \Delta f$ with the following limitations:

- $Q_{\text{steady}} = Q_{\text{max}}$, if $Q_{\text{steady}} > Q_{\text{max}}$
- $Q_{\text{steady}} = Q_{\text{min}}$, if $Q_{\text{steady}} < Q_{\text{min}}$
- $Q = 0$, if $U > U_{\text{max}}$
- $Q = I_{\text{permissible}} \cdot U$, if $|I| \geq I_{\text{permissible}}$

Figure 9 shows the dependence of reactive power on the voltage.

![Figure 9. Characteristic of reactive power on the voltage (Virtual generator mode).](image)

The disadvantage of the presented steady-state characteristics is piecewise differentiability. Because the derivatives of the quantities at critical points are equal to infinity, which makes it difficult to calculate the electric power mode and stability control.
4. Effect of EG on steady-state stability in the electric transmission scheme with its connection

For assess the effect of the EG on the limits of the steady-state aperiodic stability of the power system we turn to the simplest 35 kV power transmission scheme shown in Figure 10.

![Figure 10. Power transmission scheme with electronic generation.](image)

We define the angular characteristics of synchronous generation in the scheme with the on/off switch in the load node (load and EG of the same power). The load is represented by a typical steady-state characteristic and the EG will operate either in the mode of maintaining a constant current or in the mode of maintaining a constant generated power.

Typical steady-state load characteristics are given in table 1.

| № | Type of characteristics                                      | a₀   | a₁   | a₂   |
|---|-------------------------------------------------------------|------|------|------|
| 1 | Typical load characteristics of active power              | 0.83 | -0.3 | 0.47 |
|   |                                                            | b₀   | b₁   | b₂   |
| 2 | Typical load characteristics of active power              | 4.9  | -10.1| 6.2  |
|   | on the side of 6-10 kV                                     |      |      |      |
| 3 | Typical load characteristics of active power              | 3.7  | -7   | 4.3  |
|   | on the side of 110-220 kV                                 |      |      |      |

To determine the angular characteristics and the limit on the steady-state stability of the synchronous generator, the mode was loaded by increasing the load of the synchronous generator and by increasing the load of the all scheme in the Mustang Program. Characteristic dependencies are shown in Figures 11–13.

![Figure 11. Angular characteristics of the synchronous generator with and without electronic generation (EG) power of 10 MW.](image)
Figure 12. Angular characteristics of the synchronous generator with and without electronic generation (EG) power of 20 MW.

Figure 13. The dependence of the voltage at the point of load connection on the load value.

As follows from the presented graphs, the electronic generation has a positive effect on the steady-state stability of power system. At the same time for increase the parallel operation stability of generators in power system, EG modes are preferable with maintaining a constant output power and to prevent critical voltage drops - maintaining a constant output current.

5. The effect of electronic generation on the stability of Macrogrid
The study of the effect of EG on steady-state aperiodic stability was conducted on the example scheme of the electric power system of Mongolia. To calculate the limit value of steady-state aperiodic flow stability in Macrogrid design section it is required to load the mode (increased flow) along the lowest power limit. Both the steady-state characteristics and the places of EG connection in the power system were different.

As a calculation scheme, to determine the effect of EG on the limits of transmitted power over the main sections of the electric network, the Mongolian power system scheme was used (Figure 14).
Figure 14. Calculated equivalent scheme of Mongolia power system.

The design scheme of the Mongolian power system contains the main network voltage (35 – 220) kV, distribution network 35 kV. Red color indicates a nominal voltage of 220 kV, blue – 110 kV, green – 35 kV. Electric loads are determined on the basis of the power and electricity energy system balances of Mongolia. The load of power plants is load of maximum mode.

Below are results for two design sections of the network.

Design section № 1 is the main connection of power system between Mongolia and Russia (Figure 15). The feature of this section is maintaining a power balance of the Mongolia electric power through the exchange of power with the Russian Federation. The average power transfer is 110 MW.

Figure 15. Design section of Russian Federation connection with Mongolia.
Design section 2 (Figure 16) refers to the critical part of the power system that is deficient in power and electricity (Region 2). Thus the power flows are directed towards the Erdenet substation (Mongolia) in this section.

![Design section 2 (Figure 16)](image)

**Figure 16.** Design section of Mongolia with Region 2.

Flow distribution calculations were performed using the ANARES program.

5.1. *Calculation of flow limits in steady-state aperiodic stability for design section № 1*

Loading was carried out by increasing the load in region 3. The initial load in the load node is 185+j82 MVA. The flow limits as a result of loading for section 1 with two connection lines are presented in Table 2.

| №   | Variants                              | Increasing of general load in a load area, MVA | Section loading in initial normal mode, MWA | Limit of transmitted power, MW |
|-----|---------------------------------------|-----------------------------------------------|---------------------------------------------|-------------------------------|
| 1   | Without EG                            | 259+j116                                      | 190 – j24                                  | 527                           |
| 2   | With existing EG distribution         | 376+j169                                      | 55+j12                                     | 514                           |
| 3   | The concentrated placement of EG      | 380+j171                                      | 63+j13                                     | 540                           |

5.2. *Calculation of flow limits in steady-state aperiodic stability for design section № 2*

Loading was carried out by increasing the load in region 3. The initial load in the load node is 165+j55 MVA. The flow limits as a result of loading for section 2 are presented in Table 3.

| №   | Variants                              | Increasing of general load in a load area, MVA | Section loading in initial normal mode, MWA | Limit of transmitted power, MW |
|-----|---------------------------------------|-----------------------------------------------|---------------------------------------------|-------------------------------|
| 1   | Without EG                            | 282+j127                                      | 146 – j38                                  | 459                           |
| 2   | With existing EG distribution         | 282+j127                                      | 146 – j42                                  | 460                           |
| 3   | The concentrated placement of EG      | 443+j199                                      | 22+j41                                     | 498                           |

The limit of the transmitted power has not changed significantly when calculating the limiting modes and RES simulation that distributed throughout the energy system of Mongolia. The maximum power flow increased in the first calculated design section by 2.5%, and in the second by 8% when placing concentrated renewable energy sources in the loaded area.

It follows that the placement of EG in the power system has a positive effect on network limitations, and the stability limits depend not only on steady-state characteristics, but also on the location of the connected EG.
6. Conclusion
The article considers the effect of the location, modes and characteristics of EG on the steady-state aperiodic stability of power systems using the example of simple and complex power systems. Currently the steady-state characteristics of electronic generation are set by equipment developers. This steady-state characteristic has not taken into account the conditions of electronic generation operation in the power system including the effect on the stability of the mode. It is shown that the modes of EG with maintaining a given power and a required statism, have a positive effect on the parallel operation stability of power system synchronous parts.

The modes of EG with maintaining a constant current are useful in areas where are dangerous due to the voltage drop that is unacceptable under the condition of stability of the power system mode. The concentrated placement of electronic generation in critical areas of the power system increases the stability of modes and the transfer capacity of the electric network. At the same time balance stability of the power system mode is reduced if this generation is stochastic behaviour.

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