An approach to arranging primary and secondary control of the operating parameters in microgrids featuring inverter-connected generator sets

P V Ilyushin 1, 2, 4, K V Suslov 1, 5, A L Kulikov 3, 6

1 Power Supply and Electrical Equipment Department at Irkutsk National Research Technical University, 83 Lermontov St., Irkutsk, 664074
2 Department of Research on the Relationship between Energy and Economy at Energy Research Institute of the Russian Academy of Sciences, 31, k. 2 Nagornaya St., Moscow, 117186
3 Department of Electroenergetics, Power Supply and Power Electronics, Nizhny Novgorod State Technical University n.a. R.E. Alekseev, 24 Minin St., Nizhny Novgorod, 603950
4 ilyushin.pv@mail.ru, 5 dr.souslov@yandex.ru, 6 inventor61@mail.ru

Abstract. Various low-power generator sets (GS) are mainly integrated into microgrids by means of inverters coupled with energy storage systems (ESS). ESSs are connected either to the DC busbars of GSs or to the AC busbars of the microgrid, in this case they are equipped with individual inverters. Use of ESS helps balance power in cases of load surge / load-shedding when the microgrid is islanded. This paper overviews approaches to arranging primary and secondary control of the operating parameters of microgrids. It discusses the technical challenges of, and possible solutions for, implementing primary and secondary control in low- and medium-voltage distribution grids featuring inverter-connected GSs. Calculations of electromechanical transients show that inverter-connected GSs have advantages over conventional GSs when used microgrids that are weakly connected to the power system (the external grid) or islanded. In a microgrid featuring inverter-connected GSs, active and reactive power need to be controlled separately as in power systems featuring conventional GSs; implementation of such controls must be adjusted for the parametric and topological characteristics of low- and medium-voltage distribution grids. To address the issues of linked control, this paper proposes a comprehensive approach that adjusts microgrid design for the specifics of inverter-connected GSs, improves inductance, and incorporates algorithmic solutions. It details upon the virtual impedance algorithm, which extends the common principle of droop speed control. Its implementation helps load the GSs and the ESS with adjustments for their installed capacity; it can also simulate the mechanical constant of GS inertia. Primary control has a low margin that mainly comes from the ESS; thus, backups available to secondary control must be used to compensate for the deviations in operating parameters; this is a key challenge of secondary frequency and voltage control in microgrids. When primary and secondary voltage and frequency controls have been duly implemented in a microgrid, its GSs, the ESS, and electricity delivery to the loads within the microgrid can all operate reliably in a variety of operating situations.
1. Introduction

Microgrid is a part of distribution grid, usually low-voltage (LV) or medium-voltage (MV) that has set boundaries and connects to loads, various generator sets (GS), and energy storage systems (ESS). Microgrids can also integrate gas-turbine, gas-piston, photovoltaic, and wind power plants, microturbines, fuel cells, etc. [1-3].

The operating parameters of a microgrid can be well-controlled and coordinated whether running in parallel with the power system or islanded. Thus, GSs, the ESS, and electricity delivery to the loads within the microgrid can all operate reliably in a variety of operating situations [4, 5].

However, to remain fully functional while islanded, microgrid islanding and resynchronization challenges must be addressed. Besides, the GSs must be able to retain dynamic stability in case of emergency disturbances; they and the ESS must be able to sustain load surge and load-shedding in islanded operation by using power system protections (PSP) [6, 7].

Retaining the dynamic stability of the GSs when the microgrid is sustaining an emergency disturbance might be challenging, as modern GSs have low mechanical constants of inertia. Automatic control systems (ACS) used by the GSs and the ESS must be able to respond fast, and so must the PSPs, in order to bring the operating parameters of the microgrid within the acceptable limits.

Low-power gas-turbine units and microturbines are usually designed as single-shaft, high-speed units for efficiency and better fuel heat utilization. Therefore, to be integrated in a microgrid, either a mechanical reduction gear must be used to decouple the gas-turbine shaft and the generator shaft, or the generator outputs need to be equipped with an inverter. Feasibility studies show the latter to be a more effective solution [8-10].

Inverters that have ultralow electromagnetic constants of time are in line with the rate of microgrid transients and can therefore control the operating parameters within the acceptable limits. However, the acceptable range of capacitor charge/discharge (throttle core demagnetization/magnetization) in the inverter DC circuit is usually not sufficient to level the mismatch in transients.

When the operating point ends up outside the acceptable limits, control is implemented by changing the transfer functions of links in the automatic speed control (ASC) of the GS drive. ASCs have low constants of time and contain a delay link, which hinders the ability to control electromechanical transients in microgrids in real time.

For generators, microgrids normally use either synchronous machines excited by permanent magnets or asynchronous machines that use a variety of windings. Thus, they lack an excitation winding and an excitation system, and therefore lack an automatic excitation controller (AEC). Voltage of such generators is controlled by power electronics in the DC circuit.

As a rule, direct-conversion GSs are considered uncontrolled sources, and the active/reactive power controllability of fuel cells (a variety of electrochemical sources) is limited by their volt-ampere characteristic. This characteristic contains strongly nonlinear electrolyte reaction and diffusion activation domains. Photovoltaic and wind power plants are non-stationary sources; their electricity output is pegged to the incoming primary energy. Control of the operating parameters of a direct-conversion GS is limited in range and is only possible in the DC circuit (at the busbars) [11-13].

Thus, in order to synchronize the GSs and extend the range of control of the operating parameters, microgrids commonly use ESSs that have low inertia and no delay. An ESS can be connected to the DC busbars of GSs or separately through individual inverters.

Inverter-connected GSs and ESSs require primary and secondary control of the operating parameters similarly to how it is done for directly connected GSs.

The goal hereof is to present a comprehensive approach to primary and secondary control of the operating parameters of a microgrid featuring inverter-connected GSs.

2. Overview of approaches to controlling the operating parameters

Uninterruptible power supply systems featuring multiple ESSs use master-slave controls: one voltage inverter is used as the voltage source (the master inverter). Its output current and the measured load current set the current values for the remaining inverters, which function as the current sources (the
slave inverters). Fig. 1 shows a case of the microgrid ACS controlling the operating parameters of separate inverters.

![Dispatch administration](image)

**Figure 1.** Master-slave control of the operating parameters of inverters

The microgrid ACS structure shown in Fig. 1 has its shortcomings:
- it needs an extensive network of broadband communication channels reaching every single inverter in the microgrid;
- data communication channels must be monitored by a separate system, as they are the least reliable components of the ACS structure;
- such ACS is difficult to scale.

The advantage of the microgrid ACS shown in Fig. 1 is that its lower (hardware) level is simple. The applicability of master-slave control depends on whether the ACS structure is centralized or decentralized. Decentralized systems cannot use master-slave control [14].

A decentralized system is the better choice from the standpoint of lowering the requirements on data communication channels; however, implementing it requires local adjustments in the operating parameters at all GS connection points, as well as adopting droop speed control. Fig. 2 shows droop speed control by frequency and voltage, a common approach for conventional GSs [15].

![Output curves](image)

**Figure 2.** Output curves: (a) active GS/ESS power as a function of frequency (p.u.); (b) reactive GS/ESS power as a function of voltage (p.u).

Droop speed control has several advantages:
- even low-bandwidth data communication channels will suffice for setting the frequency / voltage and droop %;
- easily scalable microgrid ACS;
- highly reliable microgrid ACS (a channel failure will not cause the entire ACS to fail);
- low requirements on the data channel monitoring system;
- redundancy of generator capacity increases in proportion to the number of voltage inverters in the microgrid when islanded.
The shortcoming is that a decentralized ACS has a much more complicated lower (hardware) level. This overview concludes that droop speed control is the most optimal solution for primary control of the operating parameters of inverter-connected GS/ESS in a microgrid.

3. Research Methods
Electromechanical transients were calculated in MUSTANG-90 software (Russia) for two GS connections to a 10 kV microgrid, each with $P_{GS} = 4.2$ MW:
- a conventional, directly connected GS with SHUNT and PMG excitations;
- inverter-connected GSs.

For calculations, we imitated the following disturbances:
- 3-phase SC in the 110 kV external grid followed by PSP-triggered disconnection at $t_{\text{disc}} = 0.18$ s;
- a large AM starting at the busbars of the 10 kV microgrid when running in parallel with the power system;
- a large AM starting at the busbars of the 10 kV microgrid when islanded.

For each scenario, we simulated two values of the resistance of the GS-power system circuit at 110 kV:
- strong connection $X_{\text{conn}} = 2$ Ohm ($L_{\text{pl}} = 10$ km);
- weak connection $X_{\text{conn}} = 32$ Ohm ($L_{\text{pl}} = 150$ km).

4. Results
We consider the case of connecting a GS with $P_{GS} = 4.2$ MW to a 10 kV microgrid. Comparative calculations of electromechanical transients were run for a conventional gas-piston GS (SHUNT or and PMG-excited) vs inverter-connected GS.

Calculations of electromechanical transients in a strongly-connected microgrid as caused by target disturbances show that a conventional SHUNT or PMG-excited GS will keep itself and the asynchronous motors (AM) in the load stable. In case of inverter-connected GS, both the current-based and the voltage-based GS control laws will keep the GS running, and the AM will remain stable.

In case of three-phase SC in a weakly-connected grid, PSPs will disconnect the conventional GS as the voltage drops below the setpoint ($U \leq 0.8U_{\text{nom}}$) for $> 1.2$ s in case of SHUNT (Fig. 3a) and $> 0.8$ s in case of PMG, when the AMs self-start. When using an inverter-connected current-controlled GS, the voltage drops below the setting ($U \leq 0.8U_{\text{nom}}$) for $> 1.0$ s, so there is a risk the protections will disconnect the GS. If the inverter is voltage-controlled, the GS will remain online, the AMs will remain stable, see Fig. 3b. Graphs show voltage in the 110 kV grid of the power system as red lines, voltage in the 10 kV microgrid as green lines [16-18].
When starting a large AM in a weakly-connected 10 kV microgrid, PSPs will disconnect the conventional GS as the voltage drops below the setpoint \( U \leq 0.8U_{\text{nom}} \) for \( > 0.6 \text{ s} \) in case of SHUNT (Fig. 4a) and \( > 0.4 \text{ s} \) in case of PMG. When using an inverter-connected current-controlled GS, the voltage drops for \( > 0.9 \text{ s} \), so there is a risk the inverter protections will disconnect the GS. If the inverter is voltage-controlled, the GS will remain online, the AMs will remain stable, see Fig. 4b.

![Figure 4](image4.png)

**Figure 4.** Transient in case of starting a large AM in the 10 kV microgrid: (a) SHUNT-excited GS; (b) inverter-connected GS

When starting a large AM in an islanded 10 kV microgrid, PSPs will disconnect the conventional GS as the voltage drops below the setpoint \( U \leq 0.8U_{\text{nom}} \) for \( > 3.7 \text{ s} \) in case of SHUNT (Fig. 5a) and \( > 1.4 \text{ s} \) in case of PMG. When using an inverter-connected current-controlled GS, there is a risk that the inverter protections will disconnect the GS. When using voltage-based controls in the inverter, the GS will keep running, see Fig. 5a, and the direct AM start will be successfully completed.

![Figure 5](image5.png)

**Figure 5.** Transient in case of starting a large AM in an islanded 10 kV microgrid: (a) SHUNT-excited GS; (b) inverter-connected GS

Calculations show that weakly-connected and islanded microgrids had better inverter-connected GSs rather than their conventional counterparts. LV and MV distribution grids have the following peculiarities:
- cable lines and overhead lines are rather resistive in LV grids at \( R/X = 7 \), rather inductive in MV grids at \( R/X = 0.85 \) [14];
- the topology of generation nodes features low graph impedance, which is why even slight voltage deviations from the configured values induce significant circulating currents.
The predominance of reactance in the GS-to-grid circuit should be borne in mind when configuring droop speed control by frequency in the ASC, by voltage in the AEC of generator sets running in MV distribution grids. The phenomenon manifests as a slight voltage sag caused by the reactive GS current flowing through the resistance of the coupling circuit. Power characteristic in Fig. 6 and Eqs. (1) and (2) proves this statement.

**Figure 6.** Power characteristics in an MV distribution grid

\[
P = \frac{E U}{X} \sin \delta \tag{1}
\]

\[
Q = \frac{E^2}{X} - \frac{E U}{X} \sin \delta \tag{2}
\]

In LV distribution grids, given that resistance prevails, the power characteristic has the curve shown in Fig. 7, \( P \) and \( Q \) have to be changed in Eqs. (3) and (4), respectively.

**Figure 7.** Power characteristics in an LV distribution grid

\[
P = \frac{E^2}{X} - \frac{E U}{X} \sin \delta \tag{3}
\]

\[
Q = \frac{E U}{X} \sin \delta \tag{4}
\]

Active GS power output is proportional to its output voltage in LV distribution grids, which, coupled with low mutual impedance between generator sets, results in conflicting control algorithms. Droop speed control should be configured per Eqs. (3) and (4); the GS will not be able to follow the load schedule, uncontrolled power flows in the microgrid, and voltage fluctuations in nodes. Besides, it will be impossible to coordinate conventional and inverter-connected GSs and to ensure cost-
effective load distribution between GSs to minimize fuel consumption. Droop speed control coupled with linked reactive power control is not an acceptable solution, as the mutual impedance between generator sets is low.

Keeping voltage within the acceptable range in microgrid nodes is a problem that can be addressed in both design and operation [19, 20].

The design solution would consist in limiting the movement of the power partition mode in a variety of operating situations; the operating solution would consist in increasing the inductance of the grid elements. An alternative method consists in implementing droop speed control, e.g., by the virtual impedance algorithm, which:
- separates the control channels $P(f)$ and $Q(U)$;
- loads each GS depending on its installed capacity;
- is versatile and can be used with various $R/X$ ratios;
- simulates the mechanical constant of inertia ($T_j$) of generator sets;
- adapts to the dynamic characteristics of generator sets;
- is easy to configure and does not require testing the domains of parametric stability of the microgrid.

The algorithm is based on measuring phase currents and voltages at the GS inverter output to isolate a positive sequence of the fundamental harmonic. The next step is to calculate the voltage for the given virtual impedance as well as the output active and reactive GS power in polar coordinates, and to simulate the mechanical constant of inertia of generator sets. The last step is to calculate inverter-modulated voltage amplitude and frequency as functions of the configured droop speed control. $T_j$ of the GS is set by applying a low-pass filter (LPF), the cutoff frequency of which is set depending on the required inertia. At a high cutoff, the inverter functions as a GS with high $T_j$ and reacts to low-frequency fluctuations in electromagnetic power on the shaft; at a low cutoff, its reaction will be similar to that of a low-$T_j$ GS. LPF frequency response is an aperiodic link with the time constant $T$ that depends on the cutoff frequency.

Virtual impedance is what can derive the required power characteristics to connect a GS to other GSs in a microgrid. This approach simplifies configuring the transfer functions of control algorithms in the process of finding the parametric stability domains for the ACS. Voltage sag in the virtual impedance is in fact analogous to droop speed control by voltage $Q(U)$. Increase in the inductive component of virtual impedance improves GS stability in LV microgrids. Increase in the resistance proportionally increasing the damping factor, which is relevant for MV grids, as it facilitates suppression of phase asymmetry and harmonic intensity. If change in the virtual impedance is inversely proportional to the installed capacity of inverters, the load can be distributed between them should power in the microgrid fluctuate or deviate.

Secondary microgrid control faces the following requirements:
- ability to island the entire microgrid or parts thereof successfully;
- ability to provide system services to the external grid when running in parallel with it: voltage normalization, load symmetrization, active and reactive power flow optimization, etc. [21, 22].

A distinctive feature of microgrids is that their primary control is mainly based on ESS, and the ESS capacity is limited. This is why secondary control, which replenishes the reserves of primary control, is subject to much scrutiny. Secondary control uses $f/U$-control and $PQ$-control that utilizes horizontal (Fig. 8) and vertical (Fig. 9) shifts in external inverter characteristics, respectively.

As part of secondary control, $f/U$-control provides:
- spinning reserve of active power;
- dynamic microgrid support should sustain the connection node undervoltage;
- zero microgrid-to-power system power flow at the moment before the microgrid becomes islanded;
- GS-microgrid and microgrid-power system synchronization;
- return of the operating points of voltage and frequency back to nominal values once the operating conditions have changed in islanded operation in order to recover ESS charge.
PQ-control provides astatic control of the active and reactive power of master inverters.

When primary and secondary voltage and frequency controls have been duly implemented in a microgrid, its GSs, the ESS, and electricity delivery to the loads within the microgrid can all operate reliably in a variety of operating situations.

5. Conclusions
Analysis of the calculated electromechanical transients shows that integrating inverter-connected GSs into a strongly-connected microgrid will not substantially affect its operation. In islanded operation, the operating parameters of a microgrid mainly depend on the specifications and loads of larger conventional GSs.

Calculations of electromechanical transients show that inverter-connected GSs have advantages over conventional GSs when used microgrids that are weakly connected to the power system (the external grid) or islanded.

In a microgrid featuring inverter-connected GSs, active and reactive power need to be controlled separately as in power systems featuring conventional GSs; implementation of such controls must be adjusted for the parametric and topological characteristics of low- and medium-voltage distribution grids.

Droop speed control has priority as it can reliably and properly control the operating parameters at minimum costs, whether in construction or operation. Droop speed control algorithms used by power systems with conventional GSs are not applicable in microgrids per se. The reason is that GS output voltage and active power output are pegged to each other, and mutual impedance between GSs is low.

To address the issues of linked control, this paper proposes a comprehensive approach that adjusts microgrid design for the specifics of inverter-connected GSs, improves inductance, and incorporates algorithmic solutions.
Primary control has a low margin that mainly comes from the ESS; thus, backups available to secondary control must be used to compensate for the deviations in operating parameters; this is a key challenge of secondary frequency and voltage control in microgrids.

**Acknowledgement**
The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (project code: FZZS-2020-0039).

**References**
[1] Buchholz, B. M., Styczynski, Z., “Smart Grids – fundamentals and technologies in electricity networks”, Springer Heidelberg New York Dordrecht London, 2014. – 396 p.
[2] Kakran, S., Chanana, S. “Smart operations of smart grids integrated with distributed generation: a review”, Renewable and Sustainable Energy Reviews, 2018, vol. 81, part 1, pp. 524-535.
[3] Mehigan, L., Deane, J.P., Gallachóir, B.P.O., Bertsch, V., “A review of the role of distributed generation (DG) in future electricity systems Energy”, 2018, Vol. 163, pp. 822-836.
[4] Papkov, B., Oboskalov, V., Gusev, S., Tavlincev, A., Mahnitko, A., Zicmane, I., Berzina, K., “Analysis of the quality problem of electric power and the management of reliability of power supply”, in Proc. of the 10th International Scientific Symposium on Electrical Power Engineering, ELEKTROENERGETIKA 2019, 2019, pp. 147-152.
[5] Byk, F. L., Myshkina, L. S., Khokhlova, K., “Power supply reliability indexes”, in Proc. Int. Con. on Actual Issues of Mechanical Engineering, 2017, pp. 525-530.
[6] Ilyushin, P. V., Filippov, S. P., “Under-frequency load-shedding strategies for power districts with distributed generation”, in Proc. Int. Con. on Industrial Engineering, Applications and Manufacturing, Sochi, Russia, 2019.
[7] Islam, Sk. R., Sutanto, D., Muttaqi, K. M., “Coordinated decentralized emergency voltage and reactive power control to prevent long-term voltage instability in a power system”, IEEE Transactions on Power Systems, 2015, vol. 30, iss. 5, pp. 2591-2603.
[8] Zhidko, A., “Using Electromagnetic Continuously Variable Transmission in Gas Reciprocating Power Plant to Ensure Dynamic Stability”, in Proc. Int. Con. on Industrial Engineering, Applications and Manufacturing, Sochi, Russia, 2020.
[9] Ilyushin, P. V., Kulikov, A. L., Suslov, K. V., Filippov, S. P., “Consideration of Distinguishing Design Features of Gas-Turbine and Gas-Reciprocating Units in Design of Emergency Control Systems”, Machines, 2021, vol. 9, is. 3, 47.
[10] Liu, Z., Karimi, I. A., “New operating strategy for a combined cycle gas turbine power plant”, Energy Conversion and Management. 2018, vol. 171, pp. 1675-1684.
[11] Zeng, B., Wen, J., Shi, J., Zhang, J., Zhang, Y., “A multi-level approach to active distribution system planning for efficient renewable energy harvesting in a deregulated environment”, Energy, 2016, vol. 96, pp. 614-624.
[12] Zhang, R., Lin, X., Yang, P., Li, Z., “The emergency control strategies of short-run isolated island wind farm”, Proc. of the Int. Conf. on Renewable Energy Research and Application, 2014, pp. 203-211.
[13] Mahel, O. P., Shaik, A. G., “Comprehensive overview of grid interfaced solar photovoltaic systems”, Renewable and Sustainable Energy, 2017, vol. 68, pp. 316-332.
[14] Hatzigiargiouri, N., “Microgrids: Architectures and Control”, Wiley-IEEE Press, 2014, pp. 344.
[15] Hatzigiargiouri, N., Jenkins, N., Strbac, G., Lopes, J. A. P., “Microgrids – large scale integration of micro-generation to low voltage grids”, CIGRE 2006, 41-st Session Conference, Paris, France.
[16] Ilyushin, P. V. “Analysis of the specifics of selecting relay protection and automatic (RPA) equipment in distributed networks with auxiliary low-power generating facilities”, Power Technology and Engineering, 2018, vol. 51, no. 6, pp. 713-718.
[17] Razavi, S. E., Rahimi, E., Javadi, M. S., Nezhad, A. E., Lotfid, M., Shafie-khah, M., Catalão, J. P. S., “Impact of distributed generation on protection and voltage regulation of distribution systems: A review,” Renewable and Sustainable Energy Reviews, 2019, vol. 105, pp. 157-167.
[18] Kulikov, A. L., Sharygin, M. V., Ilyushin P. V., “Principles of organization of relay protection in microgrids with distributed power generation sources,” Power Technology and Engineering, 2020, vol. 53, no. 5, pp. 611-617.
[19] Mokryani, G., Hu, Y., Pillai, P., Rajamani, H. S., “Active distribution networks planning with high penetration of wind power,” Renewable Energy, 2017, vol. 104, pp. 40-49.
[20] Ghadi, M., Rajabi, A., Ghavidel, S., Azizivahed, A., Li, L., Zhang, J., “From active distribution systems to decentralized microgrids: A review on regulations and planning approaches based on operational factors,” Applied Energy, 2019, vol. 253, 113543.
[21] Xie, M., Ji, X., Hu, X., Cheng, P., Liu, M., “Autonomous optimized economic dispatch of active distribution system with multi-microgrids,” Energy, 2018, vol. 153, pp. 479-489.
[22] Padiyar, K. R., Kulkarni, A. M., “Dynamics and Control of Electric Transmission and Microgrids. In Microgrids: Operation and Control,” Wiley-IEEE Press, 2019, pp. 415-453.