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SANOAT VA TEXNIKA SOHALARIDA OLIB BORILAYOTGAN ISLOHOTLAR VA ULARNING NATIJALARI TO‘PLAM

Mazkur to‘plamda “Sanoat va texnika sohalarida olib borilayotgan islohotlar va ularning natijalari” milliy konferensiyasiga kelib tushgan tezis va maqolalar o‘rin olgan. Ushbu konferensiyada zamonaviy ta’lim tizimini rivojlantirish jarayonida innovatsion ta’lim texnologiyalarini joriy etish va loyihalashtirish, integratsion ta’limni rivojlantirishda yo‘nalishlar bo‘yicha kreativ g‘oyalar, takliflar va yechimlarni amalga oshirish maqsad qilib olingan. Bu konferensiya materiallaridan OTM professor o‘qituvchilari, akademik litsey va kasb-hunar kollejlari va umumta’lim maktab o‘qituvchilari, mustaqil tadqiqotchilar, magistrantlar, ilmiy xodimlar, iqtidorli talabalar hamda shu sohada ilmiy ish olib borayotgan tadqiqotchilar foydalaishlari mumkin.

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REDUCING FREQUENCY DEVIATIONS THROUGH COORDINATED ACTIVE POWER CONTROL OF WIND AND SOLAR POWER PLANTS

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Introduction. The growing share of wind and solar generation in power systems makes maintaining active power balance more challenging. In inverter-connected resources, rotor motion is not inherently coupled to grid frequency in the same way as in synchronous generators. When synchronous generation is displaced and system inertia decreases, a given power deficit can cause frequency to fall more rapidly. It is therefore important to use the controllable active power capabilities of renewable power plants for frequency regulation [1].

Active power control of wind plants and the use of preallocated power reserves in photovoltaic (PV) plants can improve frequency response [1, 2]. This study aims to coordinate the response of wind and PV plants through a common control signal and reserve-proportional power allocation, and to evaluate the approach using an illustrative numerical model.

A frequency decline requires additional active power injection. A PV plant operating at its maximum power point cannot provide a sustained power increase without energy storage or preallocated headroom. Extracting kinetic energy from wind turbine rotors provides only temporary support and may create a further power deficit during rotor speed recovery [1]. This study instead uses reserve capacity created by operating below the available maximum power.

Problem Formulation. The central problem is to allocate the required active power increment among plants with different reserve capacities and response speeds without exceeding their operating limits. Independent droop control leaves a steady-state frequency error under a sustained power deficit. Secondary control, such as an integral control action, is needed to eliminate this residual error when sufficient reserve is available.

The power balance in a single-area model is expressed as follows:

$$M \cdot dx/dt = \Delta P^{g} + \Delta P^{w} + \Delta P^{s} - \Delta P^{L} - D \cdot x; \quad x = f - f_0. \quad (1)$$

Here, $M = 2HS_\beta/f_0$ is the inertia coefficient in MW·s/Hz; H is the equivalent inertia constant; S_β is the base power; f_0 is the nominal frequency; D is the frequency sensitivity of the load; ΔP^{g}, ΔP^{w} and ΔP^{s} are the active power increments from conventional, wind and PV generation, respectively; and ΔP^{L} is the load increase.

Proposed Control Strategy.A central proportional–integral (PI) controller generates the total active power command from the frequency error $e = f_0 - f$. The available reserve of plant i is defined as $R_i = P_{i,avail} - P_{i,0}$, where $P_{i,avail}$ is the available power and $P_{i,0}$ is the initial operating power. In a practical supervisory implementation, reserve estimates should be updated regularly and commands reallocated when a plant reaches its limit. The illustrative calculation below assumes constant reserves.

$$u = \mathrm{sat}[K_p \cdot e + K_i \cdot \int e\,dt, 0, R^{w} + R^{s}]; \quad \alpha_i = R_i/(R^{w} + R^{s}). \quad (2)$$

$$\Delta P_{i,ref} = \alpha_i \cdot u; \quad T_i \cdot d\Delta P_i/dt = \Delta P_{i,ref} - \Delta P_i. \quad (3)$$

The function sat limits the command to the specified range; K_p and K_i are the proportional and integral gains; α_i is the reserve-based participation factor; and T_i is the time constant of the plant response channel. Equation (2) applies to underfrequency events. Overfrequency operation requires separate limits based on the plants' ability to reduce power. If the total reserve is zero, the additional power command is set to zero and the participation factors are not evaluated.Practical implementation should include filtered frequency measurements, anti-windup

protection to limit integral accumulation, inverter current limits, wind turbine mechanical limits and power ramp constraints. Maintaining reserve reduces energy production relative to maximum available generation, so the benefit of frequency support should be assessed alongside this opportunity cost.

Table 1. Parameters of the illustrative model

Parameter	Value
Nominal frequency and base power	50 Hz; 100 MW
Inertia and load frequency sensitivity	H = 2 s; M = 8 MW·s/Hz; D = 2 MW/Hz
Conventional generator response	K^g = 20 MW/Hz; T^g = 3 s
Available wind and PV power	25 MW and 15 MW, respectively
Initial power and reserves	Wind: 20 MW, reserve 5 MW; PV: 12 MW, reserve 3 MW
Plant response time constants	T^w = 0.8 s; T^s = 0.2 s
Central controller gains	K_p = 20 MW/Hz; K_i = 4 MW/(Hz·s)
Load disturbance and simulation interval	+5 MW at t = 5 s; simulation from 0 to 60 s

Simulation Method. Equations (1)–(3) were integrated numerically from zero initial deviations. The conventional generator model, $T^g \cdot d\Delta P^g/dt = -K^g \cdot x - \Delta P^g$, was retained in all cases. In the first case, wind and PV plants provided no frequency support. The second used independent droop gains of 12 and 8 MW/Hz for the wind and PV plants, respectively. In the third, the common PI command was allocated in proportions of 5/8 and 3/8. Communication delays, stochastic weather variations and measurement noise were not included.

Simulation Results and Discussion

Figure 1. Frequency response to a 5 MW load increase in the illustrative model

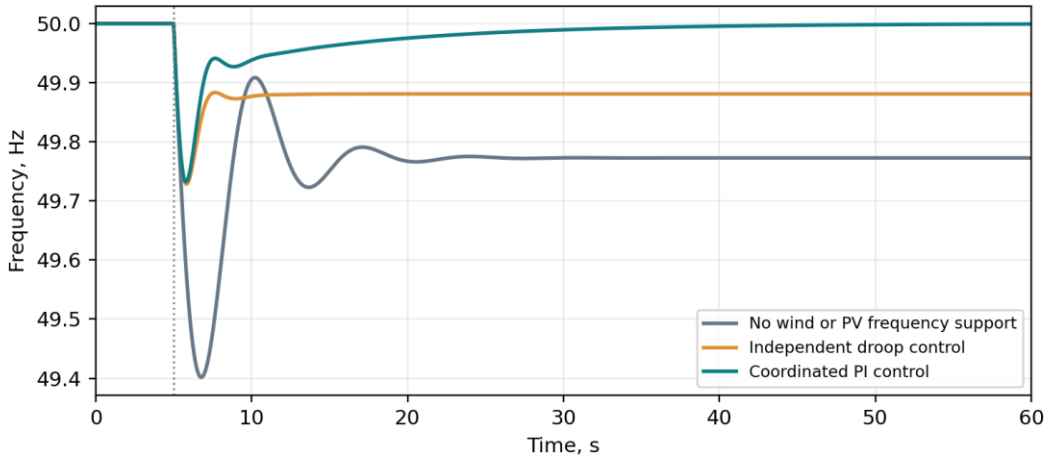


Table 2. Comparison of control strategies under the same load disturbance

Control strategy	**Minimum frequency Hz**	**Maximum |Δf| Hz**	**|Δf| at 60 s Hz**	**Return to ±0.05 Hz s**
No wind or PV frequency support	49.402	0.598	0.2273	Not within the simulation
Independent droop control	49.728	0.272	0.1190	Not within the simulation
Coordinated PI control	49.732	0.268	0.0008	6.90

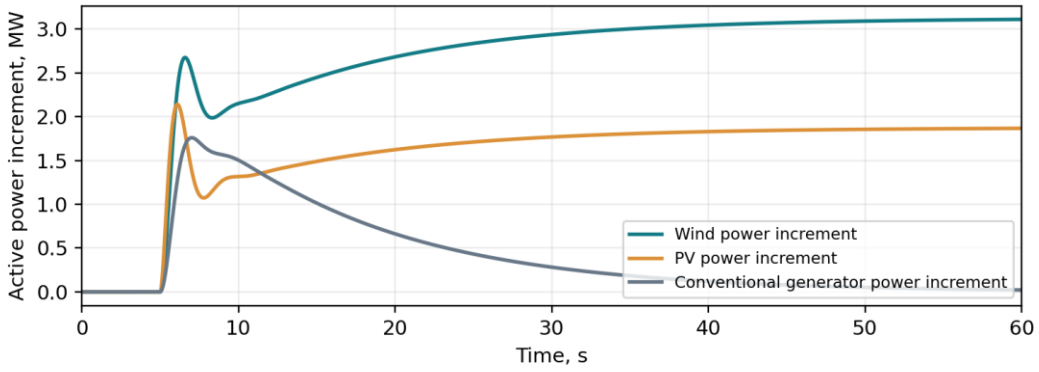
In the illustrative model, coordinated PI control reduced the maximum frequency deviation by 55.3% relative to the case without wind or PV frequency support, and by 1.5% relative to independent droop control. The return time in Table 2 is measured from the load disturbance until the frequency enters the ±0.05 Hz band around nominal frequency and remains within it through the end of the 60 s simulation. This band is a numerical evaluation criterion, not a stated regulatory requirement.

The improvement in the third case reflects the combined effects of reserve allocation and integral control. This comparison does not establish the isolated benefit of coordination. To assess that benefit, independent and central control schemes with equivalent integral action should also be compared.

The numerical results and plots are illustrative model outputs, not measurements from an operating power plant. Their interpretation is limited to the model assumptions and parameters given in Table 1.

Power Allocation and Limitations

Figure 2. Active power increments under coordinated control in the illustrative model



As the frequency error approaches zero in steady state, the conventional generator's droop contribution decreases. The wind and PV plants then supply most of the additional load. For a 5 MW command, their steady-state increments are approximately $\Delta P^{w} = 3.125$ MW and $\Delta P^{s} = 1.875$ MW, respectively. Both remain below the available reserves of 5 and 3 MW. The PV channel responds more quickly because of its smaller time constant; the prescribed allocation ratios are reached in steady state.

Immediately after the disturbance, the rate of change of frequency (RoCoF) is the same in all cases: $dx/dt = -5/8 = -0.625$ Hz/s. The plant response channels do not change power instantaneously, and the model includes no virtual inertia. The results therefore show an improved frequency nadir and subsequent recovery, rather than a reduction in the instantaneous initial RoCoF.

The results assume that the reserves remain available throughout the 60 s simulation. A sharp decline in solar irradiance or wind speed can reduce the

available reserve and limit the ability to restore nominal frequency. The model does not represent network buses, rotor speed dynamics or inverter dynamics in detail. Application to a real plant therefore requires controller retuning and testing under communication delays and different weather scenarios.

Conclusion.A coordinated control approach is proposed in which preallocated wind and PV active power reserves respond to a common frequency error and share the requested power increment in proportion to their available reserves. In the illustrative model, a 5 MW load increase produced a maximum frequency deviation of 0.598 Hz without wind or PV frequency support, compared with 0.268 Hz under coordinated PI control. Integral action reduced the residual frequency error when sufficient reserve was available. These findings apply to the numerical example; practical effectiveness should be validated using models and experiments that include variable reserves, communication delays and equipment constraints.

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