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An Improved Adaptive Load Shedding Control Strategy for Primary Frequency Regulation of Wind Power Generation System

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An Improved Adaptive Load Shedding Control Strategy for Primary Frequency Regulation of Wind Power Generation System

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Abstract. With the continuous improvement of the proportion of wind power generation, the volatility and uncertainty of wind power pose a serious threat to the stable operation of the power system. However, the traditional primary frequency regulation strategy does not fully consider the influence of wind turbine inertia. In addition, it may cause the secondary frequency drop if the instantaneous power of the wind turbine drops too much during the speed recovery. To solve this problem, this paper proposes an adaptive primary frequency regulation strategy for the mobile load shedding power tracking curve. Under this strategy, by controlling the output active power reference value, the kinetic energy stored in the rotor is fully released to support the grid frequency for a short time. Then, in the process of rotor speed recovery, the frequency secondary drop can be alleviated by moving the load-shedding power tracking curve. Finally, the simulation results in MATLAB/Simulink verify the rationality of the proposed adaptive load-shedding control strategy.

1. Introduction

With the significant reduction of fossil resources such as coal and oil, the power generation and grid connection of renewable energy have become research hotspots. Due to the low power generation cost of wind power, the proportion of grid-connected wind turbines is increasing year by year. The Wind Turbine is mainly a VSWT (Variable Speed Wind Turbine) [1]. VSWT is connected to the main power grid through power electronic equipment. Because the wind turbine rotor is decoupled from the frequency variation on the grid side, it cannot provide inertia like a synchronous generator. In this respect, scholars at home and abroad have carried out a lot of related researches. At present, there are two main measures for wind turbines to participate in system frequency regulation, namely virtual inertia control and active power load shedding control. Active power load-shedding control can be achieved through pitch angle control and over-speeding load-shedding control. Pitch angle control is applicable at any wind speed. However, adjusting the pitch angle frequently will aggravate the wear of the mechanical components of the wind turbine, shorten the life of the wind turbine, and increase the operating cost of the wind turbine [2]. The traditional wind turbine over-speeding load reduction and frequency regulation strategy fails to fully consider the influence of wind turbine inertia and does not fully tap the wind turbine's frequency regulation potential. Aiming at the above problems, this paper proposes an adaptive primary frequency regulation strategy for mobile load-shedding power tracking curve and builds a co-simulation model with a wind farm in MATLAB/Simulink. The simulation results show that this strategy can adjust the load shedding power of the wind turbine timely according to the real-time wind speed and system frequency deviation, and give full play to the frequency regulation ability of the wind turbine. At the same time, it can alleviate the problem of secondary frequency drop caused by excessive instantaneous power drop in the process of speed recovery, and the frequency regulation control effect is better than that of the traditional wind turbine over-speeding load reduction and frequency regulation strategy.

2. The traditional frequency control strategy based on over-speeding wind turbine generators

There are various implementation strategies for the over-speeding and load-shedding control of wind turbine generators[3]. This section analyses the existing typical over-speeding load-shedding control strategies, and defines the load-shedding coefficient of the wind turbine generators as d% (d%<1), and its expression is shown in Formula (1).

$$d\% = 1 - \frac{P_{m\_del}}{P_{MPPT}} \tag{1}$$

Where P_{m_del} is the mechanical power of the wind turbine generator when the load is reduced. P_{MPPT} is the active power of the wind turbine generator at the maximum power tracking point.

If a typical wind turbine over-speeding and load-shedding control strategy is adopted, it is shown in Figure 1. Based on load-shedding power P_{m_del}, an additional power simulating primary frequency regulation characteristics is introduced to adjust the given value of active power of the wind turbine rotor side converter, and its principle is shown in Figure 2. Before the system frequency drop event begins, the wind turbine runs at point B on the right panel according to the load-shedding power tracking curve. When the system under frequency occurs, additional power is added to the power tracking reference value [4]. The electromagnetic power of the wind turbine is greater than the mechanical power, and the wind turbine starts to slow down to the running point C. In the process of rotor deceleration, the active power P_{m_del} corresponding to the wind turbine load shedding tracking curve decreases continuously, which is likely to lead to a small active power reference P_{ref}, which makes it difficult to make full use of the reserve capacity and weakens the frequency support effect of the wind turbine.

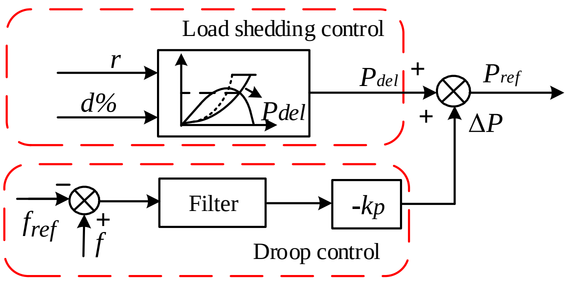

Figure 1. The traditional frequency control strategy is based on over-speeding wind turbine generators.

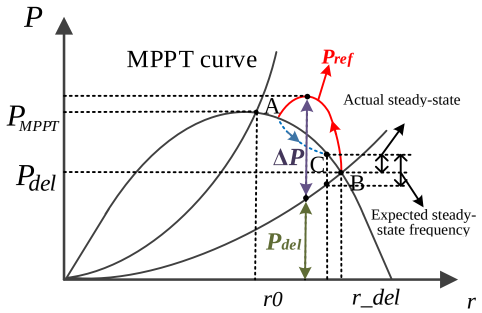

Figure 2. Schematic diagram of typical over-speeding load-shedding control principle.

The above problems can be improved by adopting adaptive droop coefficient control. Since the changes in wind turbine speed and power are not linear in the dynamic process, it is difficult to design the adaptive droop coefficient according to the changes in wind turbine operation state in the process of system frequency response. Therefore, the above control strategy can not give full play to the wind turbine frequency regulation ability, and it is difficult to achieve a good frequency regulation effect.

3. Adaptive primary frequency regulation strategy for moving load shedding power tracking curve

Because of the shortcomings of the proposed strategy, an adaptive primary frequency regulation strategy for mobile load-shedding power tracking curve is proposed to make the wind turbine output more FM power in the system frequency recovery stage[5]. This section adopts an over-speeding load-shedding control strategy of moving the load shedding power tracking curve, dynamically adjusts the load-shedding coefficient according to the system frequency offset, thereby changing the speed cubic coefficient of the power tracking curve, and realizing the movement of the wind turbine operating point. Its control strategy is shown in Figure 3. It is defined that the load reduction coefficient caused by the additional primary frequency regulation control is adjusted to $\Delta d\%$, which is proportional to Δf^*, where ΔP is the standby power used in the primary frequency regulation control of the wind turbine, and K_1 is the proportional coefficient between $\Delta d\%$ and Δf^*.

$$\Delta d\% = \frac{\Delta P}{P_{opt}} = -K_1 \Delta f^*$$

$$K_1 = \frac{d\%}{\Delta f_{\max}^*} \tag{2}$$

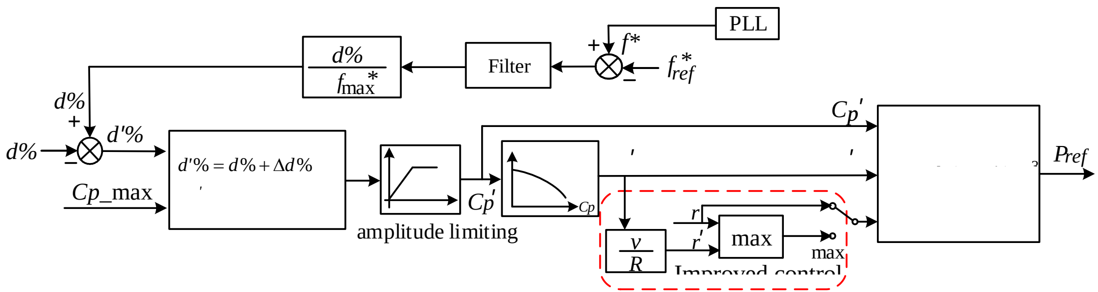

Figure 3. Over-speed and load-shedding control strategy for moving load-shedding power tracking curve.

At this time, the standard unit value K_w^* of the wind turbine unit regulating power is:

$$K_w^{\ *} = -\frac{d\% P_{MPPT}}{\Delta f_{\max}{}^{*} P_n} \tag{3}$$

In the dynamic process of the wind turbine participating in the system frequency response, the actual load reduction coefficient $d'\%$ and the actual wind energy utilization coefficient $C_p^{\ '}$ are respectively:

$$\begin{aligned} d'\% &= d\% + \Delta d\% \\ C_p^{\ '} &= (1 - d'\%) C_{p\max} \end{aligned} \tag{4}$$

The utilization coefficient of wind energy is only related to λ and β, but it has nothing to do with wind speed. During the over-speed and load-shedding operation, β=0, and the relationship between C_P and λ can be obtained. When C_P is known, two corresponding λs can be found according to the C_P-λ curve. Under the over-speed and load-shedding control, only the larger λ needs to be retained, so the one-to-one correspondence of C_P-λ can be obtained. The C_p' obtained from this calculation, the corresponding λ' can be obtained by looking up the table, and finally, the third power coefficient of speed of the corresponding load shedding power tracking curve can be obtained as follows:

$$k'(C_p', \lambda') = \frac{\frac{1}{2}\rho \cdot C_p' \pi R^5}{\lambda'^3} \tag{5}$$

The expression of the reference value of the active power output of the wind turbine is:

$$P_{ref} = k'(C_p', \lambda') \omega_r^{\ 3} \tag{6}$$

When the inertia of the wind turbine is not considered, $\omega_r' = \omega'$ (ω' is the rotor speed corresponding to λ' when the wind turbine is running), at this time, the active power reference value of the wind turbine output is equal to the mechanical power, and the expression of the additional active power of the wind turbine at a certain time during the frequency response period is:

$$\begin{aligned} P_m &= P_{ref} = k'(C_p', \lambda') \omega_r'^3 = \frac{1}{2}(1 - d\% - \Delta d\%) C_{p\max} \pi R^2 v^3 \\ \Delta P &= -K_w^{\ *} \Delta f^* \cdot P_n = \frac{-d\% P_{MPPT} \Delta f^*}{\Delta f_{\max}{}^{*} P_n} \cdot P_n = \frac{-d\% \Delta f C_{p\max} \pi R^2 v^3}{2\Delta f_{\max}} \end{aligned} \tag{7}$$

It can be seen from the above equation that the additional active power generated by the wind turbine in the process of simulating the primary frequency regulation is not only proportional to the frequency deviation, but also related to the wind speed. Therefore, the above control strategy achieves the target of adaptive primary frequency regulation according to the wind energy capture capability of the wind turbine in different wind speeds.

As shown in Figure 4, When the system frequency goes down, the coefficient of the third power curve of the speed changes accordingly, and the power tracking curve keeps moving to the left. When the inertia of the wind turbine is ignored, the operating point of the wind turbine moves from M point to N point along the mechanical power curve of the wind turbine under the additional primary frequency regulation control strategy. Given the inertia of the wind turbine, the dynamic process of the active power output of the wind turbine can be represented by the colored curve in the figure. The tracking curve of the wind turbine load-shedding power at a certain time in the frequency response process is taken as curve B in the figure for an example. Due to the inertia of the wind turbine, the rotor slows down slowly, and the actual rotor speed ω_r is greater than the speed ω_{rd}' corresponding to the ideal operating point. In this case, the active reference value of the wind turbine P_{refd} is the active power corresponding to point 1, and the mechanical power output by the wind turbine is the power corresponding to point 3. The standby power of the wind turbine and the kinetic energy of the rotor are fully utilized. In the extreme case when the system frequency deviation exceeds the maximum limit, the operating point will move along the green line in the figure. When k' reaches the maximum value, the operating point will move along the MPPT curve due to the limiting link in the figure, and all the spare capacity will be used to take part in the frequency response of the system. At this time, the wind turbine frequency regulation potential is fully tapped.

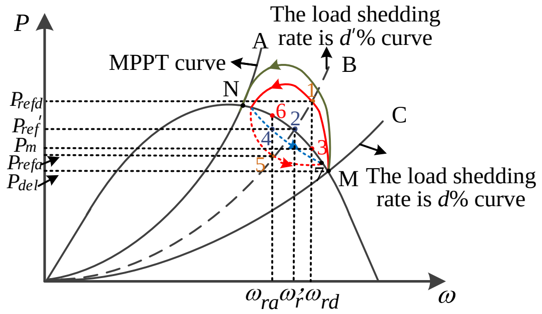

Figure 4. Schematic diagram of over-speed and load-shedding control principle for moving load shedding power tracking curve.

When the wind turbine simulates the dynamic characteristics of primary frequency regulation, the rotor speed decreases first, then increases, and finally restores to the original running point. In the process of rotor deceleration, the wind turbine operating point will move following the solid red line. This paper proposes an improved control strategy as shown in the dashed box in Figure 3 to improve the wind turbine frequency support performance by increasing the given value P_{ref} of wind turbine power during rotor acceleration. In the process of rotor acceleration, when the inertia of the wind turbine is considered, the actual speed of the rotor ω_{ra} will be less than the rotational speed ω_r' corresponding to the ideal operating point. The active power reference value of the wind turbine is the active power P_{refa} corresponding to point 5, the mechanical power reference value is the power corresponding to point 6, and point 7 is the steady operating point of the primary frequency regulation of the wind turbine. At this time, if ω_{ra} is replaced by ω_r', the active power output of the wind turbine can not only increase in the frequency response process (the operating point changes from point 5 to point 4, and the active power output of the wind turbine changes from P_{refa} to P_{ref}'), but also delay the acceleration process of the rotor. According to the above analysis, in the acceleration or deceleration process, each load-shedding power tracking curve corresponds to two speeds, the ideal operating point speed ω_r' and the actual speed ω_r. Taking the maximum speed of the two, the wind turbine can achieve a better frequency support effect.

4. Simulation and analysis

To further illustrate the control effect of the adaptive primary frequency regulation strategy of the mobile load-shedding power tracking curve proposed in this paper, the following is illustrated with a concrete example.

In this example, a wind farm with 100 2MW DFIGs is taken as an example through the grid-connected 100km transmission line, and the load connected at the middle part of the line is 240MW+20Mvar. The simulation model was built in MATLAB/Simulink. The specific parameters of the simulation model can be found in Table 1 in the Appendix. The simulation circuit diagram of the wind turbine grid-connected is shown in Figure 5.

The following is the simulation experiment of various load-shedding control strategies under 8m/s steady wind speed. We set Strategy 1 as the constant load shedding power tracking curve control strategy, Strategy 2 as the variable load shedding power tracking curve control strategy, and Strategy 3 as the improved control strategy of Strategy 2. The three strategies adopt the same droop coefficient, where K_1=-5 and the equivalent unit regulating power is K_w^*=2.1. When t=5s, 10MW+1Mvar load is increased suddenly. The simulation results of wind turbine dynamic response and system frequency response under different over-speed load reduction control frequency regulation strategies are shown in Figure 6.

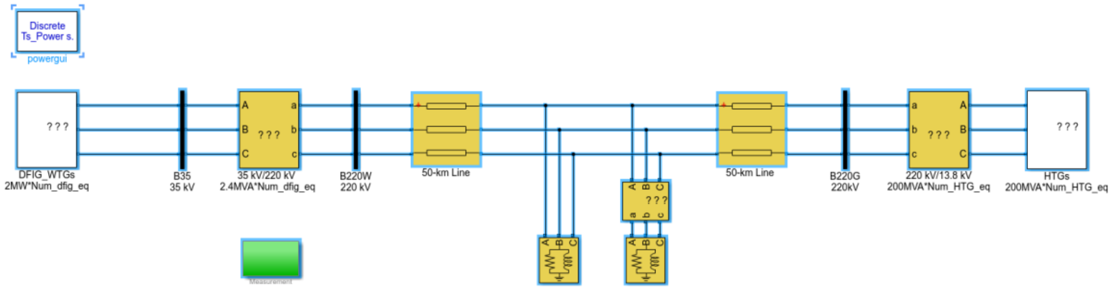

Figure 5. Grid-connected simulation circuit diagram of wind turbine

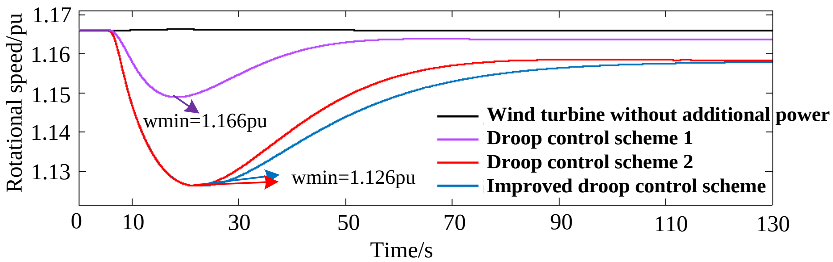

Figure 6. The frequency relation diagram of the system under constant wind speed

As shown in Figure 6, the wind turbine over-speeding load shedding control has a very strong auxiliary support effect on the system frequency. Strategy 2 and the improved strategy have the best effect, and the lowest frequency is raised from 49.14Hz without the control strategy to 49.61Hz. According to Figure 7 and Figure 8, the steady-state frequency of the system is 49.92Hz. For the wind turbine with unit regulating power Kw*=2.1, when the system has a steady-state frequency deviation of 0.08Hz, the active power should be increased by 0.00336 pu. The steady-state output of the wind turbine in Strategy 2 and the improved strategy conforms to the expected steady-state frequency response of the system, while the steady-state power of the wind turbine in strategy 1 is low. When the frequency decreases, the active power output of the wind turbine increases along with the increase of 0.016 pu in strategy 1 and 0.033 Pu in Strategy 2 and improved droop control. It can be seen that the control strategy of variable load-shedding power tracking curve can better explore the frequency support potential of the wind turbine and make the wind turbine produce more active power during the system frequency drop. In the phase when the system frequency decreases, there is little difference between Strategy 2 and the improved droop control strategy, while gradually recovering the system frequency, the wind turbine releases more active power under the improved strategy than Strategy 2, as shown in the shaded part of Figure 7. According to Figure 8, the improved strategy slows down the recovery speed of the rotor speed, thus delaying the process of the active power output of the wind turbine reducing from the maximum value to the steady value, so that the wind turbine fully releases the active power when the system frequency is recovered and provides auxiliary frequency support for the system.

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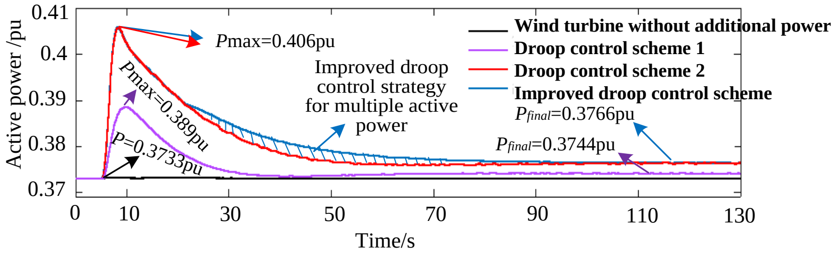

Figure 7. Relationship diagram of the active power output of wind turbine with constant wind speed

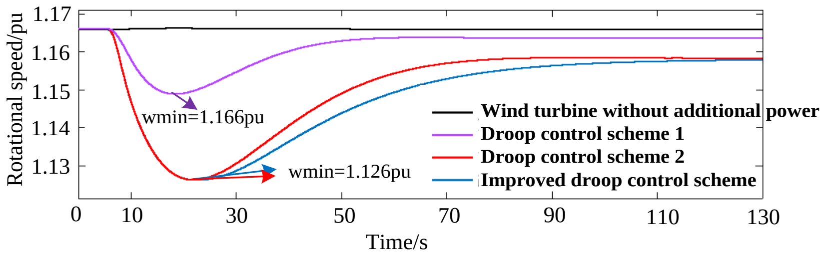

Figure 8. Relation diagram of rotor speed of wind turbine with constant wind speed

To further verify the effectiveness of the improved control strategy, a set of 120-second fluctuating wind speed data is selected below to obtain the simulation results under various load-shedding control strategies when the wind speed fluctuates, as shown in Figure 9-11. According to Figure 9, the lowest frequency of the wind turbine is lower than 49Hz when the non-control strategy and strategy are adopted, and the lowest frequency of strategy 2 and Strategy 3 is 49.21Hz. It can be seen that the variable load reduction control curve control strategy can make the wind turbine have a stronger frequency support ability. As can be seen from Figure 10 and Figure11, in the whole frequency response process, the wind turbine rotor speed changes more slowly under the improved control strategy, and the wind turbine can output more active power. In the two frequency recovery processes, the improved control strategy reaches the lower limit of frequency fluctuation of 49.8Hz in the normal operation of the system 4.9s and 7.7s earlier than Strategy 2, respectively. It can be seen that under gradual wind speed, the improved control strategy can make the wind turbine have better dynamic frequency regulation ability and make the system frequency recover to the normal operating range faster.

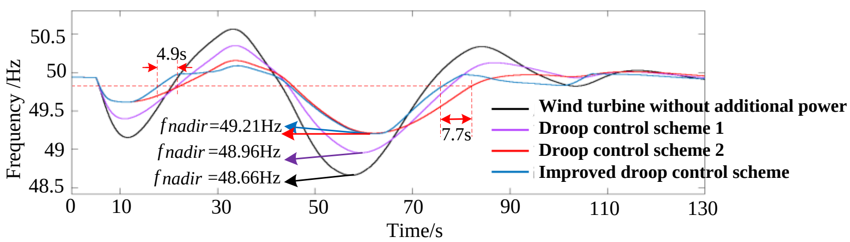

Figure 9. The frequency relation diagram of the system with gradual wind speed

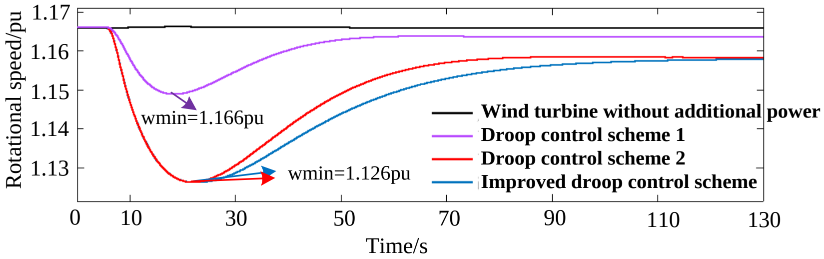

Figure 10. The relationship diagram of the active power output of wind turbine when wind speed gradient

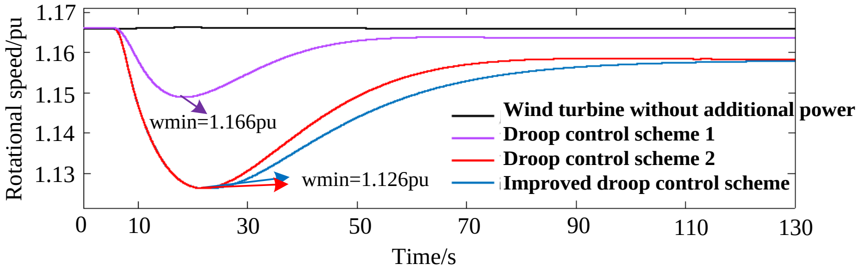

Figure11. Relation diagram of rotor speed of wind turbine with gradual wind speed

5. Conclusion

In this paper, an adaptive primary frequency regulation strategy for wind turbines based on a moving load-shedding power tracking curve is proposed. The main conclusions are as follows.

1) The traditional primary frequency regulation strategy of wind turbines fails to fully consider the influence of wind turbine inertia and fails to fully tap the frequency regulation ability of wind turbines. In the recovery stage of the rotor speed, the second frequency drop may be caused due to the excessive instantaneous power drop.

2) The strategy proposed in this paper, by controlling the output active power reference value, the kinetic energy stored in the rotor is fully released to support the grid frequency in a short time. And in the process of rotor speed recovery, each load-shedding power tracking curve corresponds to two speeds, the ideal running point speed, and the actual speed. Taking the maximum speed of the two can alleviate the secondary frequency drop caused by excessive instantaneous power drop in the process of speed recovery. Under the same load reduction, the proposed strategy can further improve the frequency support capacity of the wind turbines.

6. Appendices

Table 1. Major parameter

Device	Parameter	parameter values
DFIG	rated power	2MW
	Maximum wind energy utilization factor	0.48
	rated wind speed	9.75m/s
Additional control parameters for wind turbine	Rotor kinetic energy control factor k_p、 k_d	0.15
	load shedding factor	0.1
	Over-speeding load shedding control K_1	5

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