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An Emergency Control Strategy for Isolated Power System of Three-Phase Inverter and Diesel-Engine Generator Operating in Parallel

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ABSTRACT In the isolated power system of renewable energy power generation inverter and diesel-engine generator operating in parallel, the generator usually runs in the voltage and rotate speed droop control mode, and the three-phase inverter runs in the constant power-control mode. In this case, a sudden load change will be completely undertaken by the generator, which may lead to its overload or reverse power. In order to solve this problem, this paper has proposed an emergency control strategy based on the detection of the rate of system frequency change. In emergency conditions, the strategy can be used to automatically adjust the inverter output power to deal with the aforementioned overload or reverse power and prevent the system from shedding load and avoid protective actions of the generator. Thus, the power-supply capacity and continuity of the system are guaranteed, and its safety and stability are also improved. Time-domain simulations and experiments show that the proposed strategy is feasible and effective.

INDEX TERMS Emergency control strategy, isolated power system, inverter and generator parallel control, sudden load change.

I. INTRODUCTION

With the development of renewable energy power generation (REPG) technologies, the isolated power system (IPS) consisting of REPG devices and traditional generating sets can use more and more wind and solar energy to supply electricity to islands or remote mountainous areas. Such systems can improve the power-generation efficiency, reduce environmental pollution, and enhance the self-sufficient capability of power supply in remote areas [1]–[4]. As an interface between the REPG and the IPS, the inverter usually uses a constant voltage-control mode at the time of independent power supply in order to provide stable voltage and frequency for the system [5]–[7]. And in parallel operation with the generator, the inverter usually adopts a constant power-control mode to provide stable power for the system according to dispatching commands [8], [9].

If the load suddenly increases when the inverter and the generator run in parallel, the suddenly-applied load power will be completely undertaken by the generator. If the power exceeds the remaining capacity of the generator, the generator will be overloaded and the system frequency will decrease. In this situation, if the inverter output power remains unchanged, the generator will continue working under the overload condition, which will raise the winding temperature thus to cause mechanical damage to the prime mover. Soon afterwards, the system will take low-frequency load shedding measures to restore the system frequency or the generator will stop running because of its overload protection [10], [11].

When part of the system load is shed due to system faults or human factors, the decreased load power will also be completely undertaken by the generator. If the remaining load power is less than the inverter output power, the latter will be used for power supply to the load and its excess power will go to the generator. This will cause reverse power in the generator which will create a reverse torque in the prime mover. At this time, if the inverter output power is not limited, the generator running for long in the reverse power condition will probably cause the system frequency to increase, the windings to burn, the prime mover to be damaged, or the generator to stop operating due to its reverse power protection [12], [13].

The above two kinds of abnormal working conditions make it possible for the generator to be damaged or to stop running, with the result that affecting the IPS frequency stability and normal operation and even a decrease in the system power supply capacity. Therefore, it is necessary to develop an emergency control strategy to deal with the abnormalities caused by a sudden load change in the parallel operation of the inverter and the generator, so as to provide the technological basis for safe and stable operation of the IPS.

In [14]–[16], the virtual inertial control strategy was adopted to control the output active power of the wind turbine inverters according to changes in the system frequency. However, the inverters mentioned above are connected to a large grid, whose capacity is much larger than the inverters. It is almost impossible for the grid to be overload or reverse-power. The researches mentioned above mainly focus on the effect of the load change on the system frequency stability. But in the case of IPS, the capacities of inverter and generator are similar. The system is more likely to face the problems of generator overload or reverse-power due to a sudden load change. In [17], by adding an auxiliary power signal in the control of storage inverter, the proposed strategy can make the energy storage partially undertake the system load when it exceeds the rated power of the diesel-engine (DE) generator, thus avoiding system collapse caused by generator overcurrent. But this strategy depends on the communication between DE generator and storage inverter, it may become invalid due to malfunctions in the communication network. In [18]–[20], the equations of the synchronous generator rotor motion and the primary frequency-regulation function were introduced into the inverter control to simulate the characteristics of the synchronous generator and reduce the frequency fluctuation caused by a load change, namely the virtual synchronous generator (VSG). However, renewable energy generation converters usually adopt Maximum Power Point Tracking (MPPT) control strategy to maximize the utilization of renewable energy and avoid frequent regulation of energy management systems. Therefore, in order to avoid making major changes to the existing control structure of the converters, the emergency control strategy in this paper is proposed on the basis of the constant power-control mode, rather than the VSG control. As for conventional power systems or IPS, the active power deficiency is estimated according to the rate of system frequency change (RSFC) and rotational inertial. In an emergency, the low-frequency load shedding measures should be taken to restore the system frequency [21]. But for the system composed of generator and inverter, shedding load is apparently not the best solution when the inverter still has output capacity. It cannot make the system meet the power needs of all loads and will waste renewable energy as well.

With a hybrid power system of REPG inverter and DE generator as an object of study, this paper has proposed a novel emergency control strategy based on the detection of the RSFC to meet the control demands in abnormal conditions of sudden load change. Usually, the inverter adopts the constant power-control mode and the DE generator adopts the voltage and speed droop control mode. Using the proposed strategy, the inverter can judge the operational status of the generator according to the system frequency and its change rate via local measurements, so communication with the generator is no longer necessary. When abnormalities occur in the generator, the strategy can adjust the inverter output power at once so as to solve the problems of generator overload or reverse power due to sudden load change. Thus, the power supply capacity and continuity of the IPS can be guaranteed. A simulation model of the IPS has been established in PSCAD/EMTDC and a small prototype experimental system has been constructed in our lab. Through time-domain simulations and experiments, the proposed emergency control strategy is proved to be effective, which may lay the foundation for the application of the IPS to engineering.

II. HYBRID POWER SYSTEM OF REPG INVERTER AND DE GENERATOR ANG ITS CONTROL STRATEGY

A. SYSTEM STRUCTURE

In the hybrid power system, wind power generators, photovoltaic cells and storage batteries are connected to the DC bus through AC-DC rectifiers or DC-DC choppers. The REPG inverter transforms the direct current in the DC bus into a three-phase alternating current and then sends it to the AC bus through AC breaker BRK1. And the DE generator can run in parallel with the REPG inverter by means of AC breaker BRK2. The system structure is shown in Fig. 1.

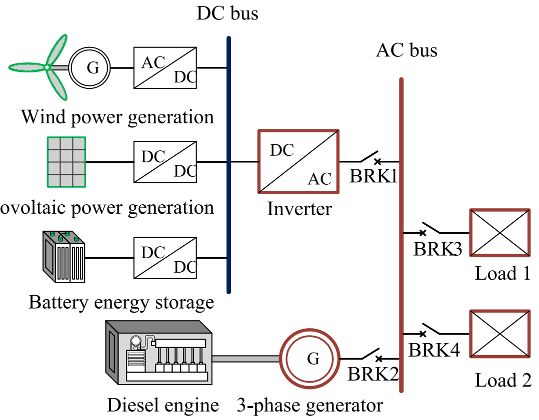


FIGURE 1. Hybrid power system of REPG inverter and DE generator.

B. CONSTANT POWER-CONTROL MODE OF INVERTER

Operating in parallel with the generator, the three-phase inverter uses the constant power-control mode, including the outer-loop power control and the inner-loop current control, as shown in Fig.2. Each control loop has different control object, so the control bandwidth also varies. The control bandwidth of the current control loop (as the inner loop) is largest, and it should not exceed one-tenth of the switching frequency f_s. The power control loop acts as the outer loop of the current loop, its control bandwidth should be no more than one-tenth of the current loop's bandwidth. Also, as a

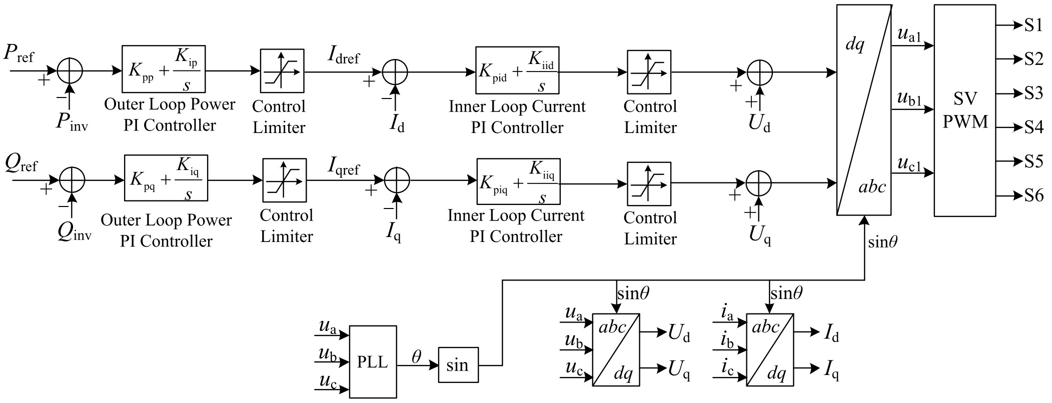


FIGURE 2. Constant power-control diagram of inverter.

periodic concept, the calculation period of power is usually considered as a period of working frequency, therefore the upper limit of the power control loop bandwidth is 50Hz.

By locking the phases of the AC bus voltage $u_{\rm a}$, $u_{\rm b}$ and $u_{\rm c}$, the phase-locked loop (PLL) provides the phase angle θ for Park transformation and the generation of three-phase modulating waves. The treatment of the three-phase modulating waves $u_{\rm a1}$, $u_{\rm b1}$ and $u_{\rm c1}$ from the control loop and the carrier signals results in generating pulse signals S1-S6, which are used to control the three-phase bridge switching tubes. Other control variables are shown in Table 1.

TABLE 1. Control variables of inverter.

Symbol	Quantity
$P_{\rm ref}$	instruction value of the inverter output active power
$Q_{\rm ref}$	instruction value of the inverter output inactive power
$P_{\rm inv}$	measured value of the inverter output active power
$Q_{\rm inv}$	measured value of the inverter output inactive power
$I_{\rm dref}$	instruction value of the d-axis current control loop
$I_{\rm qref}$	Instruction value of the q-axis current control loop
$I_{\rm d}$	measured value of the d-axis current
$I_{\rm q}$	measured value of the q-axis current
$U_{\rm d}$	measured value of the d-axis voltage
$U_{\rm q}$	measured value of the q-axis voltage
$K_{\rm pp}$	proportional coefficient of active-power PI controller
$K_{\rm ip}$	integral coefficient of active-power PI controller
$K_{\rm pq}$	proportional coefficient of inactive-power PI controller
$K_{\rm iq}$	integral coefficient of inactive-power PI controller
$K_{\rm pid}$	proportional coefficient of d-axis current PI controller
$K_{\rm iid}$	integral coefficient of d-axis current PI controller
$K_{\rm piq}$	proportional coefficient of q-axis current PI controller
$K_{\rm iiq}$	integral coefficient of q-axis current PI controller

C. CONTROL MODE OF DE GENERATOR

For the convenience of analysis, this paper uses the simplified models of the generator, in which the singly closed-loop PI control is applied to excitation and speed control. The dynamic conditions of the exciter and the diesel speed control are simulated by a first-order inertial process respectively. The control diagram is shown in Fig. 3, and the control variables are shown in Table 2.

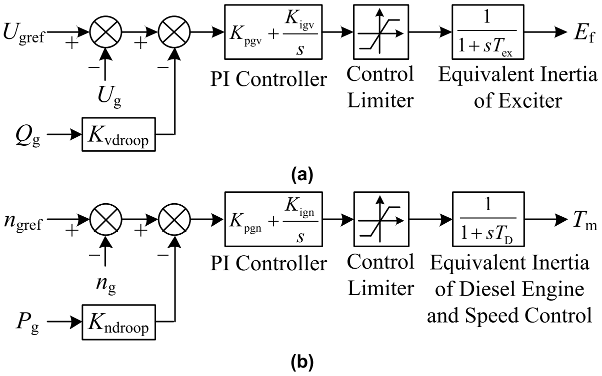


FIGURE 3. Control diagram of DE generator; (a): Generator excitation control; (b): DE speed control.

TABLE 2. Control variables of DE generator.

Symbol	Quantity
$U_{\rm gref}$	reference value of the generator output voltage
$U_{\rm g}$	measured value of the generator output voltage
$n_{\rm gref}$	reference value of the DE output speed
$n_{\rm g}$	measured value of the DE output speed
$P_{\rm g}$	output active power of the generator
$Q_{\rm g}$	output inactive power of the generator
$K_{\rm vdroop}$	droop coefficient of voltage
$K_{\rm ndroop}$	droop coefficient of rotating speed
$K_{\rm pgv}$	proportional coefficient of the excitation PI controller
$K_{\rm igv}$	integral coefficient of the excitation PI controller
$K_{\rm pgn}$	proportional coefficient of the speed PI controller
$K_{\rm ign}$	integral coefficient of the speed PI controller
$T_{\rm ex}$	time constant of the exciter
$T_{\rm D}$	time constant of the DE speed controller
$E_{\rm f}$	excitation voltage of the generator
$T_{\rm m}$	input mechanical torque of the diesel engine

III. EMERGENCY CONTROL STRATEGY

A. THEORETICAL BASIS

The equation of generator rotor motion is [22]:

$$\begin{cases} J\dfrac{d\omega_m}{dt} = T_m - T_e \\ \omega_m = \dfrac{d\theta_m}{dt} \end{cases} \tag{1}$$

Where T_{m} and T_{e} denote the input mechanical torque of the prime mover and the output electromagnetic (EM) torque of the generator respectively, J the generator rotational inertia, θ_{m} the rotor mechanical angle, and ω_{m} the rotor mechanical angular frequency. In the analysis, the electrical angular frequency ω is usually taken as a variable, and $\omega = 2\pi f$, in which f is the system frequency, so (1) can be changed into:

$$\frac{df}{dt} = \frac{p}{2\pi J\omega_n}(P_m - P_e) \tag{2}$$

Where P_{m} and P_{e} respectively represent the input mechanical power of the prime mover and the output EM power of the generator, p the number of pole-pairs, and ω_{n} the rotor rated angular frequency. When the system runs stable initially, the system frequency is constant and the input mechanical power of the prime mover balances with the output EM power of the generator. Therefore, P_{m} can be obtained from the generator initial output power P_0. According to the active power–frequency droop curve, then:

$$f = f^* - mP_e \tag{3}$$

Where f^* is the system frequency when the generator is in no-load operation and m is the active power–frequency droop coefficient. According to the initial system frequency f_0, the generator initial output power can be calculated:

$$P_0 = \frac{1}{m}(f^* - f_0) \tag{4}$$

Therefore, the proposed control strategy does not need to collect information from the generator while the inverter only requires the local information as inputs to calculate the generator output power.

When the system load suddenly changes, the generator output power P_{e} immediately follows the change but the input mechanical power of the prime mover does not change yet. The substitution of the suddenly changed load power $\Delta P = P_{\mathrm{e}}\text{-}P_{\mathrm{m}}$ into (2) leads to:

$$\frac{df}{dt} = -\frac{p}{2\pi J\omega_n}\Delta P \tag{5}$$

Apparently, the suddenly-changed load has linear relation with the RSFC. At the time of a suddenly applied load, $\Delta P > 0$ and $\mathrm{d}f/\mathrm{d}t < 0$. With an abrupt decrease in load, $\Delta P < 0$ and $\mathrm{d}f/\mathrm{d}t > 0$.

B. EMERGENCY CONTROL STRATEGY FOR SUDDEN LOAD APPLYING

If a suddenly-applied load appears in the hybrid power system, the critical condition of the generator overload is that the generator output power P_{e} after a load increase equals its rated power P_{N}. Therefore, the RSFC at the time of the load increase can be calculated according to (5). It can be used as a critical value to judge whether the generator is overloaded.

$$\left(\frac{df}{dt}\right)_{c1} = -\frac{p}{2\pi J\omega_n}(P_N - P_m) \tag{6}$$

If a suddenly-applied load leads to the generator overload, then $P_{\mathrm{e}} > P_{\mathrm{N}}$, and the RSFC at the moment of sudden load increase is less than the critical value $(\mathrm{d}f/\mathrm{d}t)_{\mathrm{c1}}$. Therefore, the detection of the change rate and comparison of it with the critical value make it possible for the inverter to judge whether the suddenly-applied load causes an overload in the generator. If the change rate $\mathrm{d}f/\mathrm{d}t \geq (\mathrm{d}f/\mathrm{d}t)_{\mathrm{c1}}$, it means the generator output power is less than or equals to its rated power. At this time, the generator is still operating normally. If $\mathrm{d}f/\mathrm{d}t < (\mathrm{d}f/\mathrm{d}t)_{\mathrm{c1}}$, it means the generator output power is larger than its rated power, and the generator is overloaded. When the inverter judges the generator is overloaded, its emergency control strategy will immediately increase its output power to share part of the increased load and solve the problem of generator overloading. According to (2) and (6), the extra output power of the inverter ΔP_{inv} is expressed as:

$$\Delta P_{inv} = P_e - P_N = \frac{2\pi J\omega_n}{p}\left[\left(\frac{df}{dt}\right)_{c1} - \frac{df}{dt}\right] \tag{7}$$

C. EMERGENCY CONTROL STRATEGY FOR SUDDEN UNLOADING

When there is sudden unloading in the hybrid power system, the critical condition of the generator reverse-power is that its output power is just zero after sudden unloading. Therefore, according to (5), the corresponding critical value of the RSFC is:

$$\left(\frac{df}{dt}\right)_{c2} = \frac{p}{2\pi J\omega_n}P_m \tag{8}$$

If the sudden unloading leads to reverse power in the generator, then $P_{\mathrm{e}} < 0$, and the RSFC at the moment of sudden unloading is greater than the critical value $(\mathrm{d}f/\mathrm{d}t)_{\mathrm{c2}}$. Therefore, by detecting the change rate and comparing it to the critical value, it is possible for the inverter to judge whether the sudden unloading causes reverse power in the generator. If the change rate $\mathrm{d}f/\mathrm{d}t \leq (\mathrm{d}f/\mathrm{d}t)_{\mathrm{c2}}$, it means the generator output power is greater than or equals to zero and the generator is still running normally; otherwise, it means the generator output power is less than 0, namely the generator reverse power. When the generator reverse power is detected by the inverter, the emergency control strategy can immediately decrease the inverter output power to deal with the situation. According to (2) and (8), the output power ΔP_{inv} which the inverter needs to reduce is expressed as:

$$\Delta P_{inv} = -P_e = \frac{2\pi J\omega_n}{p}\left[\frac{df}{dt} - \left(\frac{df}{dt}\right)_{c2}\right] \tag{9}$$

To sum up, the variant ΔP_{inv} of the inverter output power in the proposed emergency control strategy is expressed as:

$$\Delta P_{inv} = \begin{cases} 0 & \left(\left(\frac{df}{dt}\right)_{c1} \leq \frac{df}{dt} \leq \left(\frac{df}{dt}\right)_{c2}\right) \\ \frac{2\pi J\omega_n}{p}\left[\left(\frac{df}{dt}\right)_{c1} - \frac{df}{dt}\right] & \left(\frac{df}{dt} < \left(\frac{df}{dt}\right)_{c1}\right) \\ \frac{2\pi J\omega_n}{p}\left[\frac{df}{dt} - \left(\frac{df}{dt}\right)_{c2}\right] & \left(\frac{df}{dt} > \left(\frac{df}{dt}\right)_{c2}\right) \end{cases} \tag{10}$$

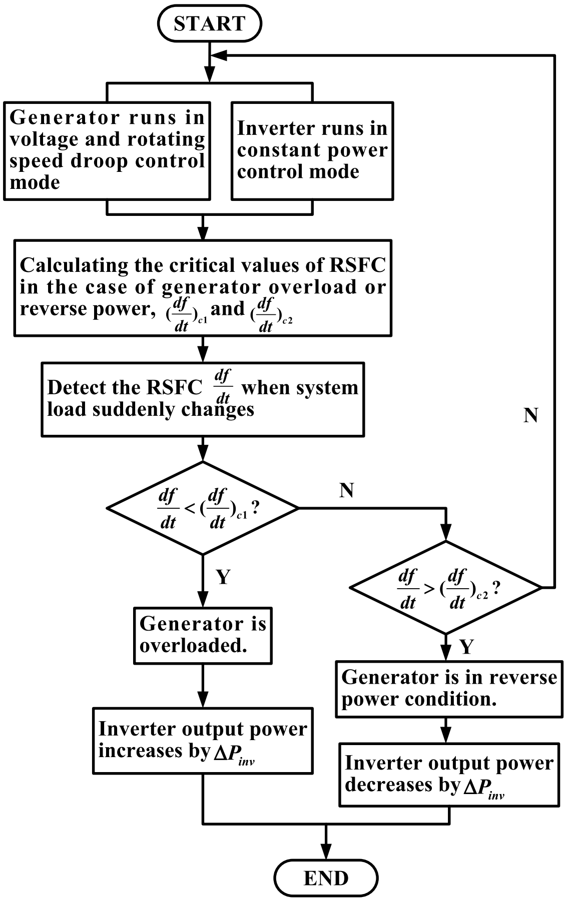


FIGURE 4. Flow chart of emergency control.

The flow chart of emergency control is shown in Fig. 4. The control process is as follow: (1) The inverter using a constant power-control mode and the generator operate in parallel to supply electricity to the loads. According to the initial system frequency and the generator rated power, the critical values of the RSFC are set for the emergency control of a sudden load increase/decrease. (2) The inverter detects the real-time RSFC in order to judge the operational status of the generator after a load change. When the RSFC reaches the threshold of emergency control at the moment of sudden load change, the inverter output power will be adjusted immediately to enable the inverter and the generator to share the suddenly changed load. Thus, the generator overload or reverse power can be quickly dealt with.

Moreover, the emergency control strategy focuses on the inverter control in generator overload or reverse power transient process. Apparently df/dt is zero in steady state, but a pulse signal will appear in df/dt at the moment of load change. When the inverter judges generator overload or reverse power based on df/dt, it will immediately adjust its output power accordingly, instead of adjusting it after the generator is working under overload or reverse power steady-state conditions. That is to say, the purpose of the proposed emergency control strategy is to prevent the generator from entering the abnormal steady-state condition of overload or reverse power. And the emergency control strategy is only applied in the transient process of load change, and lasts for a short duration. So df/dt has no effect on steady-state operation. At the same time, the noise signal of system frequency can be filtered to reduce its effect on df/dt, in order to guarantee the effectiveness and reliability of the emergency control strategy.

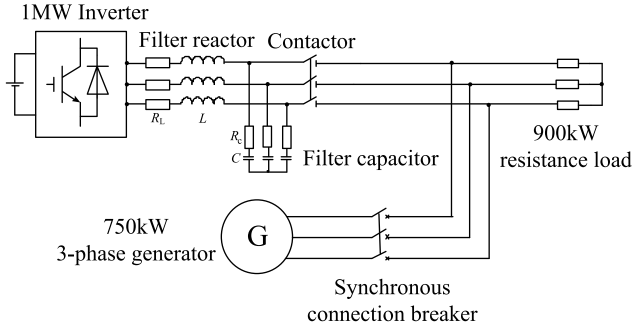


FIGURE 5. Simulation model structure.

IV. SIMULATION VERIFICATION

A. SIMULATION MODEL AND PARAMETERS

With the hybrid power system consisting of a REPG inverter and a DE generator as example, a simulation model is established in PSCAD/EMTDC to verify the proposed emergency control strategy based on the detection of RSFC. As shown in Fig. 5, the 1 MW inverter and the 750kW generator operate in parallel to supply electricity to the resistance load of 900kW. Considering that the purpose of the inner current control loop is to obtain fast current tracking characteristics, its controller can be designed as a type-I system, making the current controller a typical second-order system. The main function of the outer power control loop is to realize stable control of the output power, and the power controller can be designed as a typical three-order system in order to obtain high anti-interference capability. The proportional and integral coefficients of the controllers can be set according to the system control block diagram and the above principles. The main parameters of the system are listed in Table 3, 4 and 5.

TABLE 3. Parameters of simulation model.

Parameters	Identified value
Rated Active Power of Inverter P_{invN}	1 MW
Rated Active Power of Generator P_{gN}	750 kW
Rated Voltage of DC Bus U_{dcN}	700 V
Rated Voltage of AC Bus U_{N}	390 V
Inverter Output Filter inductance L	70 μH
Inverter Output Filter Capacitance C	1000 μF
Resistance Load P_{L}	900 kW
Generator Rotational Inertial J	4 kg•m^2
Generator Pole Pairs p	1
Rated Angular Frequency ω_{n}	314 rad•s^{-1}

TABLE 4. Control parameters.

Parameters	Identified value	Parameters	Identified value
K_{vdroop}	0.03	K_{pp}	0.1
K_{ndroop}	0.01	K_{ip}	30
K_{pgv}	60	K_{pq}	0.5
K_{igv}	200	K_{iq}	20
K_{pgn}	80	K_{pid}	0.6
K_{ign}	100	K_{iid}	20
T_{ex}	0.1s	K_{piq}	0.6
T_{D}	0.2s	K_{iiq}	20

TABLE 5. Parameters of wind turbine (WT), photovoltaic (PV) and storage battery (SB).

Parameters	Value
Rated Power of Single WT (P_{WTN})	60 kW
Rated Power of Single PV (P_{PVN})	100 kW
Battery Capacity ($E_{\text{(t)SB}}$)	200 kW·h
Maximum Capacity (SOC_{max})	0.9
Minimum Capacity (SOC_{min})	0.2
Maximum Discharge Power ($P_{\text{SBd\_max}}$)	150 kW
Minimum Discharge Power ($P_{\text{SBd\_min}}$)	60 kW
Maximum Charging Power ($P_{\text{SBc\_max}}$)	90 kW
Minimum Charging Power ($P_{\text{SBc\_min}}$)	1 kW

B. SUDDEN LOAD APPLYING

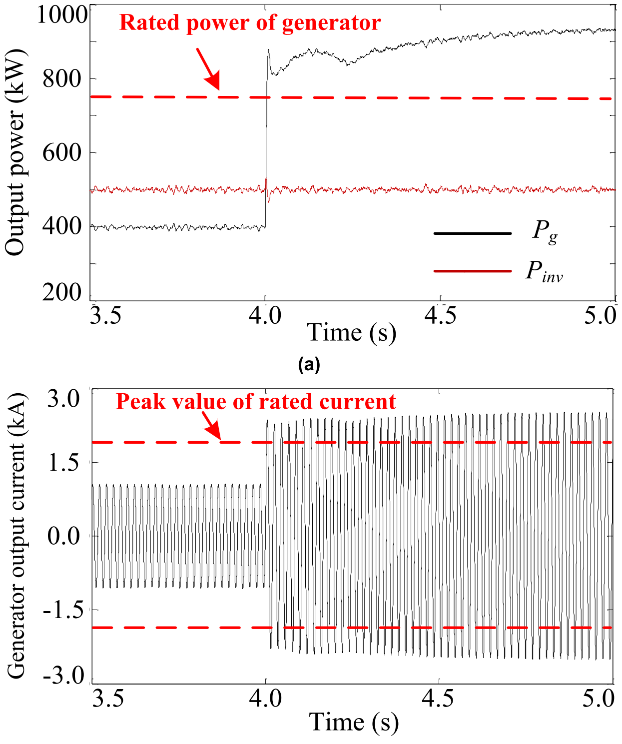
Initially, the output active powers of the inverter and the generator are 500kW and 400kW respectively. At 4s, a load of 560kW is suddenly applied to the system. Fig. 6 shows the simulation waveforms of output power of the generator and the inverter, and the generator output current when the inverter does not use the emergency control strategy.

The results show that the inverter output power remains 500kW after a suddenly-applied load, and that the increased load is completely undertaken by the generator, with the result that the generator is overloaded, its output current exceeds the rated value. In practical operation, a long-term overload of the generator will increase the winding temperature, and even lead to the winding burning, thereby damaging the power system severely.

The corresponding simulation results when the emergency control strategy is applied are shown in Fig. 7. According to (6), the critical RSFC value of the generator overloading is −44.4. It is shown in the simulation results that a load of 560kW is suddenly applied at 4s, the actual RSFC is −71, less than the critical value.

For the emergency control strategy being taken, the inverter immediately increases its output power by 210kW. After nearly 0.5s, the generator output power is stable at the rated value 750kW and the generator output current peaks at the rated 1.9kA, so that the overload problem caused by the sudden load increase is solved.

The simulation results of the system frequency in Fig.8 show that using the emergency control strategy can effectively reduce the frequency drop amplitude at the moment of sudden load increase, and restore the system frequency to 50Hz. The short-term oscillations in the frequency recovery process leads to a fluctuation of df/dt from 4.1s to 4.4s. In practice, a control dead zone can be set after every emergency control action to prevent faulty action.



(a)

(b)

FIGURE 6. Simulation results of not using emergency control strategy; (a): Output power of inverter and generator; (b): Generator output current.

C. SUDDEN UNLOADING

At first, the output power of the generator and the inverter are 400kW and 500kW. Then a load of 675 kW is suddenly cut at 4s. Fig. 9 shows the corresponding simulation results when the emergency control strategy is not used.

After unloading at 4s, the remaining 225kW load in the system is less than the inverter output power. The excess power goes to the generator, which causes the generator reverse-power and system instability. In an actual system, a reverse-power protective device is usually installed to prevent long-time reverse-power operation of the generator which may damage the prime mover. Such a device can stop the generator operation by protective actions, and decrease the power supply capacity of the system.

The corresponding simulation results when the emergency control strategy is applied are shown in Fig. 10.

According to (8), when the load suddenly decreases, the critical RSFC value of the generator reverse power is 50.7. It is shown in the simulation results that when a load of 675kW is cut at 4s, the RSFC reaches 86, greater than the critical value. The emergency control strategy can immediately decrease the inverter output power by 275kW to get

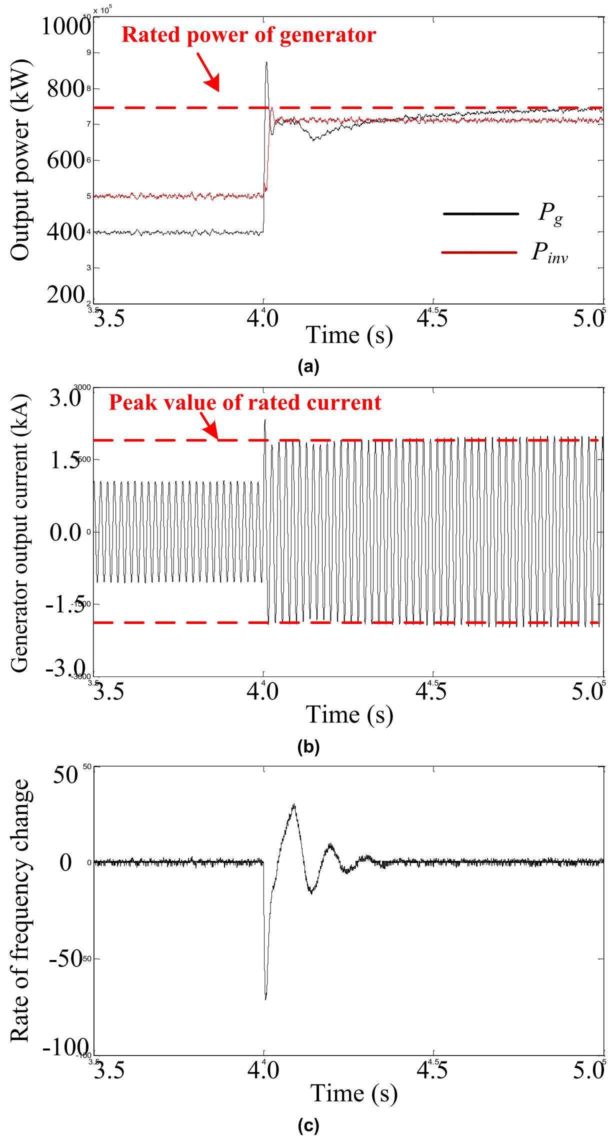


FIGURE 7. Simulation results of using emergency control strategy; (a): Output power of inverter and generator; (b): Generator output current; (c): Rate of frequency change.

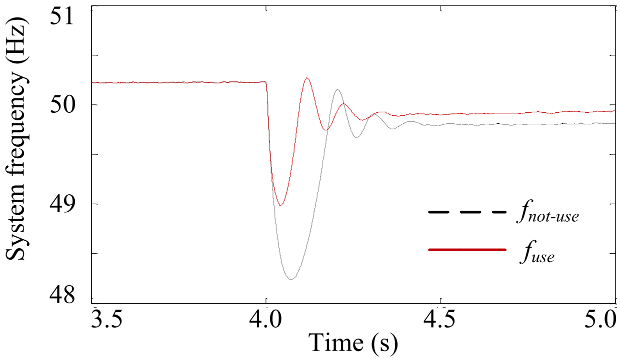


FIGURE 8. Simulation results of system frequency.

the generator output power down to 0kW and the current down to 0A. Thus, the generator reverse-power due to sudden unloading can be overcome effectively.

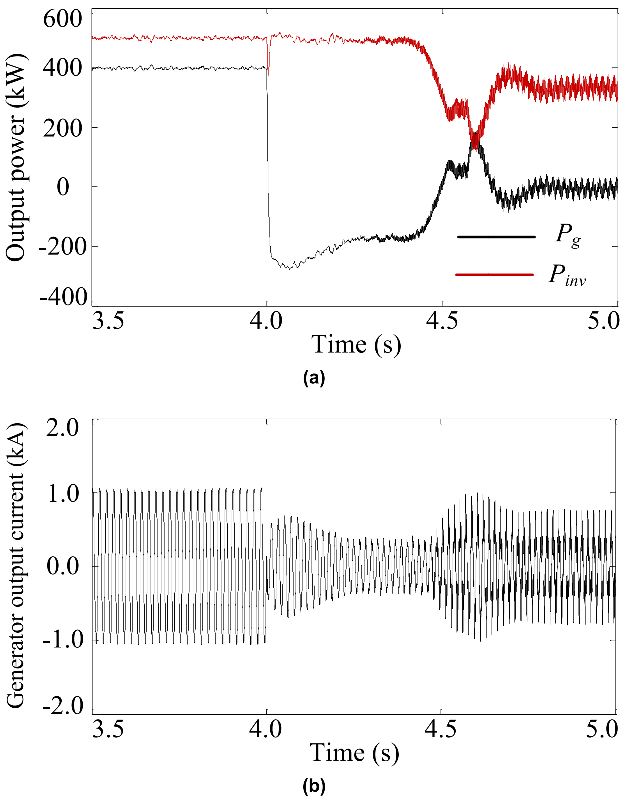


FIGURE 9. Simulation results of not using emergency control strategy; (a): Output power of inverter and generator; (b): Generator output current.

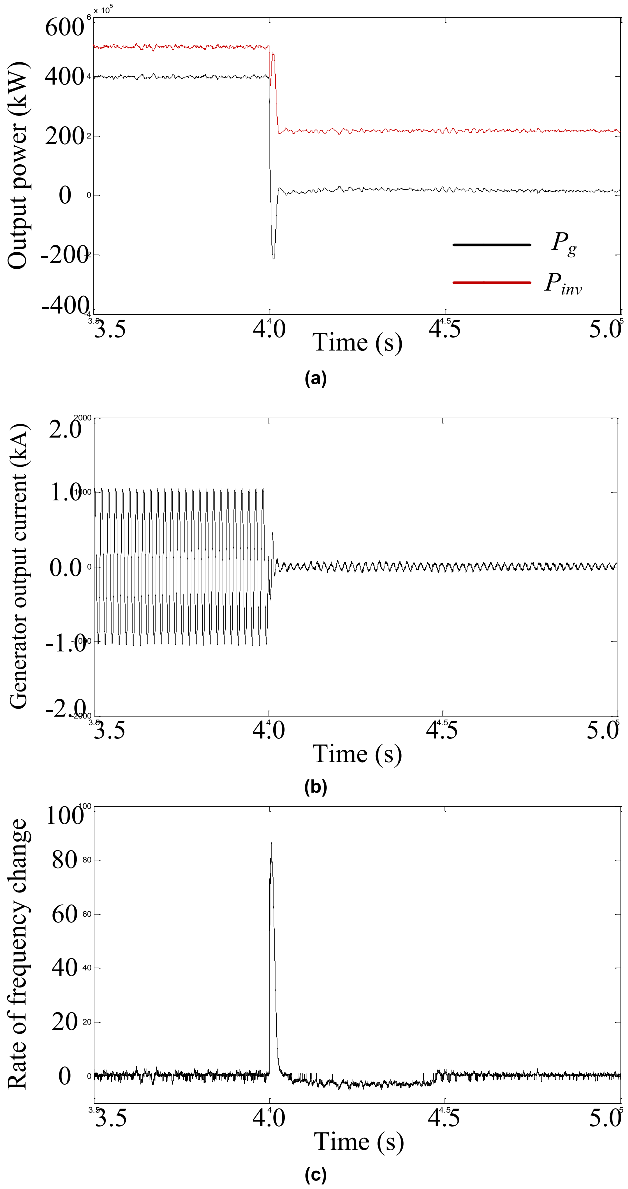
Fig.11 shows the simulation results of the system frequency. When the emergency control strategy is not taken, the system frequency rises out of range. But when the emergency control strategy is used at the moment of unloading, the frequency can be restored to 50.5Hz in about 0.5s.

In Fig. 10 (c), the df/dt is changed around 4.5s, which is because there is a descent recovery process of system frequency between 4s and 4.5s under emergency control strategy in Fig 11. When the reverse power problem of the generator is solved, the diesel generator output electromagnetic power immediately returns to zero in Fig. 10 (a), the system frequency stops rising and begins to fall back, resulting in a negative changing rate in the time of 4s and 4.5s. Therefore, the df/dt in Fig 10. (c) is a stable and small negative value between 4s and 4.5s. After 4.5s, the system frequency is restored to a stable state, and the df/dt returns to zero.

V. EXPERIMENTAL VERIFICATION

A. EXPERIMENTAL SYSTEM

This paper is based on the stand-alone micro-grid project on remote islands of the author's laboratory. According to actual engineering requirements, an isolated power system is expected to be designed, in which the inverter rating is 1MW. The simulation model is established based on actual micro-grid parameters, in order to provide reference for engineering practice. At present, a small prototype experimental system



(a)

(b)

(c)

FIGURE 10. Simulation results of using emergency control strategy; (a): Output power of inverter and generator; (b): Generator output current; (c): Rate of frequency change.

(the inverter rating is 7.5kW) has been constructed in our lab, and its main purpose is to verify the effectiveness of control strategies. Therefore, the experimental system does not select the same parameters as the simulation model.

The experimental system is shown in Fig. 12. Limited by the on-the-spot conditions, it is a simplified version of simulation model. As far as the generator is concerned, a simulative synchronous generator with the rated capacity of 10kW and inertial time constant of 6s is used for simulation which operate in parallel with a 7.5kW inverter. The actual load of the system is replaced by the changeable resistance load. In order to monitor the system in real time, a monitoring platform built on LabWindows/CVI can transmit the real-time data of the DSP to the host processor.

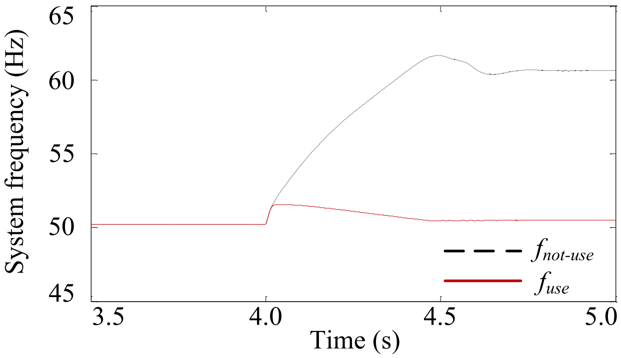


FIGURE 11. Simulation results of system frequency.

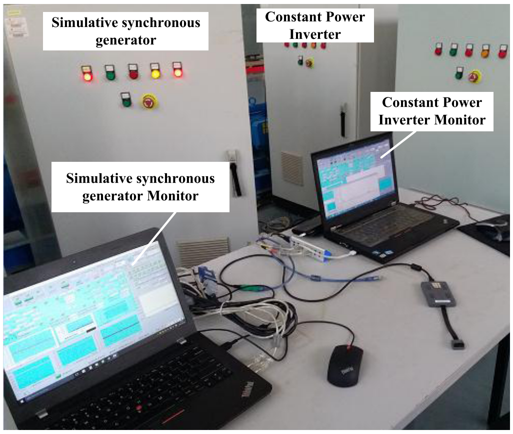


FIGURE 12. Experimental system.

The implementation principle of simulative synchronous generator (hereafter referred to as generator) is shown in Fig 13. The high frequency rectifier powered by three-phase electric power controls the DC bus voltage U_{dc} through the controller and provides stable DC power for the inverter. And the inverter adopts VSG control strategy to simulate the dynamic and static characteristics of synchronous generators [23].

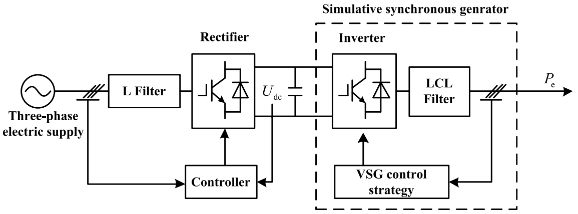


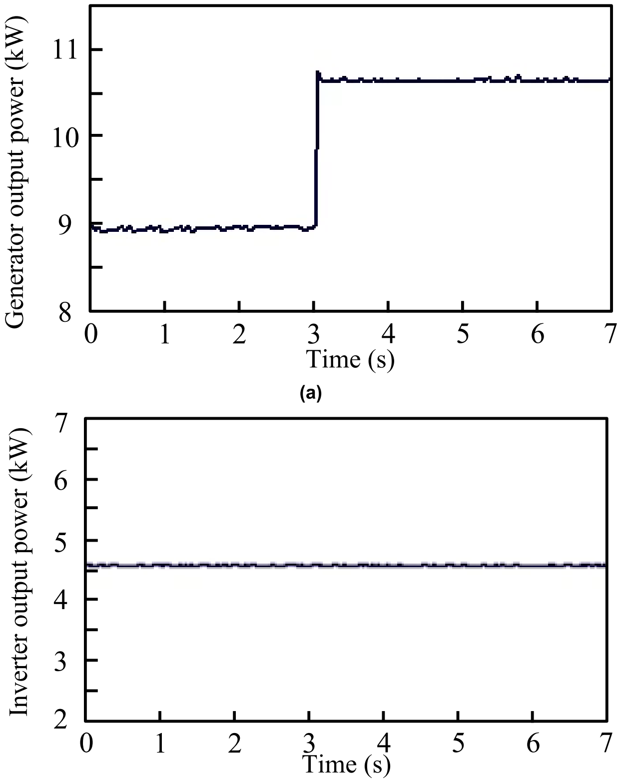
FIGURE 13. Implementation principle of simulative synchronous generator.

B. SUDDEN LOAD APPLYING

At first, the generator and the inverter running in parallel to carry a load of 13.6kW, the output power of the former being 9kW and that of the latter being 4.6kW. At 3s a 1.7kW load is suddenly applied, which is used to test of what happens in the use and non-use of the emergency control strategy.

1) NOT USING THE EMERGENCY CONTROL STRATEGY

Fig. 14 shows the test waveforms of output power of the generator and the inverter under the condition of not using the emergency control strategy.



(a)

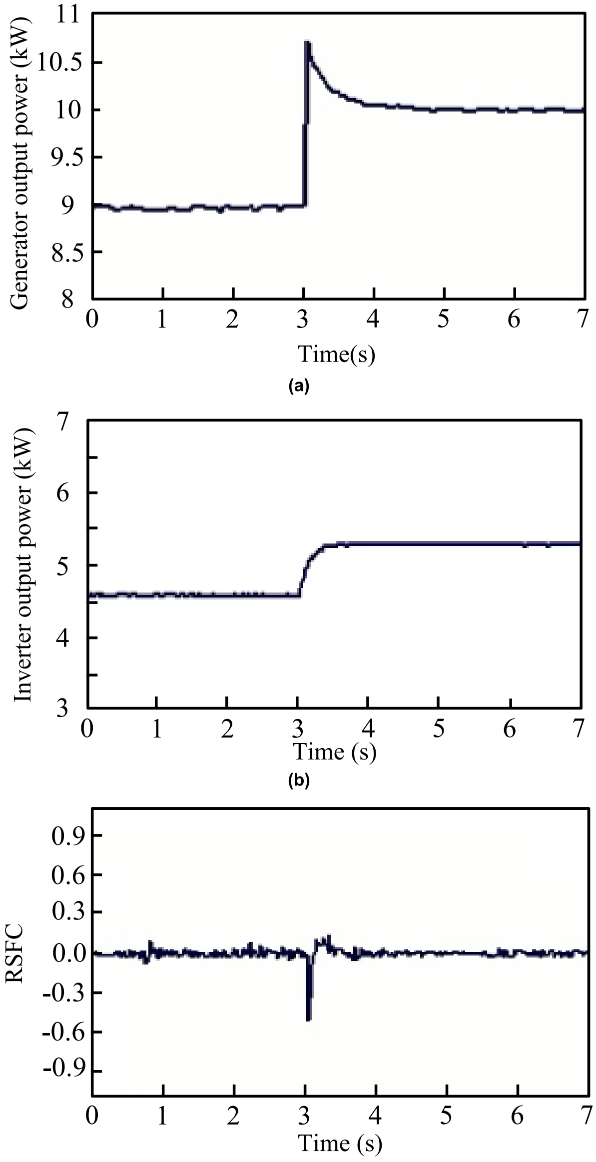
(b)

FIGURE 14. Experimental results of sudden load applying under the condition of not using the emergency control strategy; (a): Output power of generator; (b): Output power of inverter.

The results indicate that the inverter output power remains 4.6kW and the suddenly-applied load is completely undertaken by the generator, thus its output power is increased to 10.7kW, which exceeds its rated power. The generator is overloaded.

2) USING THE EMERGENCY CONTROL STRATEGY

Fig. 15 shows the test waveforms of output power of the generator and the inverter as well as the RSFC in the case of using the emergency control strategy. The inertial time constant can be used to calculate the corresponding rotational inertia and obtain the critical value of RSFC for the proposed emergency control strategy. According to (6), when there is a suddenly-applied load, the critical RSFC of generator overload is −0.33. It is found from results that the RSFC at the moment of load applying is −0.54, which is less than the critical value. So, the emergency control strategy immediately increases the inverter output power by 0.7kW. The output power of generator decreases from 10.7kW to 10kW after the moment of load application. So that, the control strategy can be applied to solve the problem of generator overload.



(a)

(b)

(c)

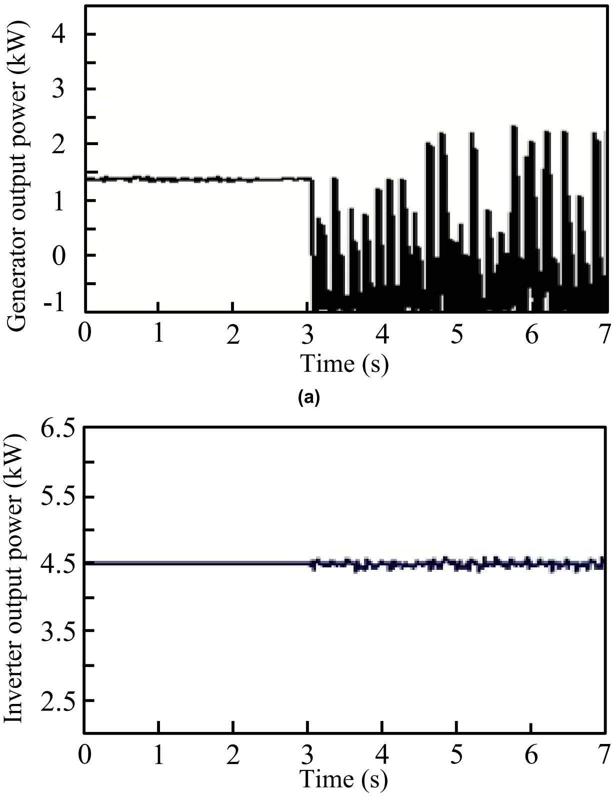
FIGURE 15. Experimental results of sudden load applying under the condition of using the emergency control strategy; (a): Output power of generator; (b): Output power of inverter; (c): Rate of system frequency change.

C. SUDDEN UNLOADING

In both simulation and experimental verification, the critical value in the proposed emergency control strategy is calculated based on specific initial load sharing conditions. Thus different initial load sharing conditions don't effect the validation of the strategy. In experimental validation, due to the limitations of experimental conditions in our lab, the load we used is not as flexible as in simulation. So experimental cases with different initial load sharing are designed to simplify the implementation. Therefore, the output powers of the generator and the inverter are respectively 1.4kW and 4.5kW when sudden unloading. Together they support a load of 5.9kW. At 3s, a 1.9kW load is suddenly cut. The conditions in which the emergency control strategy is used and not used are demonstrated through experiments.

1) NOT USING THE EMERGENCY CONTROL STRATEGY

The output power of the generator and the inverter under the condition of not using the emergency control strategy is shown in Fig. 16.



(a)

(b)

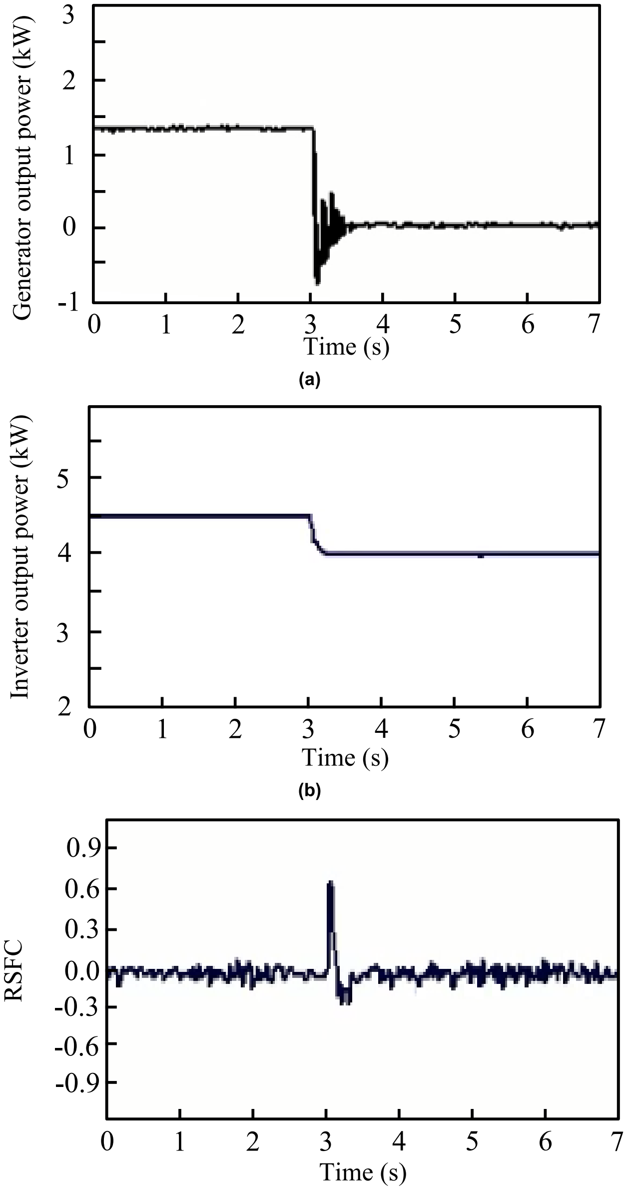
FIGURE 16. **Experimental results of sudden unloading under the condition of not using the emergency control; (a): Output power of generator; (b): Output power of inverter.**

The inverter output power remains 4.5kW when the load decreases. All the decreased part of power is undertaken by generator, whose output power should reduce to -0.5kW. The results show that the generator goes into an instable state and its output power starts to fluctuate.

2) USING THE EMERGENCY CONTROL STRATEGY

Fig. 17 shows the generator output power, inverter output power and RSFC when the emergency control strategy is used in the case of unloading.

According to (8), the corresponding critical RSFC is 0.47. In the experiment, the RSFC reaches 0.65 when there is a decrease in load, which exceeds the critical value. The emergency control strategy can be used to decrease the inverter output power by 0.5kW immediately. In Fig. 17 (c), the df/dt is a small negative value around 3.3s, which is caused by the positive fluctuation of generator active power in Fig. 17 (a). After nearly 0.5s, the generator output power



(a)

(b)

(c)

FIGURE 17. **Experimental results of sudden unloading under the condition of using the emergency control strategy; (a): Output power of generator; (b): Output power of inverter; (c): Rate of system frequency change.**

will be 0kW. As a result, the problem of generator reverse power is solved. Experiments on unloading prove the control strategy is effective.

In conclusion, simulations and experiments mainly compared the results with and without the adoption of emergency control strategy. By ensuring other conditions are the same before and after the strategy adoption, the proposed emergency control strategy can be validated through simulations and experiments separately.

VI. CONCLUSIONS

This paper has proposed an emergency control strategy to meet the control demands in abnormal conditions of sudden load change for the IPS of inverter and generator operating in parallel. Based on the detection of the rate of frequency change, the inverter can tell the operational status of the generator after a load change and carry out the emergency control in the abnormal operating conditions immediately. Therefore the strategy does not need communication between the inverter and the generator. In emergency conditions, the strategy can be used at once to adjust the inverter output power to solve the problems of generator overload or reverse-power. Thereby the strategy can effectively prevent this kind of systems from working long in abnormal conditions caused by a sudden load change, so as to avoid the low-frequency load shedding and the generator overload or reverse power protection and ensure the power-supply capacity and continuity, and the system stability.

Through the time-domain simulations and experiments of a simulation system based on the IPS and an experimental system with smaller capacity established in the lab, the proposed emergency control strategy is proved to be feasible and effective.

The proposed emergency control strategy is not only applicable to the IPS consisting of a REPG set and a conventional generator for hybrid power supply, but also to the parallel-operation system composed of inverters and auxiliary DE generators in the low voltage AC power distribution networks of vessel integrated power systems. In our future work, the proposed strategy will be improved and applied to the coordinated emergency control of multiple inverters and generators running in parallel. Also the different category of loads such as static loads and dynamic loads will be considered in our test system in the future to make the proposed emergency control strategy more practical.

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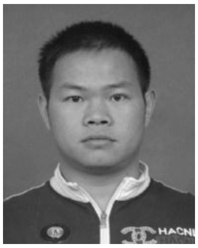

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