

Improved Virtual Synchronous Generator Control Strategy for Seamless Switching

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Abstract—To reduce the dynamic impact of seamless switching between the converter and diesel generator and improve the stability of the whole system, an improved virtual synchronous generator (VSG) control strategy is proposed in this paper. It introduces the engine governor control and the active power adjustment link into the VSG control strategy. Therefore, the angular frequency characteristics of the converter based on the improved VSG control strategy can be similar to the diesel generator, and it can make the converter possess strong rigid. Then, the virtual impedance is introduced to reduce the influence of power coupling of the converter, which is suitable for the improved VSG control strategy. Simulation model and corresponding experiment platform are established for test. Simulation results demonstrate the superior performance of the improved VSG control strategy, and experiment results validate the validity of the improved VSG control strategy.

Keywords—improved virtual synchronous generator; seamless switching; engine governor control; active power adjustment link

I. INTRODUCTION

When the ships are in the port, in order to reduce the pollutions of auxiliary engines of the ships, the shore-side power sources can replace auxiliary engines to generate electricity for ships [1], [2]. The key part of shore-side power source is converter, and the virtual synchronous generator (VSG) control strategy is a viable method to achieve seamlessly transfer from auxiliary engines to shore-side power sources. It emulate dynamic and steady-state droop characteristics of synchronous generator, which can make the converter possess damping and inertia [3], [4]. However, compared with the diesel generator, it is lack of engine governor control, so their angular frequency characteristics are different, and the degree of rigid of the converter based on the VSG control strategy is weaker than the diesel generator [5], [6]. When the converter based on the VSG control strategy and the diesel generator are in parallel, there is power impact in dynamic, and the stability of system will become worse.

In order to solve these problems, this paper proposed an improved VSG control strategy. Its speed controller model, actuator model, diesel engine model, and active power adjustment link can make the angular frequency characteristics of the converter similar to the diesel generator. Meanwhile,

the converter based on this improved VSG control strategy possesses strong rigid. And the virtual impedance is added to change the line impedance characteristic of the converter, which is benefit for the improved VSG control strategy.

The rest of this paper is organized as follows. In Section II, the block diagram of engine governor control of the diesel generator is introduced, and the improved VSG control strategy is introduced. In Section III, the parallel system model of converter and diesel generator is established. Then, simulation results are presented. Experiment results are presented in Section IV. In Section V, concludes this paper.

II. IMPROVED VSG CONTROL STRATEGY

A. Engine Governor Control of the Diesel Generator

The block diagram of engine governor control of the diesel generator is shown in Fig. 1 [7]–[9]. As shown in Fig. 1, the rotate speed (n) of permanent magnet synchronous generator (PMSG) can reach to the given rotating speed (n_{ref}) by engine governor control.

The speed controller is the PI controller, its formula is written as

$$G_s(t) = k_{ps} + \frac{k_{is}}{s} \quad (1)$$

Where k_{ps} and k_{is} represent the proportional control parameter and integral control parameter of the engine governor control, respectively.

The formula of the actuator is written as

$$G_A(t) = \frac{K_a}{(1 + T_{a1}s)(1 + T_{a2}s)} \quad (2)$$

where T_{a1} and T_{a2} are the small time constants of the actuator. K_a is the gain value of the actuator.

The formula of the diesel engine is written as

$$G_d(t) = \frac{1}{1 + T_d s} \quad (3)$$

where T_d is the small time constant of the diesel engine.

Combing (1), (2), and (3), the engine governor control is the fourth-order function.

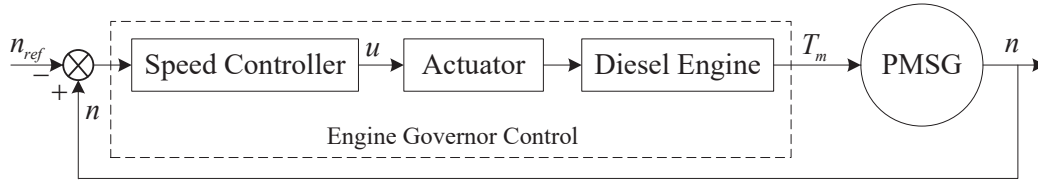


Fig. 1. Block diagram of engine governor control of diesel generator

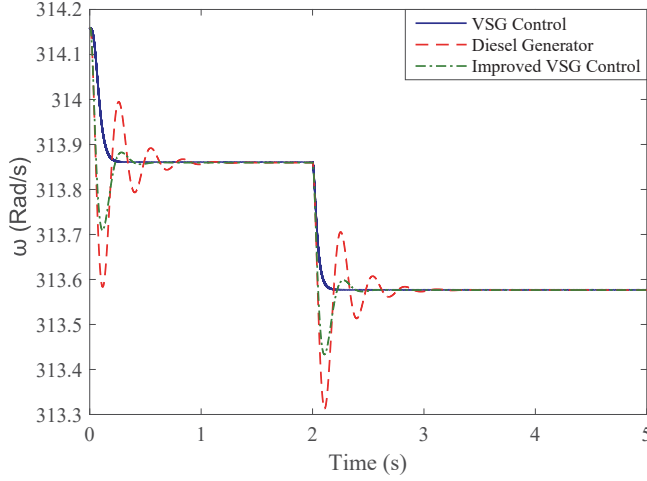


Fig. 2. Response characteristics of angular frequency

B. Improved Virtual Synchronous Generator Control Strategy

In order to emulate the engine governor control, the speed controller, actuator, and diesel engine models are introduced into the VSG control strategy. And the active power adjustment link is added to make the improved VSG control strategy possess steady-state droop characteristic. The relationship between n and angular frequency (ω) is linear [10], so n can be replaced by ω in the following analysis.

Because the engine governor control is the fourth-order function, the stability of the converter will be affected by adding this four-order function. To simplify the engine governor control, the actuator and the diesel engine can be simplified as a first-order inertial element [8], so the engine governor control can be simplified as a second-order function. The total formula of $P-\omega$ control of the improved VSG control strategy is written as

$$\begin{cases} T_m = (\omega_{ref} - \omega) \frac{(k_{pn} + \frac{k_{in}}{s})}{s + k_d} \\ = k_T(\omega_o + (P_{ref} - P)k_{e\omega} - \omega) \frac{(k_{pn}s + k_{in})}{s^2 + k_d s} \\ J \frac{d\Delta\omega}{dt} + D\Delta\omega = T_m - T = T_m - \frac{P}{\omega} \end{cases} \quad (4)$$

where k_d , ω_o , $k_{e\omega}$, P_{ref} , T_m , P , J , D , and T are coefficient of delay, angular frequency reference, coefficient of angular frequency regulating, active power reference, mechanical torque, output active power, virtual inertia, damping factor, and

electromagnetic torque, respectively. The degree of rigid of the converter can be enhanced by adding the inertial element into $P-\omega$ control.

The formula of excitation equation is written as [3], [4]

$$\begin{aligned} U_{id} &= (U_N - U_o)(k_p + \frac{k_i}{s}) = (k_v(Q_{ref} - Q) + \\ & U_{ref} - U_o)(k_p + \frac{k_i}{s}) \end{aligned} \quad (5)$$

where U_{ref} , k_v , U_o , Q_{ref} , and Q are voltage reference amplitude, coefficient of voltage regulating, output voltage amplitude, reactive power reference, and output reactive power, respectively.

C. Virtual Impedance

Because the characteristic of the line impedance of the low voltage system is resistive and inductive, there is power coupling in the converter. And because of the improved VSG control strategy does not possess the ability of the power coupling, the power coupling can influence the adjustment of the power of the converter. Therefore, this situation will reduce the dynamic characteristic and stability of the whole system. To solve this problem, the virtual impedance is adopt in this paper, it do not need add a real reactance into the system, so it is a convenience method to change the characteristic of the line impedance [11]–[13].

In order to introduce virtual impedance into the improved VSG control strategy, the electromagnetic equation is considered [14]. Its formula is written as

$$\begin{cases} U_{rd} = U_{id} - R_i i_{od} - L_i \frac{di_{od}}{dt} + \omega L_i i_{oq} \\ U_{rq} = 0 - R_i i_{oq} - L_i \frac{di_{oq}}{dt} - \omega L_i i_{od} \end{cases} \quad (6)$$

where R_i and L_i are virtual resistance and virtual reactance, respectively. By means of adding an appropriate virtual reactance, the influence of line resistance of the converter can be decreased, which means that the influence of the power coupling can be reduced. Therefore, this situation is benefit for the improved VSG control strategy.

The response characteristics of angular frequency of the VSG control strategy, the diesel generator, and the improved VSG control strategy are shown in Fig. 2. Because the VSG control strategy is lack of the engine governor control, its adjustment process of the angular frequency is smoothly. Therefore, its adjustment process of the angular frequency is different from the diesel generator. The improved VSG control

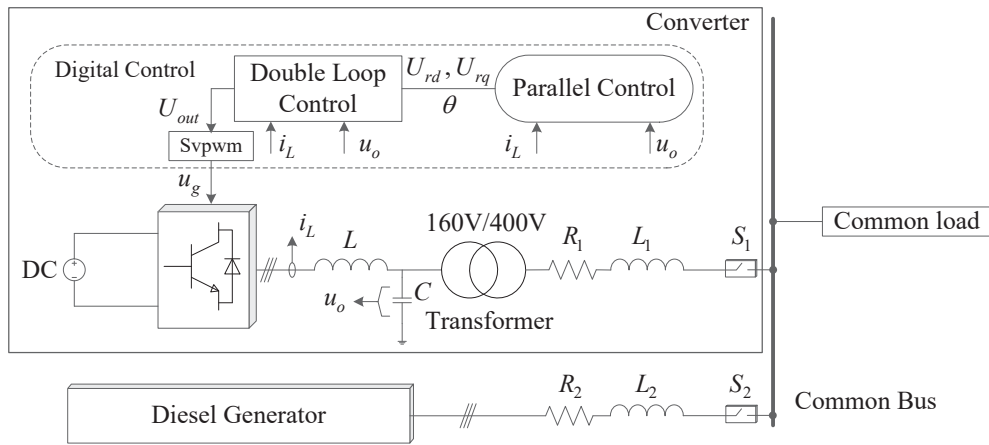


Fig. 3. Connection model of parallel system

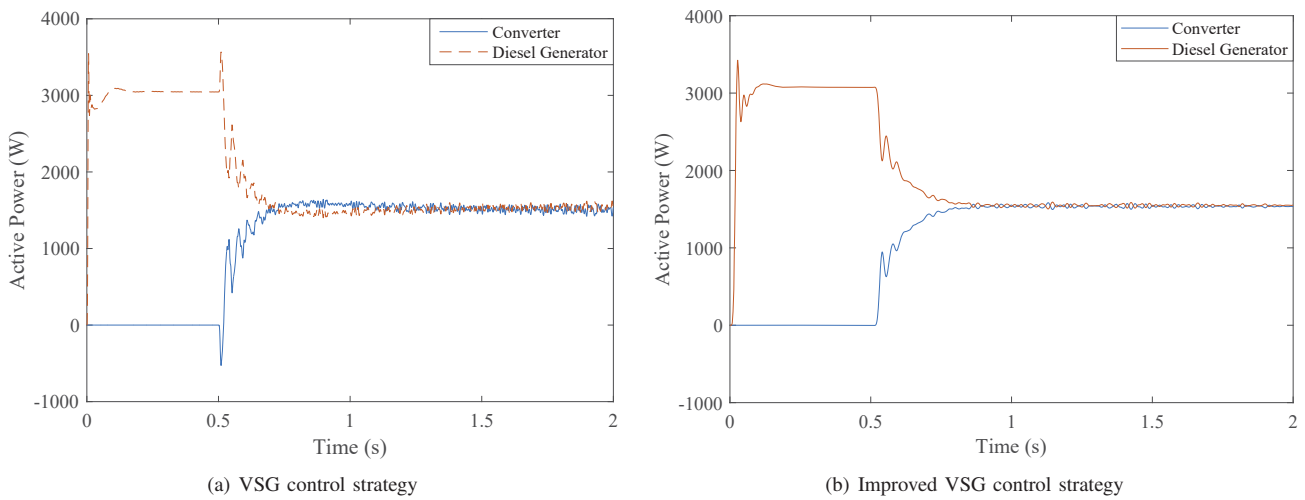


Fig. 4. Active power waveforms of converter and diesel generator

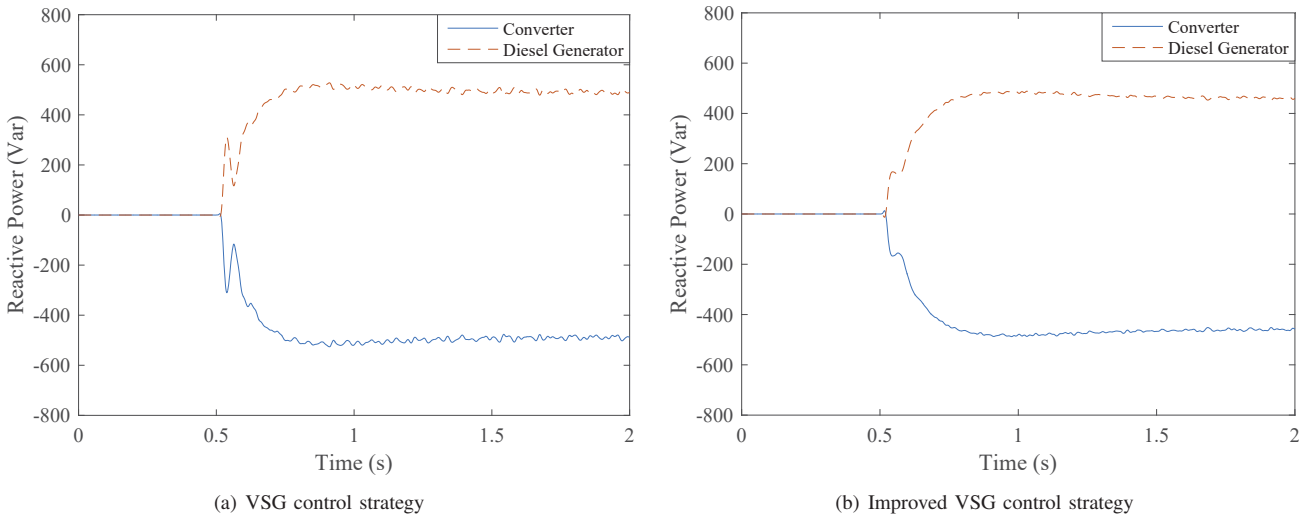


Fig. 5. Reactive power waveforms of converter and diesel generator

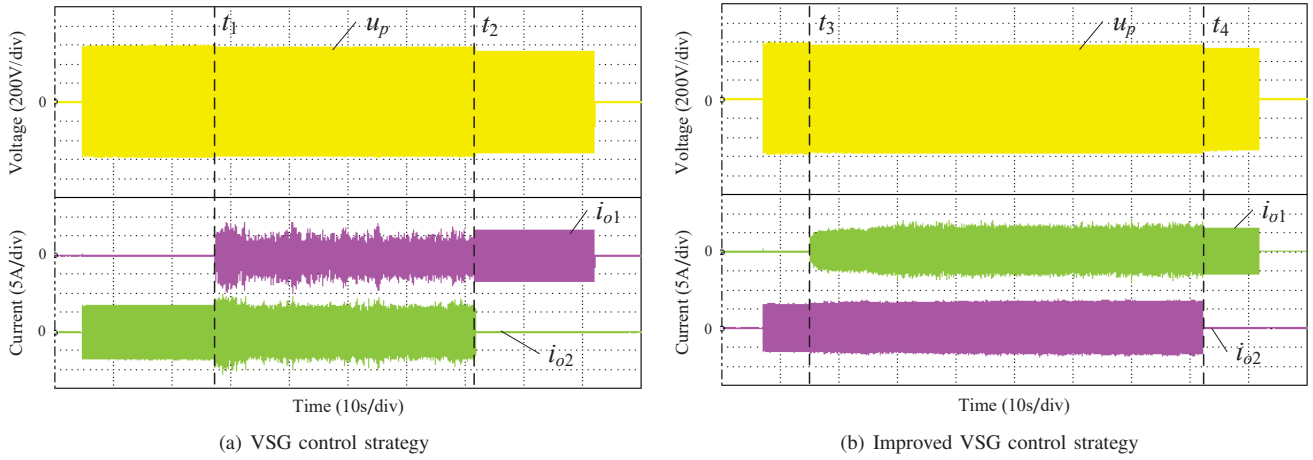


Fig. 6. Output voltage and output current waveforms of parallel system

strategy possesses the engine governor control link and steady-state droop characteristic, so its adjustment process of angular frequency can be similar to the diesel generator.

III. SIMULATION

A. Connection Model of Parallel System

The connection model of the parallel system is shown in Fig. 3. As shown in Fig. 3, the parallel system consists of the converter based on different parallel control strategies, the diesel generator, and the common load. L , C , L_n ($n = 1, 2$), and R_n ($n = 1, 2$) are the filter inductor, filter capacity, line reactance, and line resistance, respectively. The ratio of the transformer is 160/400, and the voltage level of the DC source is 400V.

B. Simulation Comparison

The active power waveforms and reactive power waveforms of converter based on different parallel control strategies and diesel generator are shown in Fig. 4 and Fig. 5, respectively. When the converter based on VSG control strategy and the diesel generator are in parallel at 0.5s, there are active power impact and reactive power impact in dynamic. When the converter based on improved VSG control strategy and the diesel generator are in parallel at 0.5s, the active power impact and reactive power in dynamic can be reduced greatly. And their active power fluctuations amplitude are smaller than half of the parallel system based on VSG control strategy. Because of there are large differences of the angular frequency characteristics between the VSG control strategy and diesel generator. And the differences of the angular frequency characteristics between the proposed VSG control strategy and diesel generator are smaller than former. Therefore, the dynamic characteristic and steady-state characteristic of the converter based on the proposed VSG control are better than VSG control strategy.

IV. EXPERIMENT

An experiment platform of the parallel system is established to further demonstrate the performance of the improved VSG control strategy. Its structure and values of the parameters are the same as those of the Fig. 3.

When the converter and the diesel generator are in parallel, the output voltage and output current waveforms of converter and diesel generator are shown in Fig. 6, including the voltage of point of common coupling (u_p), output current of the converter (i_{o1}), and output current of the diesel generator (i_{o2}). When the converter based on VSG control strategy and the diesel generator are in parallel at the t_1 , there is impact of output currents in dynamic, and there are fluctuations of output currents in steady state. When the parallel operation state is in steady state, the total harmonic distortion (THD) of u_p is around 3.47%. When the converter based on improved VSG control strategy and the diesel generator are in parallel at the t_3 , the impact of output currents in dynamic is smaller than former, and the fluctuations of output currents in steady state are also smaller than former. When the diesel generator is removed at the t_4 , there is no impact of u_p and output currents in dynamic. When the parallel operation state is in steady state, the THD of u_p is around 2.51%, which is still smaller than former.

V. CONCLUSION

Based on the VSG control strategy, this paper proposes an improved VSG control strategy to reduce the dynamic impact of the parallel system, and enhance its stability. It incorporates the speed controller, actuator, diesel engine models, and active power adjustment part into the VSG control strategy. Therefore, the $P - \omega$ characteristics of the converter based on the improved VSG control strategy can be similar to the diesel generator, and its degree of rigid can also be strengthened. Simulation results demonstrate that the dynamic characteristic and steady-state characteristic of the parallel system based on the improved VSG control strategy are better than the parallel

system based on the VSG control strategy. Experiment results further validate its excellent performance.

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