Study of the Current State of Research on Power Decoupling for Virtual Synchronous Generator

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Abstract. Virtual synchronous generator (VSG) is one of the key technologies in the context of energy transition. VSG can simulate the operation mechanism of a synchronous generator, so that the new clean energy power generation device can actively support the power grid, thus promoting the energy transition and improving the stability of the power grid. Firstly, the working principle of VSG is introduced, followed by clarifying the power coupling mechanism of VSG. Followed by stating the current popular power decoupling strategies, such as introducing voltage, current, or power compensation in the VSG control loop, decoupling methods based on virtual impedance and current compensation, and so on. After synthesising the different schemes, it is then pointed out that the different decoupling schemes have good performances under specific perspectives, but at the same time, they are limited by the conditions and have defects such as not being able to completely decouple and not being able to adapt to the situation under multiple machine connections. Finally, the research status of power decoupling of virtual synchronous machines is summarised, and the prospect of its research and future development is made.

Keywords: Virtual Synchronous Generator, Power Coupling, Power Decoupling

1 Introduction

With the gradual utilisation of renewable energy on a global scale, renewable energy sources such as wind and light based on power electronic equipment access to the grid are developing rapidly and the penetration rate is increasing [1]. At the same time, the power electronic conversion control method adopted in response to the use of new energy inputs essentially reduces the total rotational inertia of the power grid, making it less capable of supporting frequency and voltage changes. As a result, the new power system presents low inertia and low damping characteristics.

To cope with such situations, virtual synchronous technology as a solution was first proposed by Prof. K. Visscher's team at Katholieke Universiteit Leuven with Prof. Beck's team at the Technical University of Germany and Prof. Chung Ching-chang's team at the University of Schönfeld [2]. It enables PV paired with energy storage to cope with static fluctuations as well as transient disturbances in the grid through virtual synchronous generator (VSG) control. Therefore, virtual synchronous generator (VSG)

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technology, which simulates the operating characteristics of the synchronous generator (SG), has been widely used [3].

However, although VSG technology can effectively solve the low inertia and weak damping problems existing in modern power grids, there still inevitably exists a series of coupling problems. The power coupling problem inherent in the VSG control structure, i.e., the interactions between active and reactive control loops, will seriously limit the power delivery capability and grid support capability of VSGs [4]. At the same time, the coupling between power rings will not only affect the dynamic performance of the VSG itself but also deteriorate the power equalisation among multiple machines, triggering more system stability problems. Therefore, if there is coupling between powers, oscillations will be transmitted between active and reactive loops, leading to abnormal dynamic regulation processes or even oscillation dispersion problems [5].

The article reviews the current power decoupling strategies for virtual synchronous machines, analyses the power coupling mechanism, and introduces a summary of the relative power decoupling strategies and hotspots. Finally, it makes an outlook for the future with respect to the shortcomings of the current decoupling scheme, such as not being able to adapt to multi-unit systems and not being able to face non-constant currents.

2 VSG Control Principle and Coupling Mechanism Analysis

2.1 VSG working principle

The synchronous machine equivalent diagram is shown in Fig. 1. The virtual synchronous machine technique is the simulation of the external characteristics of a conventional synchronous generator, a so-called synchronous generator, which consists of two parts: the stator voltage equation and the rotor motion equation [6]. Thanks to the strong controllability of the inverter electronics, after the converter adopts the VSG control strategy, the distributed power supply is equipped with rotational inertia characteristics and damping characteristics, which improves the control characteristics of the system and improves the power grid stability greatly improved.

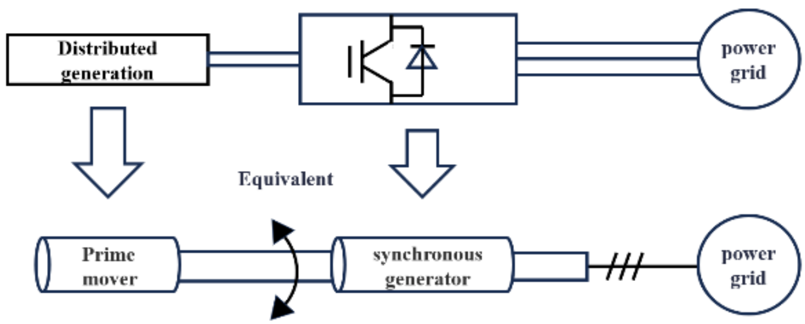

Fig. 1. Equivalent diagram of synchronizer [6]

2.2 Analysis of VSG coupling mechanism

The conventional VSG control approach assumes that the system impedance of each shunt inverter is purely inductive and the power approximation is considered to be decoupled. However, in practice, based on the working conditions of low or medium voltage levels (high R/X), the line has a large resistance-inductance ratio R/X, and the assumption of pure inductance is not reasonable [7]. At the same time, the variation of the power angle under large disturbances does not satisfy the assumption of a small power angle, when there is a coupling between active and reactive power [8]. Therefore, even if the line can be considered purely inductive under high-voltage (low R/X) conditions, the power angle will still fluctuate greatly if a large disturbance occurs, which leads to the power coupling problem [9].

The coupling between power loops not only affects the dynamic performance of the VSG itself but also worsens the power equalisation between multiple machines, which triggers more system stability problems. The team of Prof. YANG D S specified that the coupling between power loops may reduce the active power transfer limit, which threatens the transient stability. Moreover, VSG control adds virtual inertia on top of droop control, which also implies the introduction of an active power oscillation problem. Therefore, if there is coupling between the powers, the oscillations will be transmitted between the active and reactive loops, leading to an abnormal dynamic regulation process or even an oscillation dispersion problem [10]. It can be seen that the coupling problem of VSG control will bring serious consequences and needs to be focused on.

3 VSG Decoupling Strategy

3.1 Virtual impedance decoupling strategy

As in the low-voltage inverter, the coupling phenomenon of active and reactive power will exist. In order to weaken the impact of coupling on system stability, comprehensive consideration of the system voltage drop does not cause a burden, so that the impedance ratio and the power angle to meet the coupling degree of the minimum of these two aspects, some scholars have creatively proposed a series virtual impedance method [11]. The core lies in the introduction of a current feedback link in the voltage and current double closed-loop control, using the voltage drop generated by the current in the virtual impedance to correct the VSG output voltage, so that the equivalent output impedance of the VSG is inductive [12]. The specific principle is shown in Fig. 2.

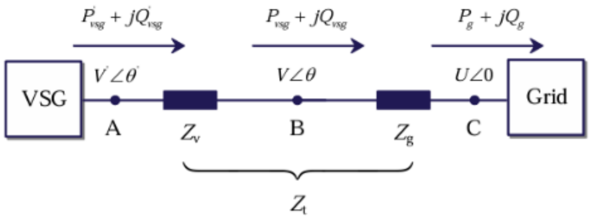

Fig. 2. Equivalent circuit of VSG grid connected after adding virtual impedance [11]

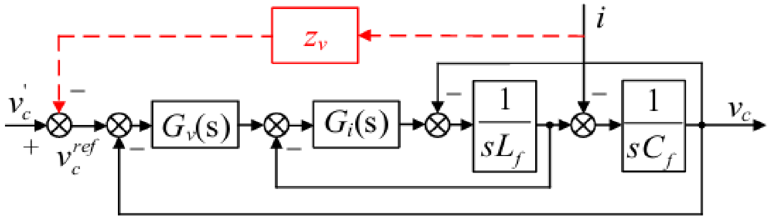

Fig. 3 Equivalent control model of VSG after adding virtual negative impedance [12]

The superiority of this method lies in its more intuitive effect, as shown in the equivalent model in Fig. 3. By connecting a virtual resistor in series at the output of the VSG, the equivalent output impedance of the VSG is approximated to be purely resistive. However, this method also has unavoidable defects. By using the VSG output voltage to control the active output and the frequency to control the reactive output, although the independent control of active and reactive power is realised from the control level, it is contrary to the P-f and Q-V sag control relationship of SG [12]. The second is the virtual negative resistance decoupling method, which is centered on offsetting the resistive component of the line impedance and increasing the percentage of the inductive component in the output impedance so that the VSG equivalent output impedance angle is close to 90°. However, the phenomenon of system impedance drift exists, and the value of the virtual negative resistance requires high accuracy of the system parameters, which will affect the transient stability of the system when the corrected system output impedance is located in the second quadrant [13].

When the virtual inductor is used, since it only affects the reactive power output, the apparent power can be reduced and the output voltage can be increased without affecting the active ring. While the real inductor can effectively inhibit the coupling of the power ring, it not only changes the line current when regulating the power output but also consumes a large amount of reactive power itself, increasing the reactive power deficit of the system [14]. In summary, there are power differences between the virtual inductor and the real inductor on the line, and these differences are a test for the design of the inverter capacity requirements, and the decoupling effect is not the same. The power coupling will also be affected by the power angle change, simply only from the perspective of improving the inductive component of the output impedance, increasing the value of the virtual inductance, will lead to a significant decrease in the output voltage, on the contrary, will affect the decoupling performance [15]. So the design of virtual inductor parameters is particularly important.

3.2 Voltage compensation strategy

Voltage-based feed-forward compensation belongs to the direct decoupling control, which is generally based on the relative gain method, for the decoupling of two-input and two-output systems. The larger the relative gain value is, the stronger the coupling between the corresponding inputs and outputs is, and vice versa, the weaker the coupling is. The idea of voltage-based feedforward compensation is to achieve pairing of strongly coupled channels and decoupling of weakly coupled channels through voltage compensation [16].

The method is based on the premise that the grid voltage V is kept constant, and aims to analyse the coupling relationship among the four variables P, V, Q, and δ. By changing the control algorithm, the coupled system with two inputs and two outputs will be simplified into an independent decoupled system with two single-input and single-outputs, and the principle is shown in Fig. 4.

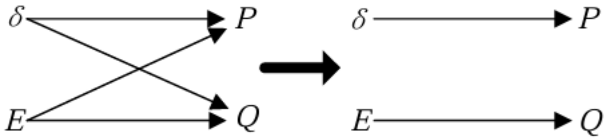

Fig. 4 Coupling and decoupling diagram of two-input and two-output system [16]

The feed-forward compensation method is precisely based on the relative gain matrix analysis method as a background, which determines the strength of the coupling by the magnitude of the relative gain coefficients and pairs the strongly coupled channels for variable matching, and the weakly coupled channels for pairing after adding the decoupling control [17].

The superiority of this method lies in the fact that, at the control level, only one output channel is retained by harmonic linearisation analysis at a set equilibrium point and the other channels are output clamped to 0, thus inverting the feed-forward compensation term, thus achieving independent decoupling control of the VSG.

However, it is worth noting that the method is essentially a local static decoupling after linearisation at the equilibrium point, and the fixed feedforward coefficients dictate that it is only applicable to a certain steady-state operating moment [18]. When the VSG changes for a given input due to small perturbations, the decoupling effect is debatable and still ignores the effect of power angle on power coupling.

3.3 Coordinate transformation control based on virtual active and reactive power

The virtual power method is mainly used to solve the coupling problem of inductive lines. By introducing the impedance transformation matrix and transforming the coordinates, the output active power and reactive power can be transformed into virtual active power and virtual reactive power by the coordinate transformation, so as to realise the one-to-one correspondence between the virtual active power and the power angle, the virtual reactive power and the voltage, and thus realize the decoupling [19]. The decoupling method based on coordinate rotation can avoid the control failure caused by coupling. The principle is shown in Fig. 5(a).

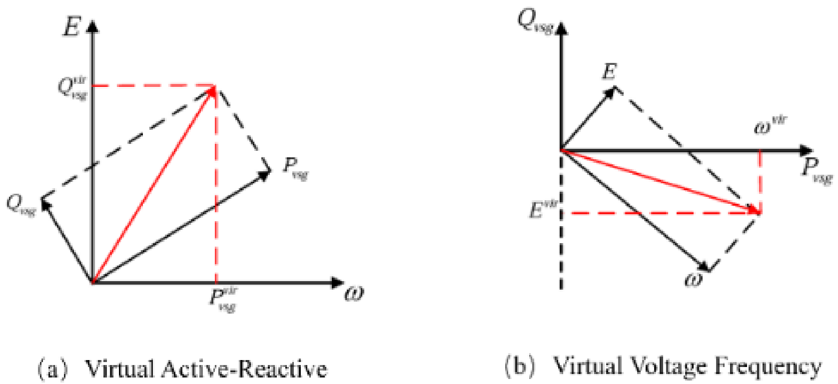

Fig. 5 Schematic diagram of power decoupling based on coordinate transformation [19]

The advantage of this approach is that the balance of the output power after being perturbed is guaranteed algebraically.

The limitation lies in the fact that the reactive power output is simultaneously affected by the impedance amplitude, and the equal division of active and reactive power is not realised in the real system so the power coupling cannot be eliminated essentially. The decoupling method based on virtual voltage-frequency coordinate transformation, as shown in 2.3.1 (b), is similar to that based on virtual power, with the difference that the amount of regulation is transformed to constrain the sag coefficients in real-time by adjusting the virtual voltage and virtual frequency [20]. In addition, the two methods of coordinate transformation only consider the impedance angle but ignore the effect of the power angle. When the VSG is connected to a low-voltage network with a relatively large impedance angle, the control method will be changed from P-f and Q-V to P-V and Q-f [21]. This not only weakens the grid support but also does not take into account other factors that cause power coupling.

4 Conclusion

In this paper, the VSG power coupling mechanism is investigated and analysed in detail, and three popular VSG power decoupling strategies are presented through a literature review: virtual impedance decoupling strategy, voltage compensation strategy, and coordinate transformation control based on virtual active and reactive power. The current VSG decoupling schemes still have various problems, such as not being able to fully decouple, and not being able to consider cases involving a single grid-connected converter-synchronous generator in parallel or multiple grid-connected converters connected to a large power grid.

At the same time, the over-idealised conditions in the study also lead to unsatisfactory decoupling results in actual operation. As for the future direction, regarding the practical application of VSGs, it should be considered that in the case of multi-generator paralleling systems, the mechanism of multi-generator paralleling oscillations and the connection between the overall system stability and the grid stability need to be further investigated, and on the basis of this research, a more reliable control strategy should be designed.

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