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Techno-Economic Analysis of Motor-Generator Pair System and Virtual Synchronous Generator for Providing Inertia of Power System

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Abstract**—**With the increasing of the penetration of renewable energy in power system, the whole inertia of the power system is declining, which will endanger the frequency stability of the power system. In order to enhance the inertia, virtual synchronous generator (VSG) has been proposed. In addition, the motor-generator pair (MGP) system is proposed to enhance grid inertia. Both of them need additional equipment to provide instantaneous energy, so the economic problem should be considered. In this paper, the basic working principle of MGP system and VSG are introduced firstly. Then, the technical characteristics and economic investment of MGP/VSG are compared by calculation and simulation. The results show that the MGP system can provide same inertia with less cost than VSG.

Keywords**—**High renewable energy penetration, inertia of power system, virtual synchronous generator, motor-generator pair system, techno-economic analysis.

I. INTRODUCTION

IN order to protect the global environment, reducing the proportion of fossil energy and improving the proportion of renewable energy power generation is the future development trend of power system [1]. However, the rapid development of renewable energy also brings a lot of challenges. Renewable energy power generation is generally integrated into the grid by power electronic inverters. Compared with traditional grid-connected methods (such as thermal power units), this approach has the characteristics of flexible and rapid response in control, but also has the deficiencies of non-linear and lack of inertia. With the increasing penetration of renewable energy power generation, there will be a large number of grid-integrated power electronic inverters in the power system. In contrast, the proportion of traditional synchronous generators will be reduced, which will reduce the rotation reserve capacity of power system and the rotational inertia, thereby endangering the frequency stability of power system [2].

For the purpose coping with the impact and challenges from renewable power generation, lots of corresponding improved methods for the inverters interface control methods have been researched [3]. Aiming at mimicking frequency regulation ability to support grid stability provided by synchronous generator, the virtual inertial control strategy has been proposed [4]. Reference [5] proposed VSG program and modeled the outer characteristics of the synchronous generator swing equation. Reference [6] proposed virtual synchronous motor (virtual synchronous machine, VISMA) technology can reflect the characteristics of inertia synchronous generator to provide frequency support for the system better. Sintai et al. and Alipoor et al. proposed VSG control based on synchronous generator electromechanical transient model, mimic synchronous generator rotor inertia frequency regulation characteristics in active power-frequency control, and output voltage stability characteristics in reactive power - voltage control [7], [8]. Considering both of the electromechanical transient and electromagnetic transient characteristics of synchronous generators, Zhong et al. proposed synchronverter based on the AC side of the dynamic model of synchronous generator, which achieved an equivalent of synchronous generator and inverter in the physical and mathematical models and self-synchronous operation of VSG [9].

The existing improvements are all focus on the control strategy of inverter. Reference [10], [11] proposed a new idea to improve the inertia when renewable energy is connected to power grid by using MGP system. The inverter is not directly connected to the grid, but in the form of inverter-synchronous motor-synchronous generator. This method can take advantage of the inherent inertia of synchronous generators to enhance the inertia of renewable energy and the control system of synchronous generator can completely follow the existing synchronous generators of thermal power units, which can greatly enhance the security of power system and reduce the impact to grid from renewable energy.

The instantaneous frequency response needs instantaneous energy. For MGP system, the energy release corresponds to the change of the rotor kinetic energy when the rotor speed changes. For VSG, the energy storage is needed, such as chemical batteries. Therefore, both of the two methods need to add additional equipment in the power grid for providing inertia, which will increase the investment cost.

In this paper, the basic working principle of MGP system and the inertia size it can provide are introduced firstly. Then, the influence of inertia parameter adjustment on VSG's control system is analyzed, and the inertia range that VSG can provide is analyzed. On the basis of the above analysis, a 50-MW grid-integrated system is taken as an example to calculate and

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compare the cost of VSG and MGP system to provide the same inertia. Then, a 30-kW grid-integrated system is simulated, and the frequency response process of MGP and VSG is compared under the condition of setting the same inertia parameters. Finally, the results show that the MGP system can provide same inertia with less cost than VSG, and MGP system can maintain the frequency stability of the power grid more than VSG with the same inertia parameters.

II. About Inertia

The inertia of the synchronous generator can be expressed by the moment of inertia J or the inertia time constant H. The inverters do not contain direct moment of inertia J, so inertia time constant H is used to express inertia of renewable energy.

For synchronous generators, the rotor kinetic energy W_{M} is

$$W_{\mathrm{M}}=\frac{1}{2}J_{\mathrm{M}}\omega_{\mathrm{n}}^{2} \tag{1}$$

where J_{M} is the rotor moment of inertia, ω_{n} is the motor speed, ignoring the motor pole pairs, the default is one pair of poles.

The inertia time constant of the synchronous generator can be expressed as a unitary form H:

$$H_{\mathrm{M}}=\frac{W_{\mathrm{M}}}{S_{\mathrm{Ng}}} \tag{2}$$

where S_{Ng} is the rated capacity of synchronous generator. For renewable energy, its inertia derives from the energy storage of the $\mathrm{D_C}$ side capacitor of the inverter. The inertia time constant of the inverter H_{C} is:

$$H_{\mathrm{C}}=\frac{\frac{1}{2}CU_{\mathrm{C}}^{2}}{S_{\mathrm{Ni}}} \tag{3}$$

where C is the inverter DC side capacitor, U_{C} is the inverter DC side voltage in the general range of 450-800 V, S_{Nij} is the rated capacity of renewable energy. For the renewable energy electric field which is formed by the parallel combination of j units, the inertia time constant H_{C}' is:

$$H_{\mathrm{C}}'=\frac{\frac{1}{2}\sum C_{j}U_{\mathrm{C}_{j}}^{2}}{\sum S_{\mathrm{Nij}}}=\frac{\sum H_{\mathrm{j}}S_{\mathrm{Nij}}}{\sum S_{\mathrm{Nij}}}=\frac{\sum H_{\mathrm{j}}}{\mathrm{j}} \tag{4}$$

For identical wind turbines, there is HC'=HC.

Assuming that the inertia time constant HM of a 900 MW synchronous generator is 6.5 s [12]. For a 900 MW wind farm consisting of 450 sets of 2 MW wind turbines, taking U_{C}'s mean value 625 V and C = 0.1 F, the inertia time constant HC' of the 900 MW wind field is 0.016 s, and the H_{M} / H_{C}'= 406.25. In this case, the large-scale access of the wind turbine to the power system will reduce the inertia of power system greatly.

III. Introduction of MGP System

The principle of MGP system is shown in Fig. 1. At the out terminal of the renewable energy electric field, a set of motor pairs consisting of synchronous motors and synchronous generators is added, and then integrated to the power system. Considering the capacity of renewable energy electric field is usually up to megawatt level, ordinary DC motor and induction motor are difficult to achieve this capacity, and the existing capacity of synchronous generators can reach hundreds of megawatts, so the generator and motor are both designed to use synchronous machines.

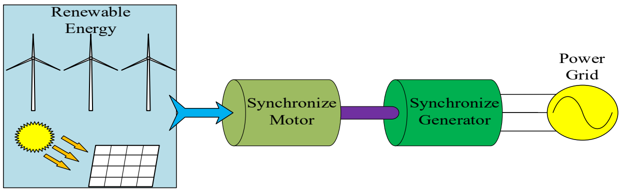

Fig. 1 Principle of MGP

For the MGP system, its inertia is determined by its rotor mass and speed. When the MGP system is deployed, its inertia can be approximated as a constant, and its inertia size is approximately 65% of the same capacity thermal power unit [12]. It is assumed that, for the set of 50 MW thermal power units with H=6.5 s, then inertia time constant of the corresponding MGP system can be calculated as 3.9 s. Assuming that the system is operating at 50 Hz, the MGP system can provide a J of 3951 kgm^2 get by (1) (2).

IV. Analysis of the Influence of Inertia Control Parameters on the Stability of VSG Control System

The equivalent diagram of VSG is shown in Fig. 2.

VSG's virtual speed equation (rotor motion equation) can be obtained from [13].

$$\begin{cases}\dfrac{\mathrm{d}\delta}{\mathrm{d}t}=\omega_{\mathrm{m}}-\omega_{0}=\Delta\omega_{\mathrm{m}}=\omega_{0}\Delta\omega_{m}\\ \dfrac{2H}{\omega_{\mathrm{n}}}\dfrac{\mathrm{d}^{2}\delta}{\mathrm{d}t^{2}}=P_{\mathrm{ref}}-P_{\mathrm{e}}-K_{D}\Delta\omega_{m}\end{cases} \tag{5}$$

All of the parameters are per unitary values, where δ: the virtual power angle of VSG. ω_{m}: the virtual angular frequency of VSG. ω_{n}: rated angular frequency. $\Delta\omega_{\mathrm{m}}$: difference between ω_{m} and $\omega_{\mathrm{n.}}$ P_{ref}: VSG power setting reference value. P_e: VSG output power. K_{D}: damping coefficient

Then, the transfer function block diagram of VSG can be obtained from (5) as shown in Fig. 3.

And the linearized state equations of MGP represented by $\Delta\omega$ and $\Delta\delta_{\mathrm{G}}$ can be written as,

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\Delta\omega_{\mathrm{m}}\\ \Delta\delta\end{bmatrix}=A\begin{bmatrix}\Delta\omega_{\mathrm{m}}\\ \Delta\delta\end{bmatrix}+\begin{bmatrix}\dfrac{1}{2H}\\ 0\end{bmatrix}\Delta P_{\mathrm{m}} \tag{6}$$

where

$$A=\begin{bmatrix} -\frac{K_D}{2H} & -\frac{K_S}{2H} \\ \omega_0 & 0 \end{bmatrix} \tag{7}$$

K_S is synchronizing torque coefficient. The working state of VSG should be taken into account to get KS.

The filter circuit impedance of VSG is

$$\begin{cases} Z=\sqrt{(\omega L)^2+R^2} \\ \alpha=\arctan(\frac{\omega L}{R}) \end{cases} \tag{8}$$

The output active power could be expressed as

$$\begin{cases} P=\frac{EU}{Z}\cos(\alpha-\delta)-\frac{U^2}{Z}\cos\alpha \\ Q=\frac{EU}{Z}\sin(\alpha-\delta)-\frac{U^2}{Z}\sin\alpha \end{cases} \tag{9}$$

Then the steady-state potential E_S and the initial power angle δ_0 could be get as

$$\begin{cases} \delta_0=\alpha-\arctan(\frac{ZQ_{ref}+U^2\sin\alpha}{ZP_{ref}+U^2\cos\alpha}) \\ E_S=\frac{ZQ_{ref}+U^2\sin\alpha}{U\sin(\alpha-\delta_0)} \end{cases} \tag{10}$$

and K_S could be get as

$$K_S=\frac{\partial P_e}{\partial\delta}=\frac{E_S U}{ZS_B}\sin(\delta_0-\alpha) \tag{11}$$

It can be seen from Fig. 3, VSG is a typical second-order system, and the closed-loop transfer function of P_e/P_{ref} can be expressed as:

$$G(s)=\frac{P_e}{P_{\text{ref}}}=\frac{\omega_0 K_S}{2Hs^2+K_D s+\omega_0 K_S}=\frac{\omega_n^2}{s^2+\zeta\omega_n s+\omega_n^2} \tag{12}$$

The natural angular frequency ω_n and damping ratio ζ is

$$\begin{cases} \omega_n=\sqrt{\frac{\omega_0 K_S}{2H}} \\ \zeta=\frac{K_D}{2\sqrt{2H\omega_0 K_S}} \end{cases} \tag{13}$$

Considering the actual situation of the system, the damping ratio is supposed to be 0-1, i.e. the underdamped systems. Then, the eigenvalues of A are:

$$\lambda_{1,2}=-(\zeta\pm j\sqrt{1-\zeta^2})\omega_n \tag{14}$$

A 50-MW example is analyzed to investigate the influence of inertia parameter adjustment on VSG's control system， where VSG rated power is 50 MVA, filter inductance L=1 mH, R=2.4 Ω, grid voltage is 35 kV, power frequency is 50 Hz, and the initial value of connected power is 5 MW, 0 Var.

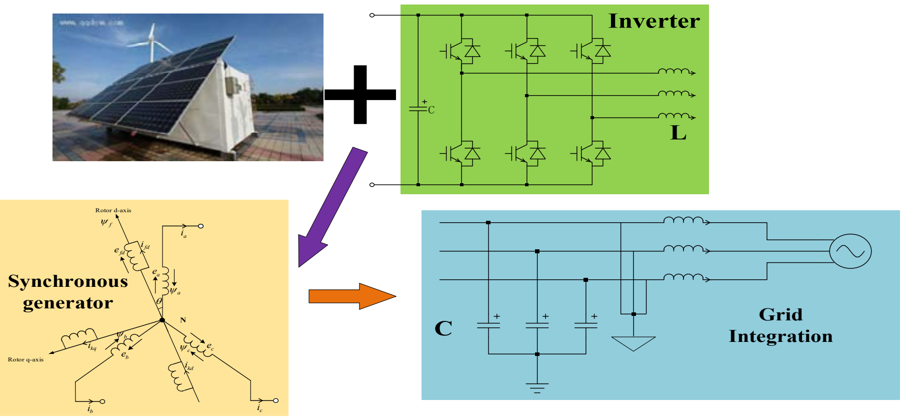

Fig. 2 Virtual synchronous machine equivalent diagram

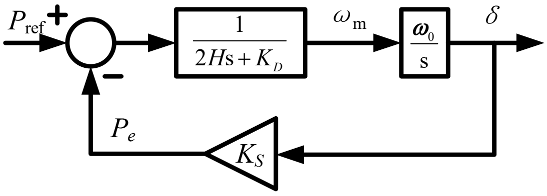

Fig. 3 Transfer function block diagram of the VSG

Fig. 4 is the root locus of the characteristic equation as H is set from 0.02 s to 5 s. It can be seen from Fig. 4, with the increase of H_{VSG}, the eigenvalues move closer to the origin. Although the system is always in a stable area, but with the increase in H_{VSG}, it gradually becomes unstable. Therefore, the H_{VSG} cannot be set arbitrarily to a very large value.

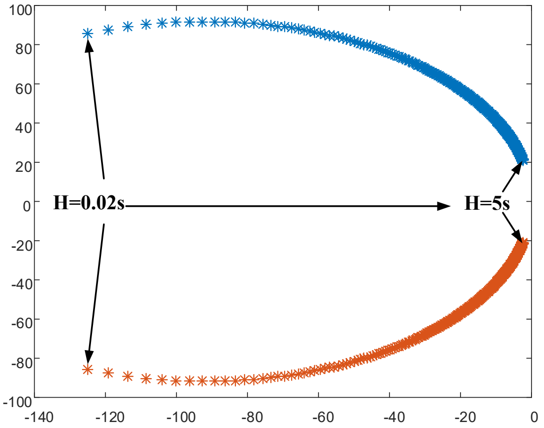

Fig. 4 Root locus of the VSG characteristic equation

V. INERTIA COMPARISON OF MGP AND VSG

A. Equivalent Moment of Inertia Comparison with the Same Capacity of VSG and MGP

Analyzing the impact of H_{VSG} for VSG by (13), (14), the results are shown in Fig. 5. (a) VSG control system damping ratio (ξ) set in different H_{VSG}. (b) The capacity of VSG needed to achieve the same moment of inertia (J) set in different H_{VSG}.

As shown in Fig. 5, H_{VSG} cannot be set too large (the damping ratio is too small), nor too small (VSG cannot provide enough virtual inertia), According to the response characteristics of the second-order system, ζ=0.707 is the optimum damping ratio, where H_{VSG} is about 0.027 s. Then, the equivalent moment of inertia can be got as 27.35 kgm^2 by (1), (2). This value is much smaller than that of the MGP system with same capacity. If H_{VSG} is forced to set as 3.9 s, the 50-MW virtual synchronous machine can also provide 3951 kgm^2 equivalent moment of inertia under the condition of sacrificing the stability of VSG's control system.

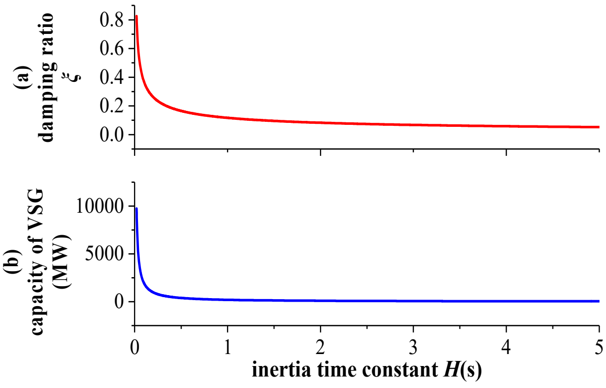

Fig. 5 Impact of H on VSG

B. Investment Comparison of VSG and MGP for Providing the Same Inertia

We compare the MGP system's electrical machines investment and VSG's energy storage investment with the 50 MW system.

MGP: The price of 50 MW synchronous machine is about $725 thousand, and a pair of machines cost $1.45 million. The excitation system and related control system costing $300 thousand and the supporting plant investment is nearly $1.25 million, then the total investment is about $3 million.

VSG: The general storage power station requires the energy storage system to maintain a minimum of four hours of discharge time, so an energy storage power station of 50 MW should have at least 200 MWh of energy. Comparison of various energy storage batteries shows that the price of liquid flow battery is relatively low [14]. The investment of 200MWh flow battery is about $ 30 million, which is 10 times as more as that of MGP system.

Based on the above results, it is considered that the MGP system has less investment in the condition of providing the same inertia.

C. Effect Comparison of Providing Inertia

In this section, the inertia lifting effect of VSG and MGP is compared by simulation.

Simulation system: As shown in Fig. 6, a 380 V/30 kW system, including a rated capacity of 30 kW small renewable energy power station, accesses to the distribution network by VSG/MGP. The distribution network is formed by 0.1-mH reactance and a 380-V voltage source which represent the transmission line and the infinite power grid respectively.

MGP system: Considering the inertia time constant as 0.5s, set J=0.3 kgm^2, the other main parameters of the synchronous machines are shown in Table I.

TABLE I
PART OF THE MACHINE PARAMETERS IN SIMULATION MODEL

machine parameter	Value (p.u.)	machine parameter	Value (p.u.)
r_s	0.003	r_f	0.0006
X_{sl}	0.13	X_{fl}	0.076
X_d	2.04	L_{dl}	0.229
X_q	1.93	L_{ql}	0.0812

VSG: set H=0.5 s, damping coefficient K_D=15, set filter inductance L=0.7 mH, filter capacitor C=15 μF.

Simulation process: At the beginning of the simulation, the renewable energy station output is 30 kW. When t=1 s, the part of the renewable energy is faulty, and the response of the MGP system and the virtual synchronous machine is observed when the power generation drops from 30 kW to 20 kW.

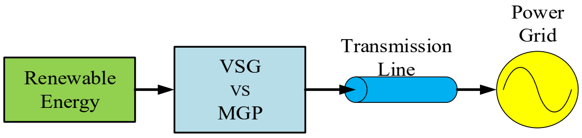

Fig. 6 Simulation model

Simulation results: The simulation results are shown in Fig. 7, where P_R is the active power of the renewable energy station detected by the VSG/MGP out terminal and f_R represents the voltage frequency of the VSG/MGP out terminal. When the new energy to the power grid issued by the active power to produces a drop, f_R also decreased. Despite MGP and VSG set the same inertial parameters, the peak of the frequency drop is smaller, and the power change process is more stable in the MGP system. Thus, the results show that the MGP system can reduce the frequency change and maintain the frequency stability of the system better than VSG.

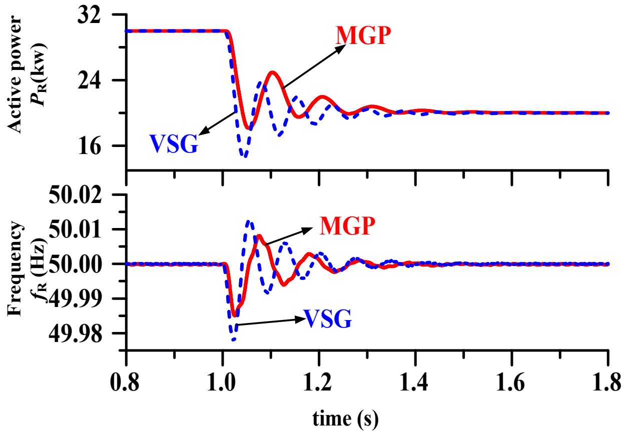

Fig. 7 Simulation result

REFERENCES

[1] Lasseter, R. H. "Microgrids and distributed generation". *Journal of Energy Engineering*, *133*(3), 2007, pp:144-149.

[2] Heydt, Gerald Thomas. "The next generation of power distribution systems." *IEEE Transactions on Smart Grid*, 1(3), 2010, pp: 225-235.

[3] Soni, Nimish, Suryanarayana Doolla, and Mukul C. Chandorkar. "Improvement of transient response in microgrids using virtual inertia." *IEEE Transactions on Power Delivery*, 28(3), 2 013, pp: 1830-1838.

[4] Xiang-Zhen, Yang. "Control strategy for virtual synchronous generator in microgrid." *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011 4th International Conference on*. IEEE, 2011.

[5] Visscher, K., and S. W. H. De Haan. "Virtual synchronous machines (VSG's) for frequency stabilisation in future grids with a significant share of decentralized generation." *CIRED Seminar 2008: SmartGrids for Distribution*. 2008.

[6] Beck, Hans-Peter, and Ralf Hesse. "Virtual synchronous machine." *2007 9th International Conference on Electrical Power Quality and Utilisation*. IEEE, 2007.

[7] Shintai, Toshinobu, Yushi Miura, and Toshifumi Ise. "Oscillation damping of a distributed generator using a virtual synchronous generator." *IEEE Transactions on Power Delivery*, 29(2), 2014, pp: 668-676.

[8] Alipoor, Jaber, Yushi Miura, and Toshifumi Ise. "Power system stabilization using virtual synchronous generator with alternating moment of inertia." *IEEE Journal of Emerging and Selected Topics in Power Electronics* 3.2 (2015): 451-458.

[9] Zhong, Qing-Chang, and George Weiss. "Synchronverters: Inverters that mimic synchronous generators." IEEE Transactions on Industrial Electronics,58 (4), 2011, pp: 1259-1267.

[10] Y. Z. Huang and S. M. Wei, "Grid-connection system of high penetration renewable energies and control methods of stability," Chinese Patent 201510695496.3, Jan. 2016.

[11] Wei Siming Zhou Yingkun, Li Song and Huang Yongzhang. "A possible configuration with motor-generator pair for renewable energy integration." CSEE Journal of Power and Energy Systems3.1 (2017): 93-100.

[12] Kundur, Prabha. *Power system stability and control*. Eds. Neal J. Balu, and Mark G. Lauby. Vol. 7. New York: McGraw-hill, 1994.

[13] Zeng Zheng, Shao Weihua, Ran Li. "Mathematical model and strategic energy storage selection of virtual synchronous generators." *Automation of Electric Power Systems*, 2015, 39(13):22-31(in Chinese).

[14] Soloveichik, Grigorii L. "Battery technologies for large-scale stationary energy storage." *Annual review of chemical and biomolecular engineering* 2 (2011): 503-527.

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