Transient stability analysis of one special type of AC microgrids with a gas reciprocating generator unit

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Abstract: More and more gas reciprocating generator units are integrated into offshore platforms, due to their compact structure and high efficiency. This paper concentrates on the transient stability analysis of one special type of AC microgrids containing a gas reciprocating generator unit. Firstly, the operation principle for the gas reciprocating generator unit is presented, which mainly consists of a reciprocating internal combustion engine and a linear synchronous alternator (LSA). Afterwards, the mathematical model for the core part of the gas reciprocating generator unit LSA is proposed, based on the principle of armature reaction in traditional synchronous and asynchronous machines. Finally, the simplified model of the independent offshore power system with a gas reciprocating generator unit is derived, and numerical simulations on the transient stability of this typical AC microgrid are performed, from which the effectiveness and correctness of the LSA model are validated. The transient stability analysis method of the independent offshore power system and the mathematical model of LSA can provide beneficial guidance for the stable operation of other types of stand-alone AC microgrids.

1 Introduction

In recent years, energy problems have become increasingly serious, and more and more oil and natural gas are needed. Building an offshore oil and gas platform has become an important means to solve the current energy crisis because of the rich reserves of oil and gas in the ocean. However, the offshore platform power system is different from the land platform, mainly due to the small capacity of the system, requirement of higher voltage stability, and close electrical connections among the system owing to the short power transmission line, which greatly reduces the probability of power angle instability. At the same time, more and more gas reciprocating generator units are integrated into offshore platforms, due to their compact structure and high efficiency.

However, the existing researches at home and abroad mainly focus on the models of traditional synchronous generator units and their transient characteristics, with few researches focusing on the models of gas reciprocating generator units. Therefore, it is essential to conduct the transient stability analysis of independent offshore power systems with a gas reciprocating generator unit, so as to ensure safe and reliable operation of offshore platforms.

A gas reciprocating generator unit is a kind of linear machine, about which there are many models, but lacking an electromechanical transient model suitable for analysing the transient stability of the power system. In [1–3], the magnetic linkage equations, voltage equations, and electromagnetic force (EMF) equation of permanent magnet synchronous linear machine are derived in detail. However, the control system of the above linear generator model is different from the gas reciprocating generator unit studied in this paper. In the meanwhile, all the models above are electromechanical transient models, which cannot be directly used in electromechanical transient analysis. According to the theory of electromagnetic field, reference [4] deduced the finite element model of a linear motor and a linear generator, which is mainly used in the design of linear machine, rather than the stability analysis of the power system. Shankar and Mukherjee [5] mainly analyses the tracking performance of microturbines in the islanded and grid-connected operation modes, respectively, in the face of a sudden increase of the step load, which provides a reference for the transient stability of the power system when the motor load with the maximum capacity is removed due to failure in this paper.

Meanwhile, the analysis of the transient stability of the existing literature and monographs is mainly aimed at the standard test system and interconnected or regional power systems at a large scale [6–9], with few researches on the transient stability of an independent offshore power system, not to mention the transient stability analysis of the sudden load reduction. Liu [10] studies the transient stability of the interconnection platform of three oil and gas fields using the time-domain simulation method under the three-phase short circuit. Liu [11] uses the neural network method to analyse the transient stability of the ship-independent power system under a typical short circuit fault, mainly aiming at the power angle stability of the system under the static load model. The models of a generator, an excitation system, a prime motor, and a static and dynamic load were established in [12]. Then transient stability of a ship-independent power system was analysed under the three-phase short circuit. The transient stability of the offshore oil platform under the three-phase short circuit fault was studied in [13].

This paper presents a method for analysing the transient stability of an independent offshore power system with a gas reciprocating generator unit, including the establishment of the model of a linear synchronous alternator (LSA) and a transient stability analysis method of independent offshore power systems, and the effectiveness of the proposed method is verified.

The remaining of this paper is organised as follows. In Section 2, the operation principle for the gas reciprocating generator unit is introduced in detail and compared with the traditional machine. In Section 3, the model of LSA is strictly deduced based on the principle of armature reaction in traditional synchronous and asynchronous machines, preparing for the analysis of the whole system’s transient stability. In Section 4, a complete model of the independent offshore power system is established and its transient stability is analysed by numerical simulation. Finally, the conclusion of the paper is summarised in Section 5.
2 Operation principle of a gas reciprocating generator unit

2.1 Composition of a gas reciprocating generator unit

The traditional synchronous generator unit is mainly composed of two parts: the prime motor and the generator. The prime motor is a steam turbine or a water turbine, and the generator is a rotary synchronous alternator (RSA).

Similarly, the gas reciprocating generator unit can also be regarded as consisting of a prime motor and a generator. However, the prime motor is no longer a steam turbine or a water turbine but a reciprocating internal combustion engine, which is composed of a gas engine (GE) and a reciprocating compressor, and the generator is no longer an RSA but an LSA.

2.2 LSA

The LSA is a kind of linear machine. A linear machine can be viewed as a developed rotary machine. Taking the plate linear machine as an example, it can be obtained by splitting the machine along the radial and then expanding it into a plane, of which the stationary part is called the stator, while the moving part is called the mover.

There are many kinds of linear machines. The LSA studied in this paper is of a bilateral mover, which is longer than the stator. Moreover, the LSA has a similar structure to a permanent magnet reciprocating linear generator, the structure of which is shown in Fig. 1.

2.3 Operation principle of a gas reciprocating generator unit

The GE and reciprocating compressor are connected by the crankshaft and a link system, as shown in Fig. 2, and provide a sinusoidal driving force for the mover of the LSA as a prime motor.

The reciprocating compressor turns the crankshaft rotary motion of the GE into the reciprocating motion of the piston through the crankshaft and the link system, and the piston is connected to the shaft of the LSA’s mover, so as to drive the mover to move sine-reciprocally between the air gaps at the similar frequency with the prime motor. Assuming that the mover is static, the stator windings move sine-reciprocally relative to the mover in the magnetic field, cutting the magnetic force line to generate the induction EMF. When the generator is connected to the load, the sinusoidal alternating current is generated to drive the load.

In summary, a linear generator unit generates sinusoidal inductive EMF through the sinusoidal reciprocating motion of the mover, while the traditional synchronous generator unit generates sinusoidal inductive EMF through the sinusoidal variation of the magnetic flux density.

3 Modelling of an LSA

3.1 Derivation of an LSA model

3.1.1 Model hypothesis: (a) It is assumed that three-phase windings of the stator are star connected and fully symmetrical. (b) The model ignores the influence of core saturation, eddy current, hysteresis loss, and end effect on the machine parameters. (c) It is assumed that the magnetic field produced by the permanent magnet of the mover is sinusoidal between the air gaps.

3.1.2 Reference direction of physical quantities and Park’s transformation: The reference direction of voltage, current, and magnetic axis is determined according to the generator practice, that is, the positive direction of the stator three-phase windings’ magnetic axis is opposite to the direction of the magnetic flux generated by the forward current of each winding, while the positive direction of the equivalent excitation winding’s magnetic axis of the mover is the same as the direction of the magnetic flux generated by the forward current of the equivalent excitation winding. At the same time, the determination of the d- and q-axes is the same as that of RSA, and the directions of each winding's magnetic linkage are consistent with the positive directions of the corresponding magnetic axis.

Suppose that \( \theta \) is the angle between the \( d \)-axis and the \( a \)-axis when the mover is at ‘X’. Then Park’s transformation can be written as

\[
P(\theta) = \begin{bmatrix}
\cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\
\sin \theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\
1/2 & 1/2 & 1/2
\end{bmatrix}
\]

Its inverse transformation is as follows:

\[
P^{-1}(\theta) = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin(\theta - 2\pi/3) & \cos(\theta - 2\pi/3) & 0 \\
\sin(\theta + 2\pi/3) & \cos(\theta + 2\pi/3) & 0
\end{bmatrix}
\]

3.1.3 Equations of the stator’s magnetic linkage: In the selected reference direction, the magnetic linkage equations of the stator three-phase windings and the excitation winding are as follows:

\[
\begin{align*}
\varphi_a &= M_{ad}(x) i_a + M_{ab}(x) i_b + M_{ac}(x) i_c \\
\varphi_b &= M_{bd}(x) i_a + M_{ba}(x) i_b + M_{bc}(x) i_c \\
\varphi_c &= M_{cd}(x) i_a + M_{cb}(x) i_b + M_{cc}(x) i_c \\
\varphi_f &= L_{f}(x) i_f + M_{fa}(x) i_a + M_{fb}(x) i_b + M_{fc}(x) i_c
\end{align*}
\]

where \( \varphi_a, \varphi_b, \) and \( \varphi_c \) are the magnetic linkages of the stator \( a/b/c \) phase windings, respectively, \( \varphi_f \) is the magnetic linkage of the excitation winding, \( L \) is the self-inductance of each winding, \( M \) is the mutual inductance between windings, \( L_{ia}, L_{ib}, \) and \( L_{ic} \) are the currents of the stator \( a/b/c \) phase windings, respectively, and \( i_f \) is the current of the excitation winding.

The ordinary differential equation (3) with a variable coefficient can be transformed into ordinary differential equations with a constant coefficient by Park’s transformation. Then, the magnetic linkage equations of the stator in the \( d/q \) coordinate system are simplified to

\[
\begin{align*}
\dot{\varphi}_a &= P M_{ad}(x) \varphi_a + M_{cb}(x) \varphi_c + M_{fa}(x) i_f \\
\dot{\varphi}_b &= P M_{bd}(x) \varphi_b + M_{cb}(x) \varphi_c + M_{fb}(x) i_f \\
\dot{\varphi}_c &= P M_{cd}(x) \varphi_c + M_{cb}(x) \varphi_b + M_{fc}(x) i_f
\end{align*}
\]

If the end effect is not taken into account, when the stator windings are completely symmetrical and the magnetic field is sinusoidal between the air gaps, the magnetic linkage equations of the stator become
\[
\begin{bmatrix}
\varphi_d \\
\varphi_q
\end{bmatrix} = \begin{bmatrix} L_d & 0 \\
0 & L_q \end{bmatrix} \begin{bmatrix} -i_d \\
i_q \end{bmatrix} + \begin{bmatrix} M_{dq} \\
0 \end{bmatrix} i_f
\] (5)

Define the permanent magnetic linkage as follows:

\[\varphi_f = M_{sf} i_f \] (6)

Then (5) is simplified to

\[
\begin{bmatrix}
\varphi_d \\
\varphi_q
\end{bmatrix} = \begin{bmatrix} L_d & 0 \\
0 & L_q \end{bmatrix} \begin{bmatrix} -i_d \\
i_q \end{bmatrix} + \varphi_f
\] (7)

It can be obtained by (7) that in the \(dq_0\) coordinate system, the magnetic linkages of the stator windings are constant, and the mutual magnetic linkages between the windings are zero, that is, there is no coupling between the windings.

### 3.1.4 Equations of the stator’s voltage

In the selected reference direction, the voltage balance equations of the stator three-phase windings are as follows:

\[
\begin{aligned}
\varphi_d &= -R_d i_d + \frac{d}{dt} \varphi_d \\
\varphi_q &= -R_q i_q + \frac{d}{dt} \varphi_q \\
\varphi_c &= -R_c i_c + \frac{d}{dt} \varphi_c
\end{aligned}
\] (8)

where \(u_d, u_q,\) and \(u_c\) are the voltages of the stator \(a/b/c\) phase windings, respectively, \(R_d\) is the stator resistance, \(i_d, i_q,\) and \(i_c\) are the currents of the stator \(a/b/c\) phase windings, respectively, and \(\varphi_d, \varphi_q,\) and \(\varphi_c\) are the magnetic linkages of the stator \(a/b/c\) phase windings, respectively.

In the \(dq_0\) coordinate system:

\[
\begin{bmatrix}
\varphi_d \\
\varphi_q
\end{bmatrix} = \begin{bmatrix} R_d & 0 \\
0 & R_q \end{bmatrix} \begin{bmatrix} -i_d \\
i_q \end{bmatrix} + \begin{bmatrix} \frac{d}{dt} \varphi_d \\
\frac{d}{dt} \varphi_q \end{bmatrix} + \begin{bmatrix} -\omega \varphi_q \\
\omega \varphi_d \end{bmatrix}
\] (9)

Similar to the RSA, there are also two simplifications for voltage equations of the LSA stator in the analysis of the stability of the power system.

On the one hand, the electromagnetic transient process of the stator circuits is ignored, that is, the inductive EMF resulting from the change of \(\varphi_d\) and \(\varphi_q\) with time is ignored, and thereby the stator’s voltage equations are simplified to the following algebraic equations:

\[
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} = \begin{bmatrix} R_d & 0 \\
0 & R_q \end{bmatrix} \begin{bmatrix} -i_d \\
i_q \end{bmatrix} + \begin{bmatrix} -\omega \varphi_q \\
\omega \varphi_d \end{bmatrix}
\] (10)

On the other hand, the change of the rotation velocity \(\omega\) is ignored. It is considered that the rotation velocity \(\omega\) of the stator’s voltage balance equations has little variation during the transient process due to various control functions, that is, \(\omega\) is always 1.0 pu. Further, the stator’s voltage equations are simplified as follows:

\[
\begin{bmatrix}
u_d \\
u_q
\end{bmatrix} = \begin{bmatrix} R_d & 0 \\
0 & R_q \end{bmatrix} \begin{bmatrix} -i_d \\
i_q \end{bmatrix} + \begin{bmatrix} -\varphi_q \\
\varphi_d \end{bmatrix}
\] (11)

### 3.1.5 Motion equations

The prime motor is composed of a GE and a reciprocating compressor. Based on the sinusoidal reciprocating motion of the mover, the prime motor can be equivalent to a spring damping system. Equation (12) is the dynamics equation of the prime motor:

\[F_m = -kx \] (12)

where \(F_m\) is the driving force, which is provided by the prime motor, \(k\) is the equivalent damping coefficient of the mover, and \(x\) is the displacement of the mover.

Based on the calculation model of electromagnetic power, the electromagnetic power of LSA is calculated as follows:

\[P_e = \frac{3}{2} \rho (\varphi_d i_q - \varphi_q i_d) \] (13)

For the electromagnetic power,

\[P_e = F_s v \] (14)

Combine (13) with (14) to obtain

\[F_s = \frac{3}{2} \rho (\varphi_d i_q - \varphi_q i_d) \] (15)

Considering the magnetic linkage (7) and \(L_d = L_q\) the EMF is simplified to

\[F_s = \frac{3}{2} \rho \varphi i_q \] (16)

Equation (17) shows the relationship between the velocity and displacement:

\[v = \frac{dx}{dt} \] (17)

where \(v\) is the reciprocating motion velocity of the mover and \(x\) is the displacement of the mover.

Based on the second law of Newton, the kinematics equation of the gas reciprocating generator unit is as follows:

\[M \frac{dv}{dt} = F_m - F_s - B_s v \] (18)

where \(M\) is the total mass of the mover and piston, \(v\) is the reciprocating motion velocity of the mover, \(F_m\) is the driving force provided by the prime motor, \(F_s\) is the EMF of the generator, and \(B_s\) is the mechanical damping coefficient.

The motion equations of the LSA’s mover can be obtained by combining (12), (16) and (18):

\[
\begin{bmatrix}
M \frac{dv}{dt} \\
F_m \\
F_s \\
x
\end{bmatrix} = \begin{bmatrix}
F_m - F_s - B_s v \\
-\kappa x \\
-\frac{3}{2} \rho \varphi i_q \\
X_p \sin(\omega t)
\end{bmatrix}
\] (19)

where \(M\) is the total mass of the mover and piston, \(v\) is the reciprocating motion velocity of the mover, \(F_m\) is the driving force provided by the prime motor, \(F_s\) is the EMF of the generator, \(B_s\) is the mechanical damping coefficient, \(x\) is the displacement of the motion, \(X_p\) is the amplitude of the displacement of the motion, and \(\omega\) is the rotation velocity of the prime motor.

Equations (19) are the electromagnetic transient model. To analyse the transient stability of the independent offshore power system with a gas reciprocating generator unit, it is necessary to establish the electromechanical transient model. If the displacement and velocity of the mover are transformed from the sine function of time to the phasor, and the effective value in the steady state is taken as the reference value of the mover velocity, the velocity phasor will become 1.0 pu in the steady state, and then (19) is changed to
\[
\begin{align*}
\frac{dx}{dt} &= v - 1 \\
M \frac{dv}{dt} &= F_m - F_e - B_d v \\
P_m &= F_m v \\
P_e &= F_e v
\end{align*}
\]  

(20)

Considering that \(v\) changes slowly in the transient process, \(F_m\) and \(F_e\) can, respectively, be replaced by \(P_m\) and \(P_e\) in (20), which is further simplified to

\[
\begin{align*}
\frac{dx}{dt} &= v - 1 \\
M \frac{dv}{dt} &= P_m - P_e
\end{align*}
\]  

(21)

3.2 Comparison with the model of the RSA

3.2.1 Comparison of important variables: By comparing the related variables of the LSA with the RSA, the following corresponding relationship can be obtained (Table 1).

3.2.2 Equations comparison: Both the models of LSA and RSA include stator's magnetic linkage equations, stator's voltage equations, and motion equations, but the specific equations are different because of the different variables of the two models. Concretely, the equations comparison is shown in Table 2.

4 Transient stability analysis of an independent offshore power system

4.1 System description

The test system in this paper is an independent offshore power system, including an RSA (alternator of the gas turbine generator unit) and an LSA (alternator of the gas reciprocating generator unit). At the same time, when the load factor is high, it will use the rig module power station to provide the power supplement for the system.

Under the normal operation mode, the system is subjected to the fault of the maximum motor load, with the 2240 kW compressor being suddenly shut down due to failure, resulting in the RSA and LSA into the transient process. The transient stability of the system under such condition is studied by numerical simulation.

4.2 Topology of the system

When the non-significant factors in the system are ignored, the simplified topology of the power system is the same as shown in Fig. 3.

4.3 Transient stability analysis

In the simple model of the whole system, for the gas turbine generator unit, the mathematical model of the alternator-RSA adopts the constant \(E_d\) model, and the mechanical power provided by the prime motor is considered as constant. For the gas reciprocating generator unit, the mathematical model of the alternator-LSA adopts the constant \(\varphi_f\) model, and it is also assumed that the mechanical power provided by the prime motor is constant. Besides, the constant impedance model is used for both the motor load and the normal working load.

The mathematical models of the units and load are connected to the network. Then, the failure occurs at 3.00 s, and the whole numerical integration period is 10.00 s, and the transient curves of state variables and operation parameters are obtained, as shown in the following figures.

First, the equivalent power angle curve of the two alternators is simulated, which is the same as shown in Fig. 4.

It can be seen from Fig. 4 that the power angle of the RSA and the displacement of the LSA change synchronously with time. Therefore, the deviation of the LSA can be considered as the equivalent power angle. At the same time, it can be obtained by the monotonous rise of the curve that shows the two alternators are all unstable under this faulted condition.

According to the equivalent power angle curve of the two alternators, the curve of the equivalent power angle difference between the two alternators can be further plotted as Fig. 5.

From Fig. 5, it can be observed that the equivalent power angle difference between the two alternators oscillates between 0.5° and 4.5° during the transient process. According to the analysis of the stability criterion of the power angle of the standard test system, the system is angle stable, while the system is actually unstable. This is because the two alternators in the system are connected to the same bus, so the two equivalent power angles have approximately synchronous changes, resulting in the variation in the equivalent power angle difference being quite small. Under this condition, the power angle stability of the system should be judged
by the change of the equivalent power angles of the two alternators rather than the equivalent power angle difference.

Further, the rotation velocity curve of the rotor of the RSA and the reciprocating motion velocity curve of the mover of the LSA are drawn, as shown in Fig. 6. It can be obtained according to Fig. 6 that the velocities of two alternators are approximately synchronous, when the inertia time constant $T_j$ of the RSA and the mass of the mover and piston $M$ of the LSA are all 0.5 pu. So the reciprocating motion velocity of the mover of the LSA can be regarded as an equivalent velocity.

To analyse the voltage stability of the system, the amplitude variation curve of the alternator terminal voltage is drawn, as shown in Fig. 7. According to Fig. 7, the terminal voltage of the alternator rises rapidly from 1.050 to 1.062 pu after the failure of the maximum motor load. Since there is no regulation of the excitation system applied, the voltage cannot recover to the steady state value of 1.050 pu. Instead, it keeps up to ~1.062 pu, which deviates from the steady state value ~1.14%. For the small power system, it requires high voltage quality; therefore, the above voltage might not meet the requirements for the stable operation of the system.

In order to analyse the cause of the rapid increase of the velocities in the transient process, the $P_e$ curves of two alternators, as shown in Fig. 8, are depicted. From Fig. 8, we can see that after the breakdown of the maximum motor load, the $P_e$ s of the two alternators decrease rapidly, and then fluctuate greatly during the transient process, while the $P_m$ of the prime motor is assumed to remain constant in the simple model. Thus, the velocities of the two alternators quickly deviate from their steady-state values.

To sum up, when the maximum motor load breaks down, the power angle is unstable and the voltage deviates from the steady-state value by ~1.14% in the independent offshore power system model, that is, the system would be unstable during the transient process.

5 Conclusion

In this paper, the operation principle of the gas reciprocating generator unit is briefly summarised. Different from the traditional synchronous generator unit that generates sinusoidal inductive EMF through the sinusoidal variation of magnetic induction intensity, the gas reciprocating generator unit produces sinusoidal inductive EMF through the sinusoidal reciprocating motion of the mover.

Furthermore, the electromechanical transient model of the LSA, the core part of the gas reciprocating generator unit, is derived in this paper, based on the principle of armature reaction in traditional synchronous and asynchronous machines. By comparing with the RSA, it is proved that the LSA model is the same as that of the RSA, except for the replacement of a few variables. Therefore, the model of the LSA can be established by the method similar to the RSA.

Finally, the transient stability of an independent offshore power system under the derived LSA model is analysed by numerical simulation. The curves obtained by simulation confirm that the electromechanical transient model of the LSA is the same as the RSA, which is applicable to be used in the future transient stability analysis of systems or AC microgrids with gas reciprocating generator units.

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