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Transient stability mechanism of grid-connected inverter-interfaced distributed generators using droop control strategy

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HIGHLIGHTS

- This paper presents the transient stability mechanism of IIDGs.
- The transient stability sensitivity to droop factors is proposed.
- The relation between the network parameters and IIDG's transient stability is analyzed.
- A accurate transient stability judgment is designed.

ARTICLE INFO

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ABSTRACT

The large-scale application of renewable energy is promising to solve the energy crisis over the world. Renewable energy is generally integrated into distribution networks or microgrids through inverters. Inverter-interfaced distributed generators (IIDGs) have the advantage of utilizing renewable energy effectively and flexibly. However, the wide interconnection of IIDGs causes transient stability to the public grid. This paper presents the transient stability mechanism of the grid-connected IIDGs using droop control. The transient stability mechanism is obtained by combining the transient stability condition and the comprehensive dynamic trace. The transient stability condition is proposed by the transient model and IIDGs' operation features. The comprehensive dynamic trace is formulated by the active and reactive power curves during transient events. The mechanism is able to reflect the relations between transient stability and droop factors and reveal the transient behaviors of IIDGs. The transient stability judgment is correspondingly developed. A series of simulations demonstrate the correctness and effectiveness of the transient stability mechanism. The transient stability mechanism better expands and develops the utilization of renewable energy.

1. Introduction

The energy consumption and environmental pollution of fossil fuels are increasing rapidly all over the world. The effective and secure utilization of renewable energy becomes a critical solution to the energy crisis [1–4]. Inverter-interfaced distributed generators (IIDGs) are considered as an efficient solution to convert different forms of resources into electricity [5–8]. They feature high flexibility in terms of control and application. The wide implantation of IIDGs greatly improves the utilization of renewable energy, reduces the power loss and cuts down pollution.

However, with the large-scale integration of DGs, there are still numerous technical challenges in utilizing IIDGs. One of the challenges is the elusive and complicated transient stability [9,10]. Most IIDGs are widely embedded in distribution networks or microgrids, which suffer numerous transient events, such as faults, instant change of loads and switch of grid structure [11–13]. The transient events usually lead to asynchronization of IIDGs with the public power grid. The asynchronization of IIDGs bring extremely negative affects towards electricity consumers, power facilities and the utilization of renewable energy [14,15]. IIDGs need to be isolated from the public grids, in case the transient events further develop.

A great deal of studies have been focusing on the transient stability of IIDGs. Simulation and mathematical models are two main approaches [32]. Simulation are used to investigate the factors that interact with transient stability. The factors can be categorized as transient events and operation parameters. Transient events include faults, induction machines starting and grid structure switch. Operation

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Nomenclature

ω	angular frequency of the IIDG
ω_n	nominal angular frequency of the IIDG
V	output voltage of the IIDG
V_n	nominal output voltage of the IIDG
θ	reference phase angle of output voltage of IIDG
P	active power output of the IIDG
P_n	nominal active power of the IIDG
Q	reactive power output of the IIDG
Q_n	nominal reactive power of the IIDG
m_P	active power droop factor
m_Q	reactive power droop factor
v_{od}	output voltage of the IIDG on the *d*-axis
v_{oq}	output voltage of the IIDG on the *q*-axis
v_{od}^*	reference output voltage of the IIDG on the *d*-axis
v_{oq}^*	reference output voltage of the IIDG on the *q*-axis
i_d^*	reference output current of the IIDG on the *d*-axis
i_q^*	reference output current of the IIDG on the *q*-axis
v_{id}^*	reference unfiltered voltage of the IIDG on the *d*-axis
v_{iq}^*	reference unfiltered voltage of the IIDG on the *q*-axis
v_i^*	reference unfiltered voltage of the IIDG
v^*	unfiltered voltage of the IIDG
P_{Load}	active power of local load
Q_{Load}	reactive power of local load
P_{nLoad}	nominal active power of local load
Q_{nLoad}	nominal reactive power of local load
Z_l	line impedance
γ	impedance angle of the line impedance.
t	time
t_c	the time when fault is cleared
δ	voltage difference angle between IIDG and public grid
δ_n	nominal voltage difference angle
δ_f	the voltage difference angle when fault occurs
δ_c	the voltage difference angle when fault is cleared
δ_t	voltage difference angle at *t*
δ_{ct}	critical voltage difference angle
V_f	the output voltage when fault occurs
V_c	the output voltage when fault is cleared
V_t	the output voltage at *t*
α	equivalent changing rate of *Q*
$Q_{\max}$	maximum value *Q* rises up to
$t_{\max}$	the time when *Q* rises up to Q_{max}
k_i	the *i*th sinusoidal amplitude coefficient of CDT. *i* is from 0 to 4
φ_i	the *i*th sinusoidal phase coefficient of CDT. *i* is from 1 to 4
δ_{con}	voltage difference angle when time is t_{max}
t_{restore}	the time the IIDG takes to restore stability
t_{period}	The oscillation period when the IIDG is transient instable.

parameters include network parameters control types. Refs. [16–19] considered the fault type, fault clearance time, loads types and control types as variables in simulation experiments to scale their influence and sensitivity of the transient stability. Ref. [20] utilized center of inertia to expand the application of the simulation and managed to provide a general analysis in various applications. The models in these literatures can concisely describe the transient behaviors of IIDGs. However, simulations fail to provide the mechanism of the transient behaviors. Other literatures use mathematical models to study the transient stability. The commonly used methods are Nyquist criterion [21], eigenvalue test [22] and Lyapunov methods [23]. Nyquist criterion and eigenvalue test are easy to give the stable boundary of the IIDGs. They are widely used for IIDGs in different grid structures [24,25] as well as for multi-IIDG system [26]. However, the two conventional methods cannot reflect the nonlinear influence from the control strategy thus making the stable boundary less convincing. Lyapunov methods is capable of solving the nonlinear feature of the control strategy [27,28]. However, these methods failed to present a thorough transient stability mechanism.

A few studies attempted to explain and describe the transient stability of the IIDGs. Some of them use the conventional transient stability analysis methodology to obtain the transient features [29,30]. Ref. [29] described the virtual angle synchronous instability of a single IIDG under droop control and virtual generator control strategies in consideration of current saturation. However, the model in the literature is only for voltage drop, which is not common in energy conversion and lacks the generality and applicability. Ref. [30] used small-signal modeling and dynamic analysis to profile the voltage changing. It is not suitable for large transient events. Ref. [31] developed the transfer function of the control system of the IIDGs that use virtual synchronous generators control. By linearizing the transfer function, the frequency characteristics and the effect of inertia were studied. The resonance was clearly explained in the frequency domain.

This study focuses on the transient stability mechanism of grid-connected IIDGs in distribution networks and microgrids. The power angle curves are derived by building and analyzing the transient model.

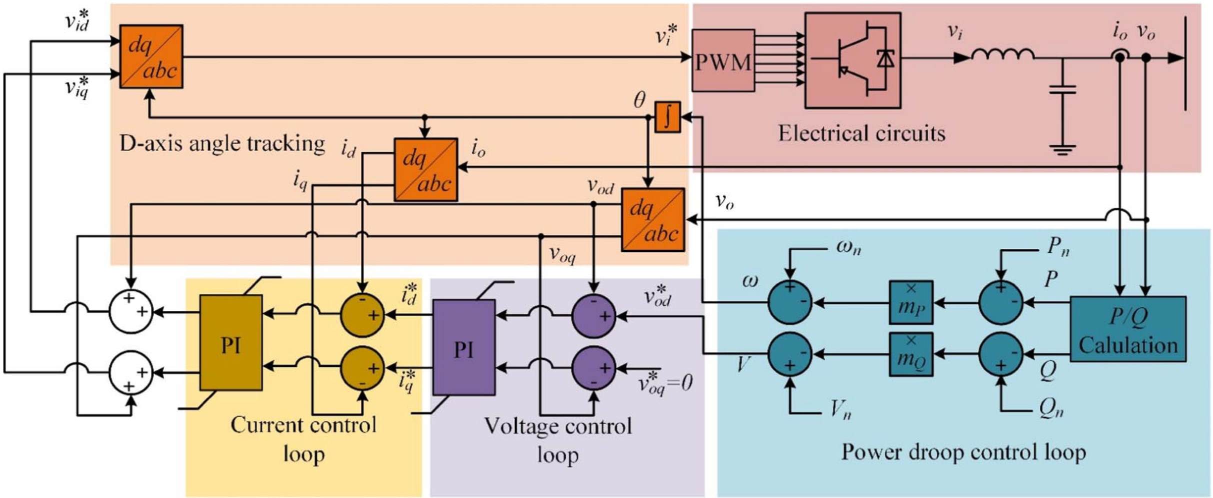

Fig. 1. Three-loop control system of IIDGs.