This paper proposes a framework to quantify the impact of uncertainty that arises from load variations, renewable-based generation, and noise in communication channels on the automatic generation control (AGC) system. To this end, we rely on a model of the power system that includes the synchronous generator dynamics, the network, and the AGC system dynamics, as well as the effect of various sources of uncertainty. Then, we develop a method to analytically propagate the uncertainty from the aforementioned sources to the system frequency and area control error (ACE), and obtain expressions that approximate their probability distribution functions. We make use of this framework to obtain probabilistic expressions for the frequency performance criteria developed by the North American Electric Reliability Corporation (NERC); such expressions may be used to determine the limiting values of uncertainty that the system may withstand. The proposed ideas are illustrated through the Western Electricity Coordination Council (WECC) 9-bus 3-machine system and a 140-bus 48-machine system.