Applied Energy 160 (2015) 541–551

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Cascading of fluctuations in interdependent energy infrastructures: Gas-grid coupling

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HIGHLIGHTS

- Fracturing and low cost of gas stimulated significant recent expansion of the natural gas networks.
- Power system operators transition to gas as the main supply, also facing new reliability challenges.
- Natural gas-fired generators vary burn-rates to balance fluctuating output of wind generation.
- Impact of the gas-generator variations is seen in diffusive jitter of pressure within the gas network.
- Fluctuating pressure impacts both reliability of natural gas deliveries and safety of pipeline operations.

ARTICLE INFO

Article history:
Received 22 March 2015
Received in revised form 31 July 2015
Accepted 22 September 2015

Keywords:
Natural gas network
Power grid network
Optimization
Uncertainty
Fluctuations

ABSTRACT

The revolution of hydraulic fracturing has dramatically increased the supply and lowered the cost of natural gas in the United States driving an expansion of natural gas-fired generation capacity in many electrical grids. Unrelated to the natural gas expansion, lower capital costs and renewable portfolio standards are driving an expansion of intermittent renewable generation capacity such as wind and photovoltaic generation. These two changes may potentially combine to create new threats to the reliability of these interdependent energy infrastructures. Natural gas-fired generators are often used to balance the fluctuating output of wind generation. However, the time-varying output of these generators results in time-varying natural gas burn rates that impact the pressure in interstate transmission pipelines. Fluctuating pressure impacts the reliability of natural gas deliveries to those same generators and the safety of pipeline operations. We adopt a partial differential equation model of natural gas pipelines and use this model to explore the effect of intermittent wind generation on the fluctuations of pressure in natural gas pipelines. The mean square pressure fluctuations are found to grow linearly in time with points of maximum deviation occurring at the locations of flow reversals.

1. Introduction

The ongoing evolution to intermittent wind and solar electric generation is causing many electrical grid operators to use more agile natural gas-fired electric generation to balance these new stochastic resources. This interdependence causes a cascade of the fluctuations of renewable generation into the systems that supply fuel to the gas-fired generators, i.e. natural gas pipelines. We develop a model of the coupling between electrical grid fluctuations and natural gas pipeline systems, analyze the resulting fluctuations of pipeline pressure, and draw conclusions about the impact of renewable electrical generation on the stability and security of natural gas pipelines.

By making unconventional natural gas sources economic to extract, hydrofracking has created a revolution in the U.S. natural gas industry [1]. Many of these new gas sources are in nontraditional locations such as the Marcellus shale in Pennsylvania, the Niobrara shale in Eastern Colorado, and the Bakken shale in North Dakota. See Fig. 1. The dramatic increase in supply has driven down prices [2] and spurred many new or expanded uses for natural gas [3,4]. This revolution in the natural gas supply and loads is creating new challenges for natural gas pipelines that transport the

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http://dx.doi.org/10.1016/j.apenergy.2015.09.085
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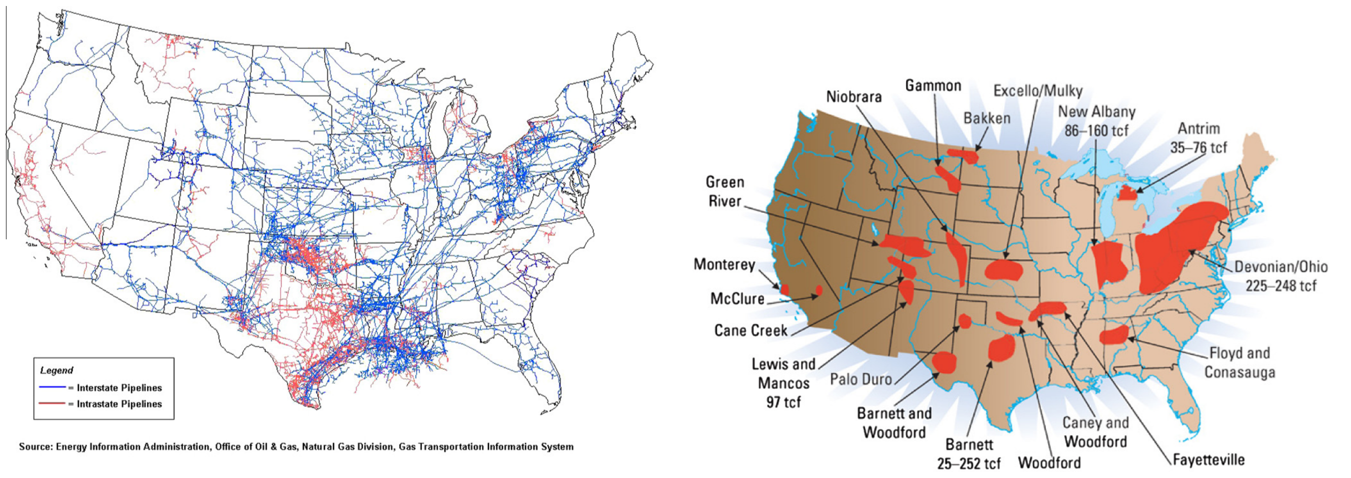

Fig. 1. (Left) The natural gas pipeline network of the United States. Interstate pipelines are not significantly meshed and primarily display a tree-like structure. (Right) Major US shale gas basins – new sources of natural gas that will encourage realignment of US national gas network.

gas from source to load. With a limited amount of throughput and short-term gas storage (in the form of pressure in pipeline itself), these pipelines may become vulnerable as their operating environment changes.

A dominant new load on the gas pipelines is natural gas-fired generators. Previously, the marginal cost of electricity from these generators was higher than from coal-fired generators. However, the rapid drop in gas prices has made gas generation competitive with coal and spurred its construction. An example of this dramatic expansion is in the electrical grid controlled by the Independent System Operator of New England (ISO-NE) where natural gas-fired electrical generation increased from 5% of total capacity to 51% in a span of 20 years [5]. A parallel development in many U. S. electrical grids is the expansion of intermittent renewable generation such as wind and PhotoVoltaic (PV) generation—a trend that is expected to continue as utilities work to meet state-imposed renewable portfolio standards [6] that mandate a certain fraction of electrical generation be derived from renewable sources. See Fig. 2. In contrast to traditional nuclear, coal, or gas-fired generation, these new forms of generation have a small degree of controllability. To maintain the second-by-second balance of generation and load, other grid resources must respond to counteract the fluctuations of the intermittent generation. Although many different types of advanced control of nontraditional resources are being considered to provide these balancing services, e.g. grid-scale battery storage and demand response, the currently most available resources are the controllable traditional generators with gas-fired generators being the most flexible among these.

The combination of expanded natural gas-fired generation and its increased use to balance intermittent renewable generation is creating loads on natural gas pipelines that are significantly different than in the past. Traditional gas pipeline loads (Load Distribution Companies or LDCs) primarily serve space or water heating or other individual customer needs and evolve slowly throughout the day in a relatively well-known pattern that can be predicted based on historical information and weather forecasts. Other traditional pipeline customers are industrial loads that, although they may change from day to day, are very predictable over the span of a day. In contrast, when gas-fired generation is used to balance fluctuating renewable generation, a component of the resulting gas loads take on a stochastic nature. Unlike the gas load of an LDC, wind and PV generation respond to *short-term* fluctuations in environmental conditions, e.g. wind fluctuations on the timescale of 10–100 min and solar insolation fluctuations on the timescale of 1–100 min. At the longer timescales, these fluctuations may contain spatiotemporal correlations that increase the aggregate fluctuations of wind or PV generation across an entire electrical grid magnifying the fluctuations of natural gas loads used by gas generators to balance these changes.

Fluctuating gas loads create new dynamics in natural gas pipelines that can impact their reliability and the reliability of all interdependent infrastructures, including the electrical grid. To a great

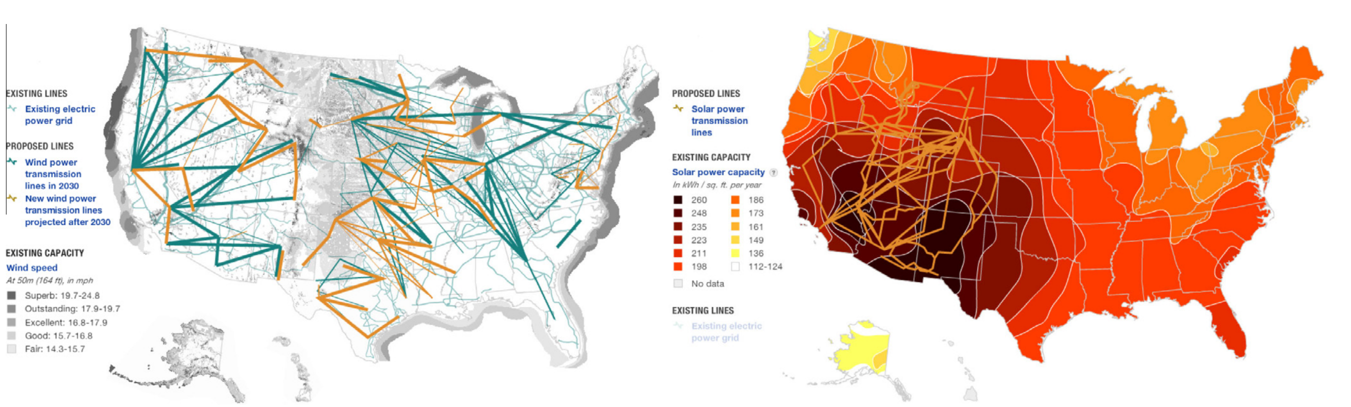

Fig. 2. (Left) US power transmission grid (including potential future transmission expansions) superimposed on wind power capacity map. (Right) Solar power capacity map with proposed transmission lines to improve the integration of solar resources into the existing power grid. (Adapted from National Public Radio, Visualizing the U.S. Electric Grid, 2009.)