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Measurement-based investigation of inter- and intra-area effects of wind power plant integration ☆

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ABSTRACT

This paper has a two pronged objective: the first objective is to analyze the general effects of wind power plant (WPP) integration and the resulting displacement of conventional power plant (CPP) inertia on power system stability and the second is to demonstrate the efficacy of PMU data in power system stability analyses, specifically when knowledge of the network is incomplete. Traditionally modal analysis applies small signal stability analysis based on Eigenvalues and the assumption of complete knowledge of the network and all of its components. The analysis presented here differs because it is a measurement-based investigation and employs simulated measurement data. Even if knowledge of the network were incomplete, this methodology would allow for monitoring and analysis of modes. This allows non-utility entities and study of power system stability. To generate inter- and intra-area modes, Kundur's well-known two-area four-generator system is modeled in PSCAD/EMTDC. A doubly-fed induction generator based WPP model, based on the Western Electricity Coordination Council (WECC) standard model, is included to analyze the effects of wind power on system modes. The two-area system and WPP are connected in various configurations with respect to WPP placement, CPP inertia and WPP penetration level. Analysis is performed on the data generated by the simulations. For each simulation run, a different configuration is chosen and a large disturbance is applied. The sampling frequency is set to resemble the sampling frequency at which data is available from phasor measurement units (PMUs). The estimate of power spectral density of these signals is made using the Yule–Walker algorithm. The resulting analysis shows that the presence of a WPP does not, of itself, lead to the introduction of new modes. The analysis also shows however that displacement of inertia may lead to introduction of new modes. The effects of location of inertia displacement (i.e. the effects on modes if WPP integration leads to displacement of inertia in its own region or in another region) and of WPP controls such as droop control and synthetic inertia are also examined. In future work, the methods presented here will be applied to real-world phasor data to examine the effects of integration of variable generation and displacement of CPP inertia on inter- and intra-area modes.

Introduction

WIND penetration levels are increasing across the US. This trend is expected to continue in the following decades [1]. In certain regions of the US, peak penetration levels can approach 30% [2]. At these penetration levels it is expected that wind power plants will, in many cases, displace conventional generation. This displacement may be permanent due to conventional plant retirements based on emissions- or age-related concerns and due to utilities preferring to install wind power plants instead of new conventional generation [3]. This displacement may also be a result of operational decisions, as high wind conditions may lead to increased wind power output and consequently a reduction of online conventional generation to meet demand [4]. This displacement of conventional synchronous generation by asynchronous WPPs will have significant stability impacts. In this paper, we focus on inter- and intra-area oscillation modes in particular. The effect of high wind penetration levels on oscillation modes in real power systems is largely unknown. Numerous simulation-based studies have been conducted, with inconclusive results suggesting that damping of modes may be improved or worsened by wind [5–8]. The consensus appears to be that WPPs do not participate directly

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in oscillation modes; however, their presence leads to displacement of CPP inertia and other topology changes that have the potential to influence the oscillation modes [8]. In our present work, we model a familiar two-area test system [9] with an additional WPP. The key finding is that not only does the displacement of inertia affect modes but the area in which the inertia is displaced affects the modes as well. The area in which the inertia is displaced may affect both the frequency and damping of an oscillation mode. This is relevant since WPPs may displace conventional plant inertia in regions other than the one they are situated in, due to wind resources being far from load centers as well as due to economic or other factors. The two-area system model is a time-domain model developed using the PSCAD/EMTDC platform [10]. This platform was chosen for its short simulation time-step, giving insight into any dynamics that may appear. This platform has been used before for two-area stability analyses [11]. The output from the simulations can be filtered and downsampled to simulate PMU data. The WPP model is based on the WECC Wind Generator Modeling Group's standard model for Type 3 (Doubly Fed Induction Generator) wind power plants [12]. The standard model is ported to PSCAD/EMTDC based on the work reported in [13]. Additional controls for synthetic inertia and voltage droop have been added to the standard model. A detailed explanation of model development is provided in Section 'Model development'.

In the future, long-term phasor measurement unit (PMU) data from real power systems can provide information about changes in oscillation modes due to wind-related or other topology changes. Currently PMUs are envisioned as a tool for enhancing stable operations of the grid but as PMU penetration improves a vast amount of data will be archived and available that could provide information about the effect of network changes on stability. This information could aid planners in evaluating the impacts of proposed generator or line additions. In an environment where system data may be frequently changing or may not be readily available, traditional Eigenvalue analysis to find damping of modes can be challenging. Instead, signal processing methods can be applied to PMU data to gather information about modes. In the work presented here, a method based on the Yule–Walker algorithm [14] is applied to analyze the simulated PMU data generated by the model. This method can be applied to real PMU data in the future. A description of the method is provided in Section 'Simulated phasor data processing'. Numerous scenarios are simulated using the model. Different WPP output levels, different locations of the WPP, different areas of inertia reduction among other factors are investigated with respect to changes seen in oscillation modes. These scenarios are discussed in detail in Section 'Simulation cases'. The results of the analysis support the consensus in the literature that the WPP does not participate in the oscillation modes but affects them indirectly through displacement of inertia. The results also indicate that WPP frequency response controls appear to have little impact on the modes. Detailed results and discussion are provided in Section 'Results'.

Model development

The model used for these simulations was developed in two stages. In the first stage, a model of the two-area system was developed in PSCAD/EMTDC. In the next stage, a model of the WECC standard wind power plant was developed and integrated into the two-area system model. The original WECC model was intended for phasor-based modeling software such as PSLF or PSS/E [15]. In our work, we use a time-domain PSCAD/EMTDC equivalent of the WECC model (discussed in detail in [13]).

Two-area system model

A one-line diagram of the two area system is shown in Fig. 1. The base system is symmetrical in terms of generation and line impedance. The model parameters are taken from [9]. In steady state conditions with no wind there is a 400 MW transfer from Area 1 to Area 2 across the weak transmission tie between the areas. It should be noted that in our model power system stabilizers (PSS) and Automatic Generation Control (AGC) are not included. However, each generator's excitation system and governor has been modeled. PSCAD/EMTDC parameters for modeling generators and controls not provided in [9] are left at default values where reasonable. Each generator is rated at 900 MVA. For this analysis, high frequency transients are not studied and a coupled-pi transmission line representation is used for modeling all transmission lines in the system.

Wind power plant model

The WPP model is a PSCAD/EMTDC equivalent of the DFIG WPP model developed by the WECC Wind Generator Modeling Group. A schematic of the WECC DFIG WPP model is provided in Fig. 2 to illustrate the model framework.

The WPP is sized such that wind penetration level in the two-area system is 10% when the WPP is supplying its rated power of 400 MW. The WPP collector system model is represented by an aggregated single-line equivalent. Details on how this aggregation

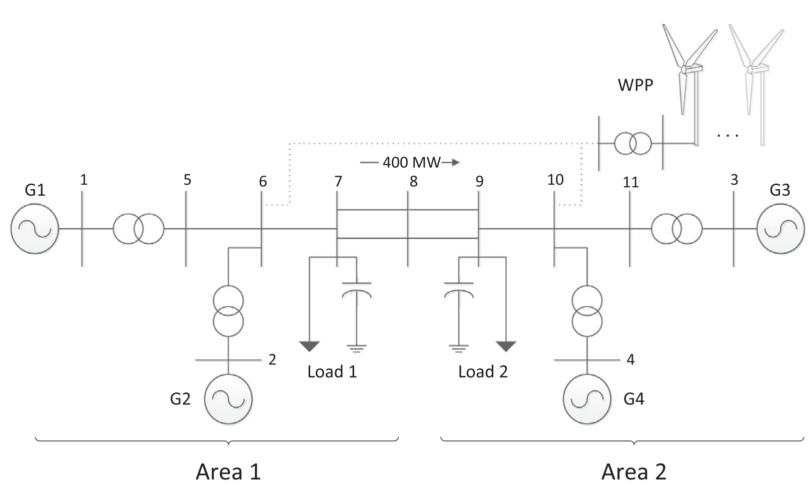

Fig. 1. Two-area system from Kundur [9] with additional WPP.