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SUPPORTING WINDPOWER WITHIN A SEPARATE ELECTRIC POWER GRID

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ABSTRACT

Utilization of windpower is considerably increasing in many countries around of the world. However, it produces an unreliable output due to the vagaries of the wind profile. To solve the problem, wind energy should be supported by local conventional sources. The requirements concerning the reliability and quality of electric energy supply can be most satisfactorily fulfilled when a windfarm is connected to a large electric power system. Then any electric power fluctuations, resulting either from wind turbulence or power demand variation, provoke system frequency variations. They should be damped by applying an appropriate control system of such a large power system.

In this paper, the problem of control of a separate electric power system composed of windpower farm and supported by a gas turbine plant or a combined cycle has been investigated. First, the impact of wind turbulence on gas turbine plant control system has been modeled and simulated. This is carried out for different amplitudes and frequencies of wind speed. Next, the structure of gas turbine plant control system and its parameters have been adapted to limit the power and frequency fluctuations resulting from wind turbulence. Then the design is further developed by considering a combined cycle instead of a single gas turbine.

NOMENCLATURE

f	electric grid frequency
CP	combined cycle power plant
CG	combined cycle power plant generator
EE	electric power exchange
GT	gas turbine
$\mathbf{K_F}$	frequency controller amplification
$\mathbf{K_P}$	power controller amplification
P	power
$\mathbf{R_P}$	combined cycle power output controller
$\mathbf{R_F}$	electric grid frequency controller
ST	steam turbine
WG	wind turbine generator
WP	wind power
WT	wind turbine
$\mathbf{T_F}$	frequency controller time constant
$\mathbf{T_P}$	power controller time constant

INTRODUCTION

Windpower produces an unreliable output due to the vagaries of the wind profile. Therefore, it does not provide a trustable source of power and generally cannot meet the demands regarding constant power level. Without any action, there could be major problems with quality of fluctuating power [1,2], when customers expect enhancing the power quality standards. In fact, the grid connection codes and standards associations are intending to ensure related requirements. Power generation using wind energy should be supported by local conventional plants. The requirements concerning the reliability and quality of electric energy supply can be most satisfactorily fulfilled, when a windfarm is connected to a large electric power system. Then any electric power fluctuations, resulting either from wind turbulence or power demand variation, provoke system frequency variations. The disturbing fluctuations have to be damped by applying an appropriate control system. Moreover, they should be damped as near to the windfarm as possible to avoid considerable disturbances of frequency and voltage in the electric power system. On the other hand the distance between a windfarm and a large electric power system is very often too long to build a transmission line, which is justified economically. Then it becomes unavoidable to produce windpower in a separate electric power system. As a result, the main task is to control the frequency in such a distributed power generation system. It means that any fluctuation of windpower has to be damped due to an appropriate action of a power plant support. To provide such a support the following aiding concepts are possible: i) gas turbine power plant, ii) diesel engine power plant, iii) pumped storage power station. Selection of a proper supporting plant directly depends on the site circumstances.

As mentioned above, the wind energy source needs local support from conventional sources. One of such solutions has been presented at the ASME Turbo Expo 2007 Conference [3]. This paper deals with the problem of control of a separate electric power system composed of windpower farm, which is designed to be supported using two different concepts: 1) supporting by a gas turbine plant, 2) supporting by a combined cycle. In this regard, the impact of wind turbulence on gas turbine plant control system has been investigated at first. Wind velocity is simulated with variable amplitude and frequency. Then, the structure of gas turbine plant control system and its parameters have been adapted to limit the power and frequency fluctuations resulting from wind turbulence. The discussed concept to provide gas turbine power plant as a support to windpower generation enables to maintain power quality standards in a electric power grid supplied by windfarm [4]. Next, a combined cycle instead of a single gas turbine has been considered, hence a combined cycle power plant seems to be better adapted to such a purpose. The reason relies on two facts: 1) supporting a wind turbine with a gas turbine causes considerable variations of gas turbine load and 2) the efficiency of any gas turbine power plant radically decreases in part loads as the gas turbine is very dependent on turbine combustion temperature and mass flow of the incoming air [5]. Figure 1 shows the difference between gas turbine and combined cycle power plant efficiencies [6]. Advanced combined cycle power plants operate at thermal efficiencies of 53 to 58 percent, while gas turbines in the range of 33 to 38 percent (in some cases up to 60 to 64 percent and 40 to 45 percent, respectively). Moreover, the combined cycle power plant efficiency does not drop so quickly at part loads as the gas turbine efficiency does. This fact is enhanced when the inlet guide vane is adjusted to reduce the flow at off–design loads, and to maintain the high exhaust gas temperature (see Figure 1). The efficiency at part load makes that the combined cycle power plant prevails over gas turbine one in the concept of supporting windfarm generation within a separate electric power grid.

Additionally, it should be noticed that using a set of several gas turbines combined with one steam turbine should be particularly effective. Another advantage of supporting windpower with combined cycle power plant is the possibility of heat generation in a heat and power distributed cogeneration system.

The simulation technique is used to compare usefulness of these two concepts.

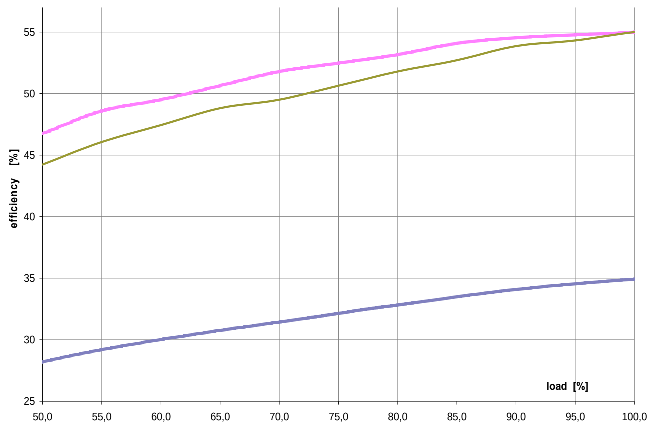


Figure 1. Part load efficiency of a combined cycle plant without (green), and with (pink) variable inlet guide vane in the compressor, and of gas turbine plant (blue).

MATHEMATICAL MODEL OF THE WIND TURBINE AND COMBINED CYCLE POWER PLANT COOPERATION

It has been assumed that the wind turbine produces as much power as possible, depending on the wind speed ν, when it is in the range of $\nu_{cut\text{-}in}$ (3 to 5 m/s) and $\nu_{cut\text{-}off}$ (25 m/s). The next assumption for modeling is that the combined cycle power plant is required to make as smooth as possible any frequency variations provoked either by wind speed turbulence or by power demand fluctuations. Generally, here it is tried to deliver the most simplest form of mathematical model of the considered elements, e.g turbines, hence, the main goal of study is synthesis of frequency control system rather than modeling of physical phenomena and processes. Therefore, for each element a simple transfer function has been introduced. After proper design of frequency control system, then higher order transfer functions or nonlinear mathematical models available in the literature can be applied for better understanding of the system and improving the quality of control process regarding different system parameters, not included here.

Wind Turbine Model

As a simplified mathematical model of a middle range wind turbine the first order transfer function is suggested [7]:

$$G_{WT}(s) = \frac{P_{WT}}{P_{WW}}$$
$$= K_W \frac{1 + s \cdot T_{W1}}{1 + s \cdot T_{W2}}$$

Where P_{WW} and P_{WT} denote wind power and wind turbine power output respectively. Parameters K_W, T_{W1} and T_{W2} depend on two variables: 1) the angular velocity of wind turbine rotor and 2) profile an configuration of wind turbine blades. For a middle range wind turbines these parameters have been evaluated as follows [7]:

$$K_W = 1, T_{W1} = 3.3\text{s}, T_{W2} = 0.9\text{s}$$

Similarly, the mathematical model of wind turbine generator has been assumed as the following transfer function:

$$G_{WG}(s) = \frac{1}{z + T_G \cdot s}$$

in which T_G and z denote the turboset rotor time constant and damping coefficient, respectively. The parameters have been evaluated based on the constructional parameters data for Enron EW 900 wind turbine [8] and finally, the wind turbine generator transfer function has been approximated as follows:

$$G_{WG}(s) = \frac{0.5}{1 + 10 \cdot s}$$

In further steps, it has been assumed that a windfarm integrates several identical wind turbines.

Combined Cycle Power Plant

For modeling, a single shaft combined cycle power plant has been considered. Figure 2 shows the block diagram of its mathematical model and applied control system [9]. In this diagram R_P denotes the plant power output controller and R_F plant frequency controller. LF is fuel flow rate limiter, LT is combustion chamber exhaust temperature limiter and the IGVC block represents the steady state characteristic of the inlet guide vane position controller.

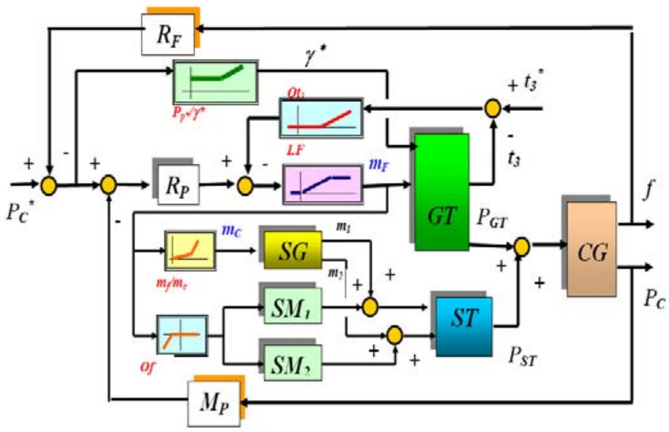


Figure 2. Simplified block diagram of combined cycle power plant control system

As an example an ABB 165 MW gas turbine has been taken into account. Based on data available for this turbine type, the parameters of the high temperature steam generator as well as of the double pressure steam turbine have been evaluated. Since, the nonlinear steady state characteristics of compressor were not available, the mathematical model of compressor has been adapted according to some similar data found in related references [10].

Wind Process

The wind process can be determined by wind velocity. Wind speed vagaries resulting in wind turbine power output fluctuations are of stochastic nature. In a short time the changes of wind speed amplitude can be considerable. These changes can be simulated like a stochastic process or can be represented using Fourier series. In the latter case, the wind speed is represented by the following relationship:

$$v(t) = v_0 \left[1 + \sum_k A_k \sin(\omega_k \cdot t) \right] + v_g(t)$$

where v_0 means the average wind speed, A_K and ω_k indicate amplitude and angular velocity of the k^{th} harmonic, respectively, and v_g is the gust speed. In the preliminary investigations the aim has been to verify if the conventional power plant is able to react fast enough to the wind turbine power output fluctuations. Therefore, in a simplified model the wind speed variations have been assumed as

$$v(t) = v_0 \left(1 + A \cdot \sin \omega t\right)$$

Then, the relative wind power fluctuations are given as

$$\frac{\Delta P_W}{P_{W0}} = 3A^2 \cdot \sin \omega t + 3A \cdot \sin^2 \omega t + A^3 \cdot \sin^3 \omega t$$

For simulations purpose the following data have been considered:
$v_0 = 9$ m/s,
$A = 0.1$ and
$\omega = 0.1$ Hz and 0.2 Hz.

Computational Model

The computational model of a separate electric power grid in which a combined cycle power plant cooperates with a windfarm is represented in Fig. 3. It has been assumed that the rated power of the combined cycle plant is equal to the windfarm maximum output power. The windfarm is composed of a number of identical wind turbines. Then, the relative change of wind turbine power output can be correlated to the relative change of output power of cooperating combined cycle plant. This is represented in the simplified block diagram of Fig. 3, in which block EE corresponds to the electric power exchange between the generators. The transfer function of this block has been assumed as follows:

$$G_{EE}(s) = \frac{50}{1 + 0.1s}$$

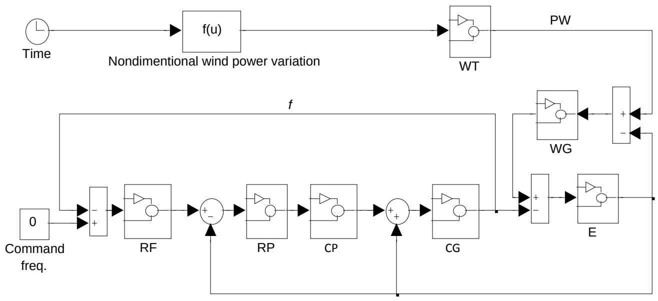


Figure 3. Simplified block diagram of wind turbine and combined cycle power plant cooperation within a separate electric power system. WT: wind turbine, CG: generator of the combined cycle power plant , CP: combined cycle power plant, WG: wind turbine generator, EE: electric power exchange, RP: combined cycle power output controller, RF: electric grid frequency controller, PW: wind power, *f*: electric grid frequency.

SIMULATION RESULTS

Wind speed variations results in both wind turbine power and frequency fluctuations. Supporting a windfarm with a combined cycle power plant gives considerable diminution of frequency fluctuations.

Frequency Control within a Separate Electric Power Grid

The combined cycle power plant is equipped with power output and frequency controllers, see Fig. 2 and Fig. 3. Both controllers have been optimized by minimization of Integral of Squared Error (ISE) criterion:

$$ISE = \int_{0}^{\infty} (e(t))^2 \, dt = \min$$

by assuming step change of set point signal.

The plant power output controller has been assumed as a PI-action type. Its parameters have been adopted as

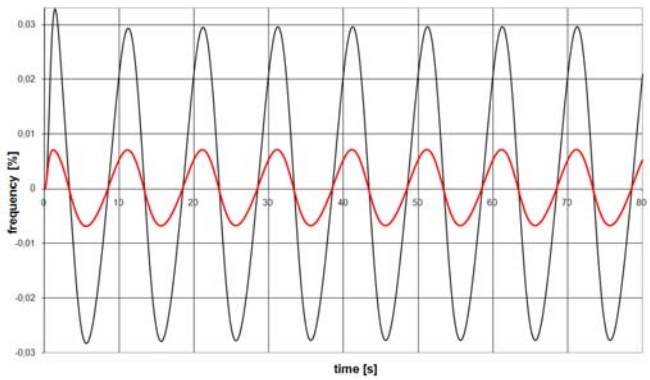
$$K_P=5,\ T_P=0{,}4\text{s}$$

When an electric power grid supplied by the windfarm and the combined cycle power plant is not connected to any external large power system, then the frequency controller is also of PI-action.

The simulation investigations have started with A=0.1, ω=0.1 Hz. The parameters of combined cycle power plant frequency controller have been adopted as K_F=25, T_F=0.1s. Then, the amplitude of electric grid frequency fluctuations does not surpass 0.03% of its nominal value, see Fig. 4a while without any local frequency control it attaints about 1%, see Fig. 5a. Increasing frequency controller amplification up to K_F=100 makes the frequency to be much more damped up to 0.008%, see Fig. 4.

For higher frequency of wind speed change the transients of electric power grid frequency still remain satisfactory (Fig. 4b shows an example for ω=0.2 Hz). The maximum value of frequency amplitude depends mainly on the amplification of frequency controller. For K_F=25 and T_F=0.1s it is equal about 0.06%, however for K_F=100, T_F=0.1s about it reduces to 0.013%, see Fig. 4b.

a)



b)

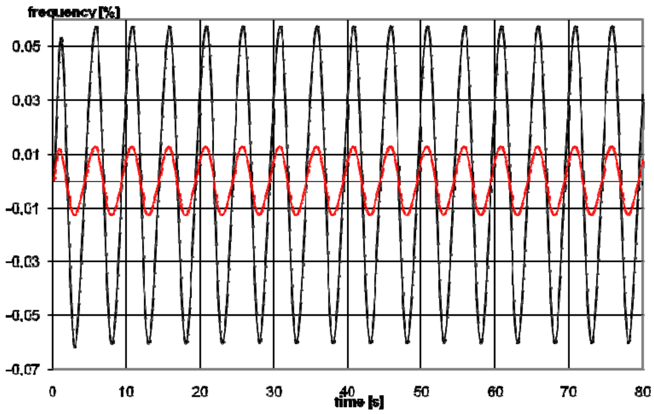


Figure 4. Frequency fluctuations
a) A=0.1, ω=0.1 Hz, b) A=0.1, ω=0.2 Hz
K_F=25, T_F=0.1s (black) K_F=100, T_F=0.2s (red)

Cooperation of Separate and Large External Electric Power Grids

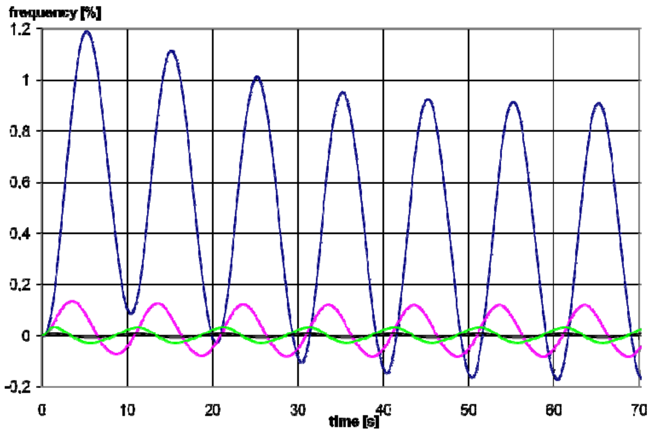
When a separate electric power grid and a large external one are interconnected, the frequency controller of combined cycle power plant must be of proportional action (T_F=∞) to enable their adequate cooperation in transient conditions. Fig. 6

shows an example of frequency transients in the case of separate electric power grid operation.

Concluding the Simulation Results

Fig. 5 summarizes the simulation results . In Fig. 5a behaviors of electric power grid frequency in transient conditions, corresponding to different frequency controller's structure and parameters, have been compared. Moreover, all of them have been compared to the frequency transient representing a windfarm operation without any frequency control. Fig. 5b enables an analogous comparison of power output transients.

a)



b)

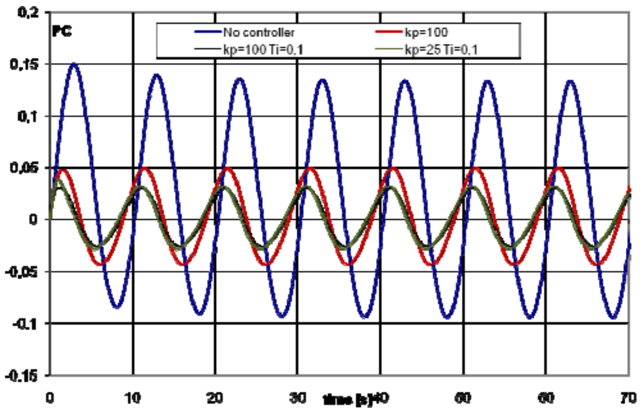


Figure 5. Influence of frequency controller's structure and parameters on a separate electric power grid transients
a) Frequency, b) power output
K_F=0, T_F=∞ (blue) **K_F=100, T_F=∞ (pink)**
K_F=100, T_F=0.1s (black) **K_F=25, T_F=0.1s (green)**

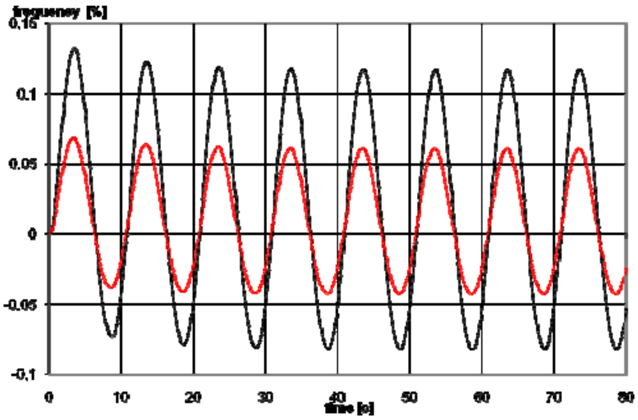


Figure 6. Frequency variation in transient conditions for P-action frequency controller, K_F=100, K_F=200

CONCLUSION

In the coming years, the renewable resources will be given heavy priority over fossil-based power. However, they increase electric power system variability and instability. Therefore, as more renewable resources are added, better ways are needed to balance out the intermittent production of electric power, [11].

Windfarms produce unreliable output due to the vagaries of the region's wind profile and as a result cannot meet the requirement of constant frequency with stable output power. Without action there could be major problems with fluctuating power quality. Wind power generation has to be supported as near as possible by conventional power generation. Thermal generating units are called upon such a support. Fast-starting, dispatchable generating units that have operational flexibility are needed to back up wind power. Gas turbines can meet those requirements. However, there is also a need for units that can operate at lower power rates without major loss of efficiency. New combined cycle power plants offer greater efficiency and better operational characteristics required by a grid generator. A concept to back up wind power with a combined cycle power plant has been discussed in this paper. Supporting a windfarm with conventional power plants causes considerable load variations of these plants. On one hand both gas turbine and combined cycle power plants enable to maintain power quality standards in an electric grid supplied by windfarm. Their control systems are fast enough. On the other hand the combined cycle power plant prevails over the gas turbine one. Its efficiency is much higher at rated power and is less sensitive to its load decrease. It can operate at lower minimum value of load without major loss of efficiency. From this point of view, a combined cycle power plant is better adapted for frequency control in a separate electric power grid. The effect is enhanced by using a set of e.g. two gas turbines combined with one steam turbine.

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