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Contribution of small-scale wind generation to primary frequency control

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SUMMARY

The connection of small-scale embedded generation to the grid may influence the frequency and voltage stability of the power system. A load-frequency control technique for systems with high penetration of small-scale wind generation is proposed. The proposed controller has been successfully implemented and tested using PSCAD/EMTDC (PSCAD Power System Simulation, HVDC Research Centre, Manitoba, Canada). In this study, the impact of small-scale wind turbines on frequency stability of the system is studied in detail. This study shows that large penetration of small-scale wind turbines with load and frequency has a significant impact on the stability and security level of electrical network. Copyright © 2012 John Wiley & Sons, Ltd.

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KEY WORDS: small-scale wind turbines; load-frequency control; primary frequency control

1. INTRODUCTION

Small-scale wind turbines (SSWTs) are among the most efficient and cost-effective small-scale embedded generation currently available on the UK market. Previously, the majority of SSWTs were installed at schools or environment centres, and very few domestic systems existed especially in urban areas. However, more recently, the small wind turbine industry has started to focus on developing the smaller ($<$1.5 kW) building-integrated turbine market. In particular, there has been a push to develop rooftop installations that are suitable for domestic properties in the urban environment [1, 2]. The connection of SSWTs to the grid may influence on power system frequency. System frequency is generally regulated through primary and secondary frequency controls. Primary frequency control regulates the system frequency in a dynamic process, and the secondary frequency control regulates the frequency as close as its nominal value by adjusting the loads of units participating in system frequency control [3, 4]. Previous research work has explored the impact of Distributed Generation (DG) on the system frequency [5–12].

This paper describes the design and implementation of a control technique for load-frequency control for systems with high penetration of SSWTs. The controller can respond to the disturbance such as load increase and load loss.

2. LOAD-FREQUENCY CONTROLLER DESIGN

A block diagram of the proposed controller is shown in Figure 1. The controller is mainly a set of mathematical instructions used to control and check system operating condition, and it differentiates from conventional automatic generation by including control logic instructions. The controller consists of the following five functional blocks:

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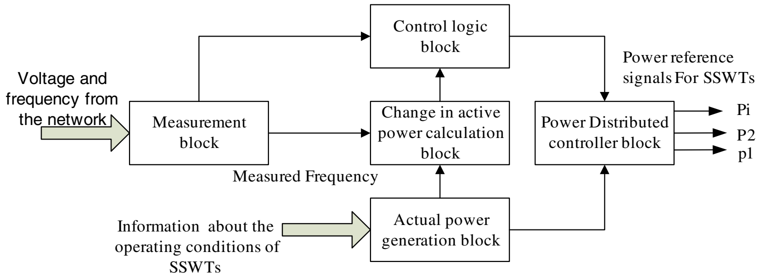

Figure 1. A block diagram of the load-frequency control system.

- measurement block;
- actual power generation block;
- control logic block;
- change in active power calculation block; and
- power distributed controller block.

2.1. Measurement block

The measurement block consists of two modules, one for measuring the voltage and one module for measuring frequency.

2.2. Actual power generation block

This calculates the SSWTs generation in per unit as follows:

1. First, the actual power of SSWT unit (*i*) is calculated as

$$P_{i\text{-ac}} = P_{i\text{-rat}} \cdot P_{i\text{-pu}} \tag{1}$$

where $P_{i\text{-ac}}$ is the actual power of SSWT unit (*i*) in [MW], $P_{i\text{-rat}}$ the rated power of SSWT unit (*i*) in [MW] and $P_{i\text{-pu}}$ the rated power of SSWT (i) in [pu] based on the rating of the unit.

2. Then, the rated participation of SSWT unit *i*

$$P_{\text{ir-}par} = \frac{P_{i\text{-}rat}}{P_{TWT}} \tag{2}$$

where $P_{\text{ir-}par}$ is the participation of SSWT unit *i* at the rated power based on the total rated power generation of all SSWTs [pu] and P_{TWT} is the total rated power of all SSWT units in [MW].

$$\text{where } P_{\text{TWT}} = \sum_{i=1}^{i=n} P_{i\text{-rat}} \tag{3}$$

3. After that the actual participation of SSWT unit *i* is calculated on the basis of the total rated power of all SSWT units

$$P_{i\text{-par}} = \frac{P_{i\text{-ac}}}{P_{\text{TWT}}} \tag{4}$$

where $P_{i\text{-par}}$ is the actual participation of SSWT unit *i* based on the total rated power of all SSWT units [pu].

4. Thus, the average value of total actual generation of SSWT units can be calculated by the following equation:

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$$P_{\text{av}} = \sum_{i=1}^{i=n} P_{i\text{-par}} \tag{5}$$

where P_{av} is the average value of the total actual generation of SSWT units [pu].

5. From the aforementioned equations, the per unit power P_{dif} and P_{OVF} are calculated as follows:

$$P_{\text{dif}} = [1 - P_{\text{av}}] \times P_{\text{TWT}} \tag{6}$$

$$P_{\text{OVF}} = [0.5 - P_{\text{av}}] \times P_{\text{TWT}} \tag{7}$$

where P_{dif} is the actual MW power that can be provided by SSWT units in case of under-frequency event [MW] and P_{OVF} is the power that can be reduced from the SSWT units when over-frequency occurs in MW.

2.3. Control logic block

This block checks the system operating condition and makes the decision to increase or decrease the output power from SSWT units if a system frequency deviation occurs based on the following equation:

$$f_{\text{error}} = f_0 - f_{\text{meas}} \tag{8}$$

where f_{error} is the frequency error [Hz], f_{meas} the measured frequency [Hz] and f_0 the steady-state system frequency [Hz] where $f_0 = 50\,\text{Hz}$; f_{meas} is the frequency measured from the system. A comparator determines if an over-frequency or under-frequency event is developing according to the following logic:

$f_{\text{error}} <$ zero (over-frequency)
$f_{\text{error}} >$ zero (under-frequency)
$f_{\text{error}} =$ zero (normal operation)

2.4. Change in active power calculation block

This block calculates the change in active power in the system and determines the required change in the reference power setting for all SSWT units, ΔP_{ref}, according to the total load capacity of all SSWT units. ΔP_{ref} is calculated as follows [13]:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \left(-\frac{f_0}{2.E_{\text{system}}} \times \Delta P_{\text{ref}} \right) \tag{9}$$

where $\frac{\mathrm{d}f}{\mathrm{d}t}$ is the rate of change of frequency [Hz/s], $\Delta P_{\text{ref},}$ the change in the reference power setting for all SSWT units and E_{system} the total stored energy of all generators and loads connected to the system at the nominal system frequency in [MW/s].

$$\frac{df}{dt} = \left(-\frac{f_0}{2.\,H_{\text{system}} \quad S_{\text{max}}}. \times \Delta P_{\text{ref}} \right) \tag{10}$$

$$\Delta P_{ref} = \frac{df}{dt} \left(\frac{-2 \quad H_{\text{system}} \quad S_{\text{max}}}{f_0} \right) \tag{11}$$

where S_{max} is the total generation rating of the system [MVA] and H_{system} is the inertia constant of all generators and loads in the system referred to base S_{max} [s].

From Equations (10) and (11), ΔP_{ref} can be calculated as a function of the rate of change of frequency $\frac{\Delta f}{\Delta t}$ multiplied by gain (K) as

$$\Delta P_{\text{ref}} = -K \quad \frac{\Delta f}{\Delta t} \tag{12}$$

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$$\text{where K is given by } K = \left(\frac{2 \quad H_{\text{system}} \quad S_{\max}}{f_0}\right) \tag{13}$$

2.5. Power distributed controller block

This block identifies how much active power should be provided by each SSWT unit based on its capacity and sends the appropriate signal to every SSWT unit to increase or decrease its output.

In steady state, the outputs of this block are predefined power set points determined by a local controller fitted in each SSWT unit. When a disturbance is detected, this reference will be changed by the controller according to the type of disturbance (e.g. over-frequency or under-frequency) and on the basis of the capacity of the unit.

The change in the power reference setting for all SSWT units (ΔP_{ref}) is first expressed in per unit:

$$\Delta P_{\text{pu} \quad \text{ref}} = \frac{\Delta \quad P_{\text{ref}}}{P_{\text{dif}}} \tag{14}$$

Then, the new set point for one SSWT unit *i* can be calculated as follows:

First, calculate ΔP_i share for unit *i*

$$\Delta P_i = \left\lfloor \Delta P_{\text{pu} \quad \text{ref}} \times \left(P_{\text{ir-par}} - P_{\text{i-par}}\right) \right\rfloor \tag{15}$$

where $P_{\text{ir-par}}$ is the participation of SSWT unit *i* at rated power based on total rated power generation of all SSWTs [pu] and $P_{\text{i-par}}$ is the actual participation of SSWT unit *i* based on the total rated power of all SSWT units [pu].

Thus, the new set point is

$$P_{\text{pu} \quad \text{iref}} = \left\lfloor \Delta P_i + P_{\text{i-par}} \right\rfloor \tag{16}$$

From Equations (15) and (16), the new set point P_{i} for unit *i* is determined as follows:

$$P_{\text{pu} \quad \text{iref}} = \left\lfloor \Delta P_{\text{ref}}\left(P_{\text{ir-par}} - P_{\text{i-par}}\right) + P_{\text{i-par}} \right\rfloor \times P_{\text{TWT}} \tag{17}$$

3. TEST NETWORK

The load-frequency controller has been implemented and tested using PSCAD/EMTDC (PSCAD Power System Simulation, HVDC Research Centre, Manitoba, Canada). Figure 2 shows the EHV1 33 kV rural network model [14] used in the study. Three synchronous generators (G1, G2 and G3) with equal rating represent the main system providing 34.2 MW connected to a 132 KV bus (bus 100). One interconnected generator that provides 4 MW to the network is connected to a 33 KV bus at bus 336. The total load is 38.16 MW/7.74 MVar. The network also comprises 10 MW (26.2% penetration) of small-scale wind generation represented by five coherent wind turbines units rated 2 MW. These units are connected to the EHV1 33 kV rural network at different locations (1101, 1106, 1108, 1114 and1115). The actual output power of these units is as follows: unit connected to bus 1101 is 1.6 MW (80%), the unit connected to bus 1108 is 1.5 MW (75%), the unit connected to bus 1106 is 1.46 MW (73%), the unit connected to bus 1115 is 1.4 MW (70%) and the unit connected to bus 1114 is 1.34 MW (67%).

4. SIMULATION RESULTS AND ANALYSIS

The performance of the load-frequency controller is tested following a frequency disturbance due to a load increase in the system.

4.1. Testing the performance of the controller

The duration of the simulation is 70 s. At the start, the balance between consumption and generation is ensured and maintained. At $t = 10$ s, the load 'load 1102' is increased by 3.816 MW (10% from the

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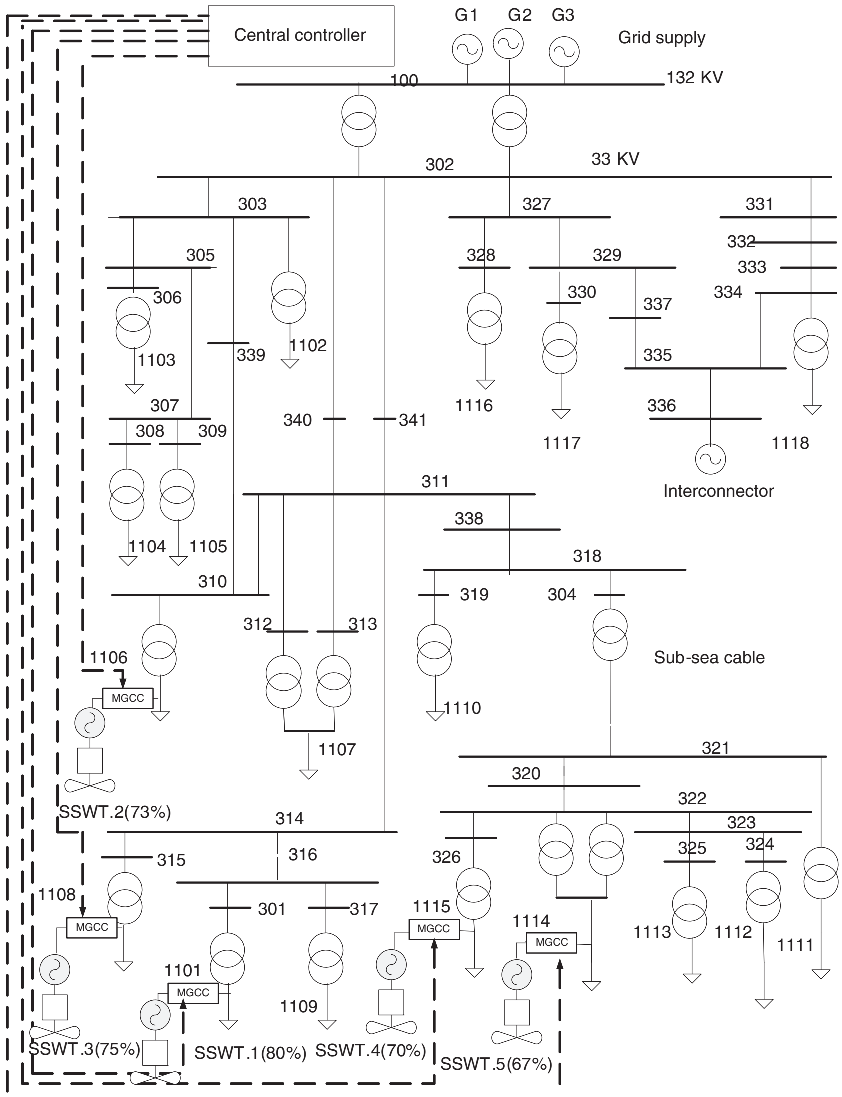

Figure 2. Network with small-scale wind turbines used in the analysis.

total load), which leads to a decrease in the system frequency as shown in Figure 3. In the very few moments after the load increase, the main system generators (G1, G2 and G3) increase their output to supply this load as shown in Figure 4. Once the disturbance is detected by the central controller, it sends signals to SSWTs to increase their output power as shown in Figure 4. It can be observed that the total output power from SSWTs increases to a maximum value during the first 3 s after the disturbance. This is achieved by controlling the output power of each wind unit by means of pitch control as shown in Figure 5. During the disturbance, each unit injects the power required from it according to reference

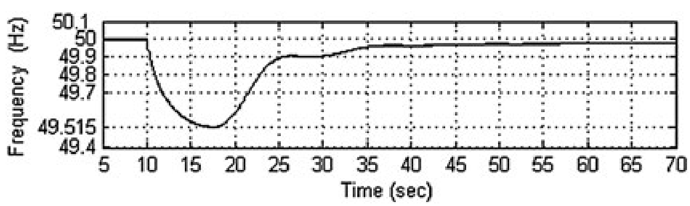

Figure 3. System frequency behaviour of SSWTs with load-frequency control.

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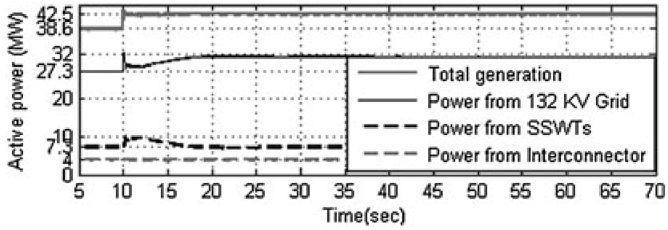

Figure 4. Active power generation in the system.

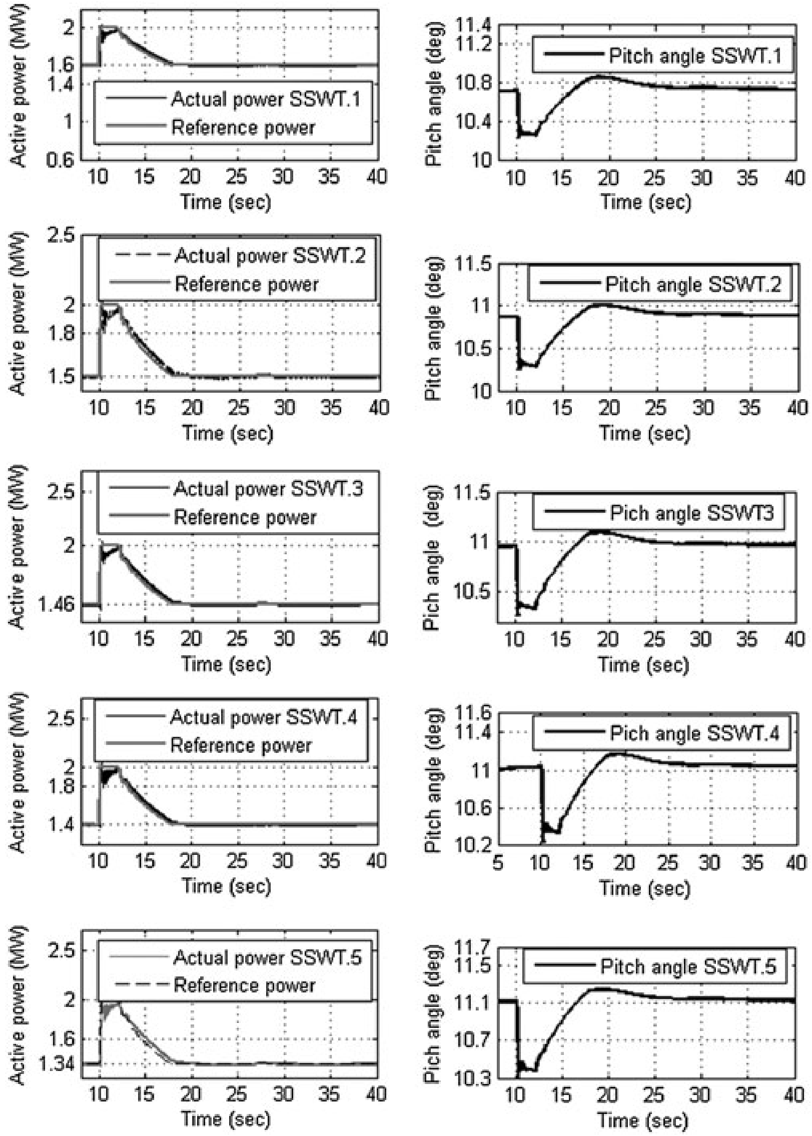

Figure 5. Active power and pitch angle for SSWTs (load increase).

signal received from the central controller. When the main generators start to increase their output power, the central controller starts to reduce the power required from SSWTs until it reaches a value equal to the value before the disturbance.

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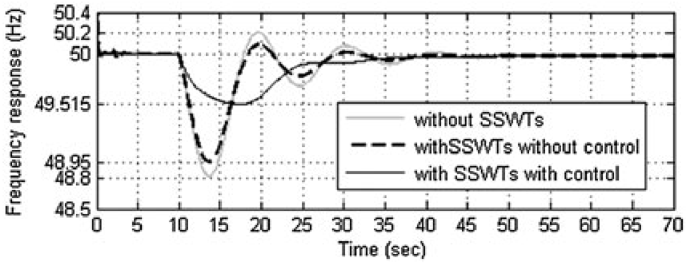

Figure 6. Comparison of system frequency response (load increase).

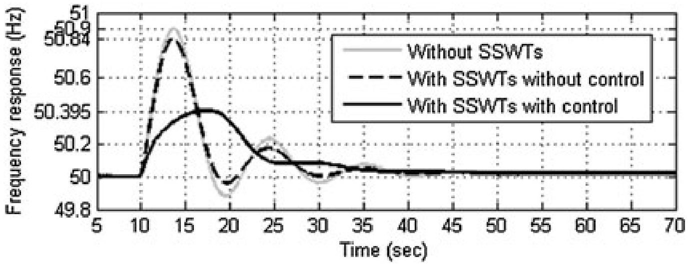

Figure 7. Comparison of system frequency response (load decrease).

4.2. Comparison of system frequency response during different operating conditions

The simulation results illustrate the performance of the load-frequency controller for under-frequency and over-frequency events, with and without SSWT. The base case is when system is running in steady state without SSWTs.

Figure 6 illustrates that without SSWTs, the frequency of the system decreases to value 48.8 Hz when a new load is connected. The threshold value is 49.5 Hz, which may activate the protection system if suitable controls are not in place. When SSWTs are connected to the system (without load and frequency control), the frequency drops to 48.95 Hz, which may also activate protection devices. However, when the SSWTs units are provided with the load and frequency controller, the frequency drops to 49.515 Hz, avoiding exceeding the limit and giving more time for the system generators to cope with the additional load for the longer term.

Additional tests were conducted to assess the controller performance in the case of a decrease in load (to simulate an over-frequency event). To this aim, 'load 1105' is disconnected at $t = 10$ s representing a 10% decrease in load. Figure 7 illustrates that without SSWTs, the frequency of the system increases to 50.9 Hz, which again may trigger over-frequency protection (assuming a threshold of 50.5 Hz). When SSWTs are connected without the controller, the frequency increases to 50.8 Hz, which is still above the upper limit. However, when the load-frequency controller is operating, the system frequency is well-controlled below the limit at 50.395 Hz, which allows the system to continue normal operation

5. CONCLUSIONS

The load-frequency controller has been successfully implemented and tested using PSCAD/EMTDC. A real distribution system with a load scenario is used in the test. This study shows that large penetration of SSWTs connected near the load area with load and frequency control has a significant impact on the stability of the system. Moreover, using the proposed controller, we found that there are no oscillations in the system frequency before restoration to its initial condition. In addition, the results show that it is necessary to coordinate between the central controller and the local controllers of SSWTs in order to maintain the system frequency within limits.

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