Integration of Wind Power Plant (WPP) for primary frequency regulation

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***Abstract* -- Power system frequency stability is crucial to be controlled and monitored. A speed governing system performs the primary frequency control function in a conventional power system where synchronous generators are used. However, due to load increase, the generator's speed governing system can only maintain the system frequency to the new steady-state, which is the level below its nominal value. If the load demand keeps on increasing, the power system grid can become unstable. The frequency instability can result in power system grid collapse and lead to blackouts. To avoid the power system grid collapse, utilization of a wind power plant as the active power compensator is proposed. The control logic is also developed using DIgSILENT Simulation language (DSL) for wind active power scaling. The frequency stability analysis is performed on modified IEEE 14 Bus Network. Various case studies are performed to assess the effectiveness of the control scheme.**

***Index Terms*— Power system stability, Primary frequency control, protection, speed governing system, wind power plant integration**

I. INTRODUCTION

Power system frequency control is performed in three-level stages: primary, secondary, and tertiary. Primary frequency control performed by the governing system is based on its droop characteristics. The droop characteristic acts as the regulation factor, and hence the frequency can not be fully recovered on primary control provided the disturbance remains unchanged [1]. This is the fastest control stage which usually occurs in less than 30s post-disturbance [2]. The next control stage is the secondary control. This type of control is supplementary to the primary control. It enables the frequency to be restored to its nominal state provided that there are enough generation reserves to cater for the deficit. Secondary control is initiated after the primary control; its control action is between 30 seconds up to 15 minutes following a disturbance. This function is also known as load frequency control (LFC) which is performed by the automatic generation control (AGC). The third stage of control is the tertiary control function. This control function is performed by re-adjusting the generation's schedule power to recover the power utilized during the primary and secondary control[1] [2][3][4].

When the three control stages have been exhausted and no other active power compensation to supply the load demand, emergency frequency control is implemented as the last resolution.[5] developed a multi-stage load shedding scheme, this control system can be applied when the primary, secondary, and tertiary control systems cannot process any required control function due to insufficient energy reserves.

This paper emphasizes that the emergency control stage should be avoided if alternative energy sources can be dispatched to the power grid to accommodate the increased load demand.

A. *Primary frequency control.*

Numerous research proposals in regards to frequency control strategies considering the integration of wind turbine generators were conducted. In [6], a nonlinear control strategy to temporarily improve the primary frequency through the contribution of a double-fed induction generation wind turbine is proposed. In [7], three frequency control strategies were proposed. The first strategy is frequency control through pitch control, and this option is regarded as a simple method, although its disadvantage is the loss of renewable base energy as it reduces the output power of the wind turbines under its normal operating condition. The second strategy is kinetic energy control, and this control strategy re-adjusts the set point of the wind turbine power output; however, its drawback is that it shifts the power tracking curve to a range of low rotational speed resulting to small power losses. The third strategy is also a kinetic energy control but operating in a reverse direction by shifting the operating point to higher rotational speed and consequently de-loading the turbine at the initial point of disturbance. This control option surpasses the second option as the efficiency of the wind turbine generator is improved. Another advantage of option three against option two is that the power tracking curve can be maintained and when the machine is decelerating, it can produce more kinetic energy before the the rotor critical rotational speed is reached. In [8] and [9], type 3 Wind turbine generator is implemented for onsite validation, also to verify its compliance with North American Electric Reliability Corporation (NERC) standards.

The generic model of this type 3 wind turbine generation was developed by Western Electricity Coordinating Council (WECC) in collaboration with Internation Electrotechnical Commission (IEC). In [10], a nonlinear droop control was proposed. In this scheme, a droop coefficient is adjusted to respond to a frequency deviation. The modulation of the droop coeficiecnt effectively controls the frequency variation towards the targeted value. However, the simulation results indicate that, this control scheme only improves the frequency nadir and maintains the frequency of the system post-disturbance at the same level as the conventional droop control scheme. In [11], a pitch and speed control scheme of the wind turbine generator was proposed. The relay element is used for switching the overall control scheme. However, this method can be detrimental to the power system during the switching process. Frequency overshoots can be experience in the switching process. In [12], a comparative study is made on the wind turbine generator inertial respose and primary frequency control with that of the synchronous generators. In [13], frequency control methodologies are reviewed. Classical control and soft computing or artificial intelligent techniques are also reviewed. The use of classical Propotional Integarting control technique is still widely used in the power system control. The general model of type 3 double-fed induction generator (DFIG) wind turbine is described in [14] and its dynamics.

From the literature review, it is evident that, to utilize wind power plant to support grid frequency stability, additional control loop is required.

II. SUPPLEMENTARY PRIMARY FREQUENCY CONTROL STRATEGY OF TYPE 3 DFIG.

The DFIG model presented in [7], is used in this study. It comprises of various control loops with different functions. A detailed specific control functions of the DFIG are also specified in [8]. However, modifications were done on the pitch control loop and the torque control loop for the developed supplementary frequency control loop. This is done to support primary frequency in the power system grid through utilizing DFIG. The control logic is developed using DIgSILENT Simulation Language. The logic is shown in figure 1 below. The guide in developing the control logic below was inspired by [4] when they developed an automatic generation control using DIgSILENT.

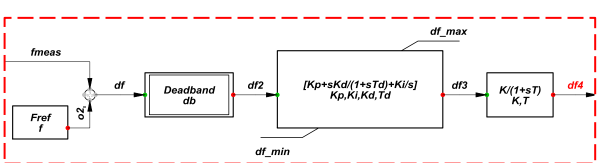


Fig. 1. Primary frequency control logic.

A. *Operating principle of the develop primary frequency control loop.*

The operation of the developed control system make use of the system frequency measured (fmeas) at the Point of Common Coupling (PCC). Under normal operating conditions, the reference frequency is equal to the measure frequency (fmeas=Fref). When a disturbance occurs, fmeas will change, and this will result in change in frequency which is calculated as per equation 1 below:

$$df = F_{ref} - f_{meas} \tag{1}$$

The developed control scheme is model in such a way that it complies with the primary frequency control requirement as per the grid code requirements. According to the Grid Code requirements, the primary frequency can be regulated if it is less than 49.9Hz and more than 50.1Hz and it should be maintained withn these limits (49.9Hz<f<50.1Hz) [10]. Even the droop characteristic of the synchronous generator used in power system needs to comply with this requirement. The allowable deadband according to South African Trasmission Grid Code is 15mHz [15]. According to [10], the safest deadband to be maintained is ±10mHz as shown in figure 2 below.

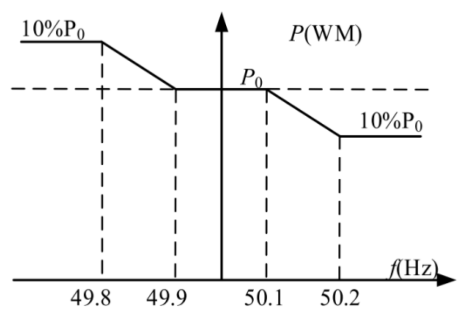


Fig. 2 The frequency response droop curve for power generation [10]

10mHz deadband is used for this study. From figure 1 above, when the frequency deviation is more than 10mHz, df2 is obtained as per equation 2 below:

$$df2 = (F_{ref} - f_{meas}) \quad \therefore \ if\ db\ is\ \pm 10mHz \tag{2}$$

the control signal (df2) will be sent to the PID control and the output (df3) is filtered through the low pass filter as indicated in figure 1 above, and df3 is calculated as per equation 3 below:

$$df3 = K_p(df2) + \int_0^t (df2)\, dt + K_d \cdot \frac{(df2)}{dt} \tag{3}$$

Where K_p is the proportional gain, and K_d is the derivative gain.

The overall output of the primary frequency control logic signal (df4) is sent to the pitch control and the torque control of the wind turbine generator, and df4 is calculated as per equation 4 below:

$$df4 = \left[K_p(df2) + \int_0^t df2\, dt + K_d \cdot \frac{df2}{dt}\right] \times \left(\frac{K}{1+T}\right) \quad (4)$$

Where K is the low pass filter gain, and T is the time constant. The parameters of the developed primary frequency control scheme are sown in Table 1 below:

TABLE 1
PRIMARY FREQUENCY CONTROL SCHEME PARAMETERS.

NAME	VALUE
Db dead-band [p.u]	0.002
F Reference frequency [p.u]	1.00
K Low pass filter signal gain [p.u]	-20.00
T Low pass filter time constant [s]	10.00
Kp Proportional gain of PID controller [p.u]	20.00
Ki Integral gain of PID controller [s-1]	0.01
Kd Derivative gain of PID controller [p.u]	0.05
Td Derivative time constant of PID controller [s]	0.05
df_min Minimum limitation of signal scaling [p.u]	-0.05
df_max Maximum limitation of signal scaling [p.u]	0.05

The developed primary frequency control scheme needs to be tested to verify its effectiveness in primary frequency control of the power system grid using WTG active power compensation.

III. POWER SYSTEM MODELING AND CONTROL APPROACH

To effectively investigate the proposed primary frequency control scheme, an IEEE-14 bus network system is modeled using DIgSILENT power factory version 2020. The data or parameters for the IEEE 14 bus network used can be found in [16]. The network diagram is shown in figure 3 below.

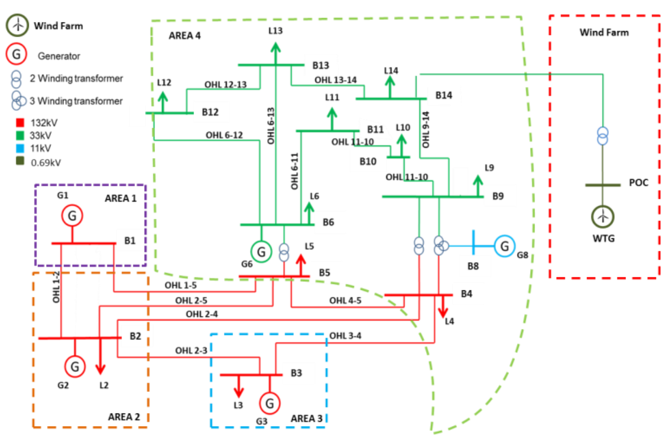


Fig. 3 Four-area power system network [16]

From the network shown in figure 3 above, the installed generation capacity is 367MW, and the spinning reserve is 42.65MW. The total load demand is 259MW. The rated system frequency is 50Hz. The integrated wind farm consists of 22 wind turbines of 2MW. However, under their normal operating condition, these wind turbine generators are not dispatched. Their primary role is to compensate for active power when the load demand changes.

In order to test the frequency response of grid understudy, a 10% load increase is implemented. Load increase in the power system can be in ramp or step form. An example of a step form load increase would be the re-integration of load supply after a power outage. A ramp form can be associated with the day-to-day load increase scenario during peak time. However, in this study, a ramp form load increase is considered.

The additional control signal to the existing wind turbine generator control scheme from the developed primary frequency control scheme is implemented. This is the additional control loop to enable the wind turbine generator to participate in active power compensation in the event of load increase contingency. Figure 4 illustrates the modified pitch controller, where the additional control signal is applied. The role of pitch angle control is to keep the turbine shaft torque within its design limits by limiting the aerodynamic power higher than the rated wind speed [17], more details are given in [18].

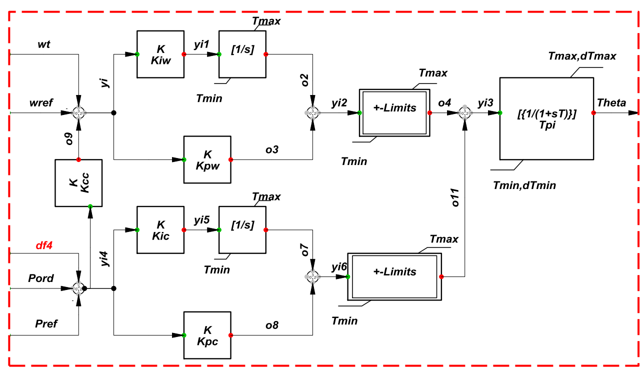


Fig. 4 modified pitch controller

Figure 5 below is the modified torque controller with an additional control signal from the developed primary frequency control scheme. The torque control in the wind turbine control scheme is to track the rotor speed profile from wind speed at an efficient tip speed ratio to ensure maximum power extraction from the wind. It also assists the pitch blade control to keep the rotor speed within the operating limits while regulating the electric power produced by the wind turbine generator [17], and more details are given in [18].

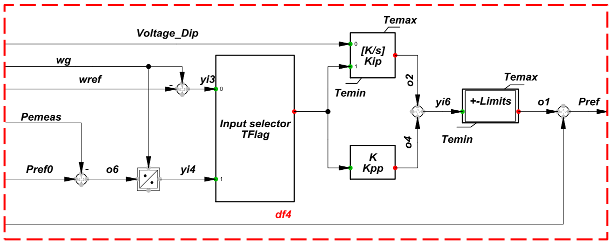


Fig. 5 modified torque controller

IV. SIMULATION ANALYSIS

The simulations are performed using DIgSILENT Simulation Software. This software is equipped with various simulation tools, and they are used for different analyses. For the frequency control process analysis, EMT/RMS simulation tool is used. The EMT option is for electromagnetic transient (short duration or instantaneous) analysis, while the RMS is for electromechanical transient analysis [19]. For the purpose of this study, the RMS option is used as the frequency analysis needs to be analyzed for a longer duration. These simulations are conducted for two conditions, and the first one is when there is no additional primary frequency control loop. The second condition is when the control loop is utilized. The red graph indicates when the primary frequency control loop is out of service, and the lime graph illustrates when the primary frequency control scheme is activated.

The simulation is set for 200s duration, and two load contingencies are applied. The first load contingency is the increase in load demand which is initiated 10 seconds later of the simulation. This load increase is ramped by 10% for 30 seconds duration, and the ramp state finishes at 40 seconds of the simulation duration. In 70 seconds later, post the finishing of the initial load demand increase contingency, a second contingency is applied at t=110s. This load contingency resets the initial contingency by decreasing load demand to its initial state before the load increase contingency (10% drop). The applied load contingency is shown in figure 6 below. The 10% load demand increase resulted in a total demand increase of 284.76MW from 259MW.

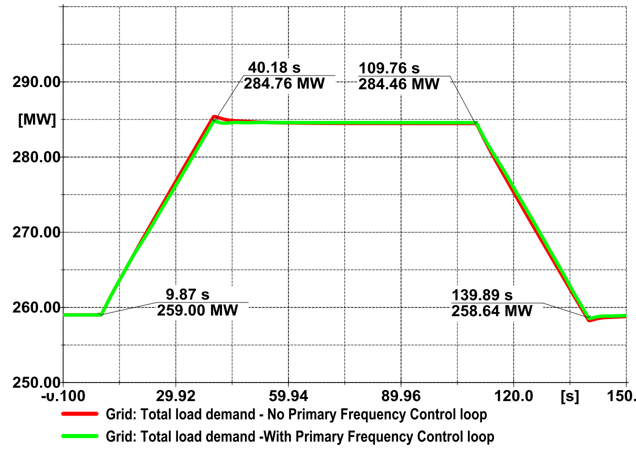


Fig. 6 Total load demand.

The 10% load demand increase resulted in additional generation supply as shown in figure 7 below. The generation supply increased from 267.60MW to 294.83MW

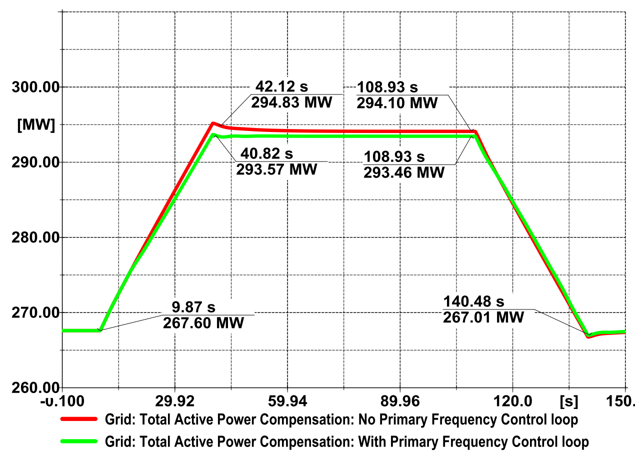


Fig. 7 Total generation supply.

The load demand increase resulted in power system frequency deviation from its nominal value of 50Hz. Considering figure 8 below, where there is no supplementary control loop in the wind turbine generator control system, the frequency was not supported and it decreased to 49.55Hz and the governing system brought the frequency to a steady-state of 49.58Hz as indicated on red graph. When the primary frequency control scheme was brought into inservice, the control scheme stabilized the system frequency at 49.87Hz due to the support of the wind turbine generators. It is also evident that the additional control loop settled the system to the new steady-state quicker than the governing system response. The second contingency applied at t=110s proves that the additional control scheme is adapting to the condition when the load is being returned to its initial state. Hence there is no frequency overshoot experienced.

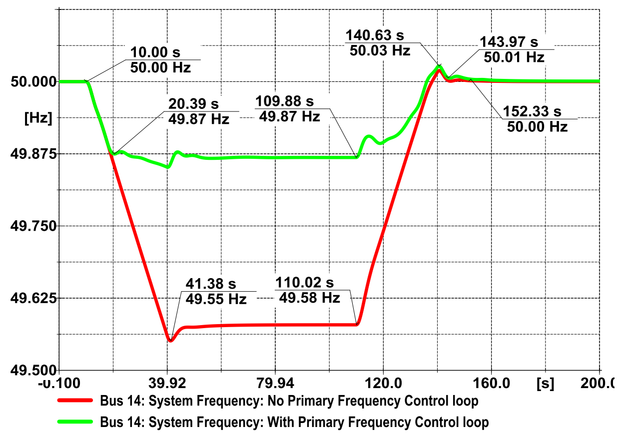
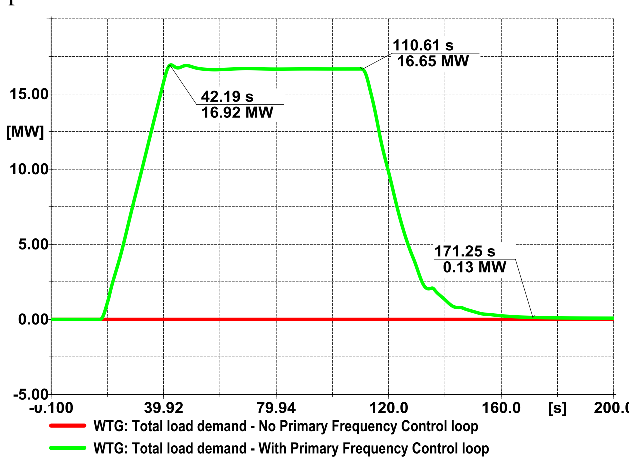


Fig. 8 Power system frequency.

Another feature of the developed primary frequency control scheme is its adaptability to the changing frequency conditions. In figure 9 below, it can be noted that the WTGs were not contracted to supply active power under normal conditions to the grid. When the frequency changed due to load increase, the WTG started to supply additional active power to the grid. When the load demand is restored to its initial state, the WTG active power is dropping back to its initial state. Hence the control scheme is regarded as being adaptive.



V. CONCLUSION

In this paper, the primary frequency control scheme that enables WTG utilization to support the system frequency under changing load conditions was introduced. The primary control scheme was implemented on type 3 WTG. The simulation results prove its effectiveness and considering the primary frequency control band shown in figure 2 above, and it also proves its compliance to the grid code requirement as the primary control action should only be performed when the frequency deviation is more than 10mHz. The simulation results also prove that the proposed control scheme is adaptive to the power system conditions. Its settling time is compared to that of the governing system, and the results show that the proposed control scheme reaches the steady-state quicker.

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