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Integration of Acceleration Feedback Control with Automatic Generation Control in Intelligent Load Frequency Control

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Abstract**—**This paper investigates the effects of knowledge-based acceleration feedback control integrated with Automatic Generation Control (AGC) to enhance the quality of frequency control of governing system. The Intelligent Acceleration Feedback Controller (IAFC) is proposed to counter the over and under frequency occurrences due to major load change in power system network. Therefore, generator tripping and load shedding operations can be reduced. Meanwhile, the integration of IAFC with AGC, a well known Load-Frequency Control (LFC) is essential to ensure the system frequency is restored to the nominal value. Computer simulations of frequency response of governing system are used to optimize the parameters of IAFC. As a result, there is substantial improvement on the LFC of governing system that employing the proposed control strategy.

Keywords**—**Knowledge-based Supplementary Control, Acceleration Feedback, Load Frequency Control, Automatic Generation Control.

I. Introduction

FLUCTUATIONS in frequency may affect the operation of power system plant and customer equipment, initially appearing as a malfunction and, in the extreme, causing damage [1]-[3]. Hence, generator tripping and load shedding schemes are implemented in power systems to avoid damage of the generating units and customer load units due to large disturbances. However, these schemes which activated by large frequency deviations are undesirable actions as they reduce the security and profitability of the power system operation. It is therefore important to ensure the frequency remains within the allowable frequency band. The typical variation limit set in the countries' Electricity Grid Code is ±1% of the system frequency [4]-[7], i.e. between 49.5 Hz to 50.5 Hz for 50 Hz system.

The highly competitive market of electrical power industry has led to research on the intelligent adaptive control in improving the conventional frequency control actions by several researchers [8]-[13]. This intends to offer the utilities to have high security of supply in terms of the operation of power plants and system control and also economically dispatch the load demand. It has been recognized that knowledge-based acceleration feedback controller can reduce over and under frequency occurrences and improve substantially the quality of frequency control of steam-turbine generators [9], [10]. On the other hand, non-fixed integral gain of Automatic Generation Control (AGC) can minimize the frequency deviations and restore the nominal frequency the soonest possible, in which fixed integral gain fails to do so over a wide range of off-nominal operating conditions [12].

This paper is motivated by the desire to integrate an Intelligent Acceleration Feedback Controller (IAFC) with AGC to enhance the performance Load Frequency Control (LFC) of governing system model. The proposed system integration implements knowledge-based technique to study the feasibility and effect of LFC. Computer simulations of frequency responses for a gas turbine generator model (GAST) [14] are used to optimize all parameters of the integrated system and demonstrate its performance for major disturbances in power system. As a result, it is shown that over and under frequency occurrences can be suppressed, and frequency deviation is minimized then system frequency is restored to the nominal value as soon as possible.

II. Control Strategy

For simulation purpose, the LFC is represented by a widely used model for representing the dynamic behavior of Gas Turbine Generator proposed in [14], GAST model (see Fig. 1). Descriptions of parameters of the model are noted in Table 1.

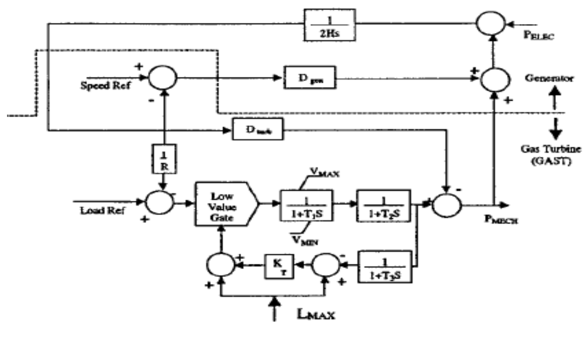

Fig. 1: GAST model

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TABLE I
PARAMETERS OF THE GAST MODEL

Parameter	Description
R	Governor speed droop (pu speed / pu MW)
T_1	Fuel system lag time constant 1
T_2	Fuel system lag time constant 2
T_3	Load limiter time constant
L_{max}	Load limit
K_T	Temperature control loop gain
V_{max}	Maximum value position
V_{min}	Minimum value position
D_{turb}	Turbine damping
D_{gen}	Generator damping
H	System inertia

In this project, computer simulations on the GAST model are conducted without exceeding 75% of machine rating. This is due to the fact that the model does not represent gas turbine operations accurately at higher load levels when the power control is done based on the exhaust gas temperature rather than the machine speed [14].

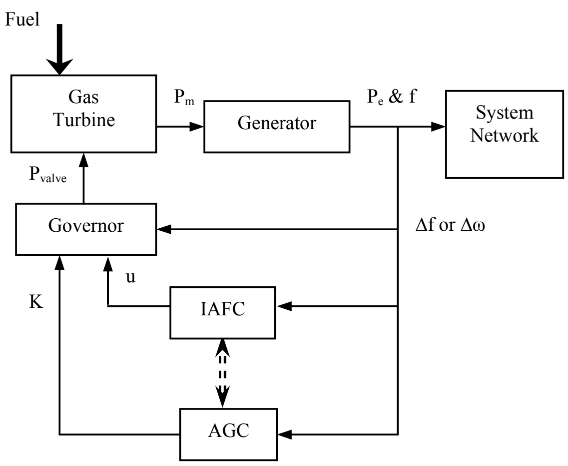

Fig. 2: Configuration of proposed Intelligent Acceleration Feedback Controller (IAFC)

The frequency variation, Δf is a result of the disproportion between the mechanical and the electrical power of the generator units. A surplus of mechanical power due to load decrease causes the generator speed to increase and the frequency to rise. Meanwhile, a deficit of mechanical power due to load increase or generator outage causes the generator speed to decrease and the frequency to drop. Therefore, in this project, typical frequency limitations of ±1% of system frequency as mentioned earlier are introduced during the simulations to study the effect of the proposed control strategy in reducing the over and under frequency events.

Since acceleration/deceleration of generators is proportional to the difference between their mechanical and electrical power, large differences between mechanical and electrical power are followed by large initial acceleration/deceleration of generators. This leads to the large frequency deviations in the system. Thus, the positive or negative maximum frequency deviation, i.e. f_{max}-f_o and f_{min}-f_o is proportional to the initial acceleration, a(0) [9], [10]. If the positive initial acceleration is large, the maximum frequency deviation is also large.

Subsequently, for a large negative initial acceleration, i.e. the large deceleration, the maximum frequency deviation is negative large. Conventional controllers using the speed governors are not perceptive to acceleration. Therefore, the proposed IAFC that is sensitive to the acceleration and uses a knowledge-based control strategy can be used as an effective measure against the large frequency deviations.

The acceleration is calculated using the following expression.

$$a(nT) = \frac{\left[\Delta f(nT) - \Delta f\left((n-1)T\right)\right]}{T} \quad (1)$$

Hence, only one past data of frequency deviation, Δf((n-1)T is required in addition to the current measured data, Δf(nT) to calculate the turbine acceleration and memorized control strategy is required.

The a-Δf plane shown in Fig. 3 is used in the control strategy of the IAFC. The upper-half plane represents the positive acceleration while the lower-half plane represents the negative acceleration, i.e. deceleration. The area in the right-half plane represents a frequency that is greater than the nominal value or the speed faster than the desired synchronous speed. The area in the left-half plane represents a frequency that is less than the nominal value or speed slower than the desired synchronous speed. The origin 0 is the desired equilibrium point in which all dynamic performance should reach the steady state level without neglecting the synchronous speed or frequency nominal value.

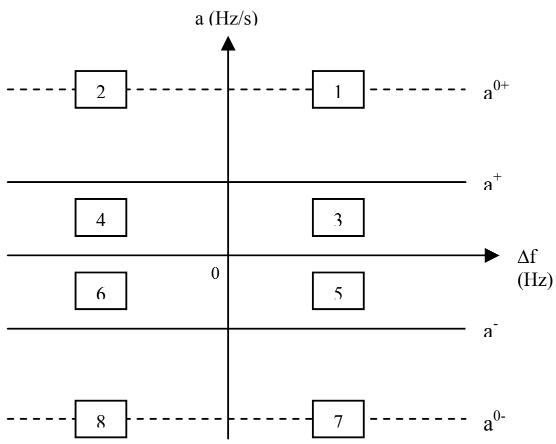

Fig. 3: Eight areas divided in a-Δf plane

The plane is divided into eight areas. The division of the eight areas is bordered by $a=a^+$, $a=a^-$, a=0 and Δf=0. The required control strategies are based on the characteristics of each area and also depend on the occurrences of the disturbances. The controller has to differentiate whether it is over or under frequency event. Both events are discriminated using the initial acceleration by introducing the positive and negative initial acceleration constraint, i.e. a^{0+} and a^{0-} respectively. By establishing the event and which area the generator state belongs to, the proposed IAFC should be able to decide whether the discrete supplementary digital control signal, u is positive large (U^{+max}), positive small (U^{+min}), negative large (U^{-max}), negative small (U^{-min}) or u=0. The u=0 means that the controller is not activated. The control strategies are determined as follows:

Area 1: The frequency is greater than the nominal frequency and the generator speed is faster than the desired synchronous speed, i.e. $\Delta f>0$. At the same time, the acceleration of the unit is considered large, i.e. $a>a^{+}$. Thus, if the occurrence is large over frequency, i.e. $a(0)>a^{0+}$, the large negative signal, U^{-max} is required. However, if the occurrence is under frequency, i.e. $a(0)<a^{0-}$, the small negative signal, U^{-min} is required.

Area 2: The frequency is less than the nominal frequency and the generator speed is slower than the desired synchronous speed, i.e. $\Delta f<0$. But, the unit is accelerating at large acceleration value in which the speed is increasing rapidly towards the desired speed. Therefore, u=0 is required regardless the events.

Area 3: The frequency is greater than the nominal frequency and the generator speed is faster than the desired synchronous speed. At the same time, the acceleration of the generator unit is considered small, i.e. $0<a<a^{+}$ in which the speed is increasing slowly leaving the desired speed. Therefore, the small negative signal, U^{-min} is required for both events to shift the generator speed to the desired speed. This region is used to ensure the minimum deviation and fluctuation of frequency by setting up the optimal value of a^{+} and U^{-min}.

Area 4: The frequency is less than the nominal frequency and the generator speed is slower than the desired synchronous speed. However, the unit is accelerating at small acceleration value in which the speed is increasing slowly towards the desired speed. Thus, the small positive signal, U^{+min} is required for both events to boost up the shifting process of the generator speed to the desired speed. This region is used to ensure the minimum deviation and fluctuation of frequency by setting up the optimal value of a^{+} and U^{+min}.

Area 5: This region is the inversion of the area 4. Thus, the small negative signal, U^{-min} is required for both events to boost up the shifting process of the generator speed to the desired speed. This area is also used to ensure the minimum deviation and fluctuation of frequency by setting up the optimal value of a^{-} and U^{-min}.

Area 6: This region is the inversion of the area 3. Thus, the small positive signal, U^{+min} is required for both events to shift the generator speed to the desired speed. This area is also used to ensure the minimum deviation and fluctuation of frequency by setting up the optimal value of a^{-} and U^{+min}.

Area 7: This area is the inversion of the area 2. Hence, u=0 is required regardless the events.

Area 8: This area is the inversion of the area 1. Thus, if the event is large under frequency, the large positive signal, U^{+max} is required. However, if the event is over frequency, the small positive signal, U^{+min} is required.

In addition to the above control strategies, a variable integral gain, K representing the AGC is introduced to achieve the best performance of the frequency response once the IAFC is switched OFF (deactivate). This is necessary to avoid wear and tear of the IAFC on the generating units.

III. Rule-Based Acceleration Feedback Controller

Now, the desired control rules for the IAFC from the eight proposed areas can be defined. Each proposed area represents a rule for the controller design for each type of disturbances, i.e. large over and under frequency events. The following rules are developed to respond to large over frequency problems, $a(0)>a^{0+}$.

State A: For $m\leq 300$;

Rule A1: if $a(0)>a^{0+}$ and $a(nT)>a^{+}$ and $\Delta f(nT)>0$, then
    m=0;
    $u(nT)=U^{-max}$;
    $K(nT)=K^{0}$;

Rule A2: if $a(0)>a^{0+}$ and $a(nT)>a^{+}$ and $\Delta f(nT)<0$, then
    m=0;
    u(nT)=0;
    $K(nT)=K^{0}$;

Rule A3: if $a(0)>a^{0+}$ and $a(nT)>0$ and $a(nT)<a^{+}$ and $\Delta f(nT)>0$, then
    m=m+1; for m=0,1,2,……300
    $u(nT)=U^{-min}$;
    $K(nT)=K^{0}$;

Rule A4: if $a(0)>a^{0+}$ and $a(nT)>0$ and $a(nT)<a^{+}$ and $\Delta f(nT)<0$, then
    m=m+1; for m=0,1,2,……300
    $u(nT)=U^{+min}$;
    $K(nT)=K^{0}$;

Rule A5: if $a(0)>a^{0+}$ and $a(nT)>a^{-}$ and $a(nT)<0$ and $\Delta f(nT)>0$, then
    m=m+1; for m=0,1,2,……300
    $u(nT)=U^{-min}$;
    $K(nT)=K^{0}$;

Rule A6: if $a(0)>a^{0+}$ and $a(nT)>a^{-}$ and $a(nT)<0$ and $\Delta f(nT)<0$, then
    m=m+1; for m=0,1,2,……300
    $u(nT)=U^{+min}$;
    $K(nT)=K^{0}$;

Rule A7: if $a(0)>a^{0+}$ and $a(nT)<a^{-}$ and $\Delta f(nT)>0$, then
    m=0;
    u(nT)=0;
    $K(nT)=K^{0}$;

Rule A8: if $a(0)>a^{0+}$ and $a(nT)<a^{-}$ and $\Delta f(nT)<0$, then
m=0;
$u(nT)=U^{+min}$;
$K(nT)=K^{0}$;

State B For m>300;
u(nT)=0;
$K(nT)=K^{1}$;

In this project, the maximum frequency limit for over frequency disturbances is 50.5 Hz. The rules for over frequency events are divided into two states, i.e. state A and B in which state A denotes that the IAFC is triggered once the initial acceleration exceeds the threshold and it has to go through rules A1 until A8. During this state, the IAFC can either be switched ON, i.e. activate (rule A1, A3-A6, and A8) or switched OFF, i.e. deactivate or reset (rule A2 and A7). The supplementary control signal, u, i.e. U^{+max}, U^{+min}, U^{-max} and U^{-min} for each rule (rules A1 until A8) is basically adopted from the control strategies from area 1 to area 8 (ascending). Meanwhile, the integral gain, K is K^{0}, i.e. the existing value before the IAFC is activated..

Furthermore, state A is described by m≤300, whereby m is a counter for rules A3 until A6. The counting of 300 samples is considered sufficient and able to provide enough information that the frequency has reached the steady state of its nominal value or almost reaching it. The counter will be reset, m=0, if during the simulation, rule A1, A2, A7 or A8 is triggered.

State B is described by m>300 whereby the IAFC is being switched OFF when the frequency is considered to have reached the steady state level of its nominal value or almost reaching it. At this point, the supplementary control is no longer necessary since the system is operated within the allowable tolerance. Simultaneously, the integral gain, K is changed from K^{0} to K^{1} in order to achieve the best performance of the frequency response once the IAFC is switched OFF.

On the other hand, for large under frequency conditions, $a(0)<a^{0-}$, the minimum frequency is expected to drop below 49.5 Hz. Again the rules for this type of disturbances are also divided into two states, i.e. state C and D in which state C denotes that the IAFC is triggered once the initial deceleration exceeds the threshold. Therefore, state C is the inversion of state A and the integral gain, K will cahnge from K^{0} to K^{2} as state C and D are designed to deal with large under frequency disturbances.

State E

Rule E: if $a(0)<a^{0+}$ or $a(0)>a^{0-}$, then
m=0;
u(nT)=0;
$K(nT)=K^{0}$;

State E as described above shows that the rule is applicable for minor frequency fluctuations, i.e. $a(0)<a^{0+}$ or $a(0)>a^{0-}$. The initial acceleration or deceleration does not exceed the allowable limits. Consequently, the IAFC is not activated at all, u=0 and the integral gain remains constant, $K=K^{0}$. In addition, the counter is also not operated. Rule for state E is necessary to avoid wear and tear of the IAFC on the generating units.

IV. Parameter Setting

There are 4 important parameters need to be considered in the rule-based computer programming development to ensure the proposed controller to function effectively in preventing major disturbances. Those are:

i. Initial acceleration limit, a(0).
ii. Updating acceleration sample limit, a(nT).
iii. Supplementary digital control signal, u(nT).
iv. Variable integral gain, K.

Details of the parameters are noted in Table 2 and 3.

TABLE II
PARAMETERS FOR THE IAFC

Parameter	Value	
	Positive Limit	Negative Limit
a(0)	a^{0+}	a^{0-}
a(nT)	a^{+}	a^{-}
u(nT)	U^{+max} and U^{+min}	U^{-max} and U^{-min}

TABLE III
DIFFERENT VALUES OF INTEGRAL GAIN

Integral Gain, K	Description
K^{0}	Existing integral gain
K^{1}	After over frequency event
K^{2}	After under frequency event

The positive and negative limits of initial acceleration are defined as constraint parameters. They are determined from the knowledge that maximum and minimum frequency deviations are proportional to the initial acceleration. For 60 Hz system, a deceleration of -0.5 Hz/s corresponds to f_{min}=59.5 Hz [9]. Hence, for 50 Hz system, f_{max}=50.5 Hz will suggest a^{0+}=0.5 Hz/s and f_{min}=49.5 Hz will give a^{0-}=-0.5 Hz/s.

The optimal value of positive and negative limits for updating acceleration sample are determined by the computer simulations and also categorized as constraint parameters. The value of a^{+} and a^{-} secure the minimal frequency deviations. For example, if we use a+=0.05 Hz/s and a-=-0.05 Hz/s for the controller which corresponds to f_o=50.05 Hz and 49.95 Hz respectively, we want the frequency response to be in that range and close to the nominal value with the help of the IAFC signal, u before being restored to its nominal value via integral gain, K of the AGC.

The limits of IAFC signal are defined as control parameters. Setting up these parameters is the most challenging task compared to other parameters for the controller. Positive values of supplementary digital control signals are used to counter negative frequency deviations and vice-versa. The optimal values for U^{-max} and U^{+max} are obtained via computer simulations by minimizing the positive and negative maximum frequency deviations correspondingly, i.e. f_{max}-f_o and f_{min}-f_o. Whilst, the optimal values for U^{-min} and U^{+min} are gained by minimizing and smoothing the positive and negative frequency deviations correspondingly so that the frequency response close to the nominal value.

Integration of the IAFC with the AGC is meant by introducing variable integral gain, K of the AGC. The determination of variable integral gain, K value is also done from the computer simulations. Optimal value of K^0 is obtained before applying the IAFC on the dynamic model. Thus, it is defined as the existing integral gain value. In order to permanently reset the IAFC when the frequency has reached the steady state and returned to its nominal value after over and under frequency circumstances, the K value has to be changed from K^0 to K^1 or K^2 as shown in Table 4. Therefore, optimal K^1 and K^2 are determined by minimizing the frequency deviations caused by permanently switching off the IAFC, i.e. u=0. The change of K from K^0 to K^1 or K^2 should be synchronized with the change of u from U^{-min} or U^{+min} to zero in order to minimize the frequency fluctuation and deviation.

V. Simulation Resutls

The performances of the proposed controller are investigated using load increase and decrease tests that signify the large under frequency and over frequency event respectively. This paper demonstrates an example of results when sudden load increased (step input from 0.4 pu to 0.6 pu) is applied to electrical power input of the GAST model. Keep in mind that the step inputs applied consider the generator loading that must not over than 75% of the machine rating as previously mentioned. Table 4 shows the parameter values that representing a 95 MVA machine [14] used in this investigation.

TABLE IV
COMBINED-INERTIA, GENERATOR DAMPNG AND GAS POWERED TURBINE-GOVERNOR SYSTEM PARAMETERS OF THE 95 MVA MACHINE

Parameter	Value
H	6.5
D_{gen}	1
R	0.042
T_1	1.5
T_2	0.1
T_3	3
L_{max}	1
K_T	1
V_{max}	1
V_{min}	-0.02
D_{turb}	0

Optimal parameters for the AGC and IAFC to function effectively based on the given event of over and under frequency are shown in Table 5. Initially, the system is simulated without IAFC. Thus, the integral gain of AGC remains constant as K^0. However, as the AGC is integrated with IAFC, fixed integral gain is no longer suitable. Hence, K1 and K2 are introduced to support the integration so that the desired system response can be obtained.

TABLE V
OPTIMAL PARAMETERS FOR THE IAFC AND AGC

Parameter	Value
a^{0+}	0.01
a^{0-}	-0.01
a^{+}	0.005
a^{-}	-0.005
U^{+max}	1.2
U^{-max}	-1.2
U^{+min}	0.16
U^{-min}	-0.16
K^0	-1.6
K^1	-1.15
K^2	-2.2

The frequency responses after a sudden load increased with fixed and non-fixed integral gain K of AGC are illustrated in Fig. 4 and 5. It is obvious in both conditions that the IAFC able to significantly offset the large overshoot of under frequency response that occurred before using the IAFC. Thus, load shedding program can be avoided. However, the difference between both conditions is at approximately t=43s when the IAFC is switched OFF, u=0 (see Fig. 6). Result with fixed AGC, K^0 shows that the frequency started to decrease hugely immediately after the IAFC is switched OFF. Nevertheless, when variable AGC is integrated with the IAFC the frequency performance is improved extensively without large fluctuations. In this case, the K^0 is changed to K^2 as shown in Fig. 7.

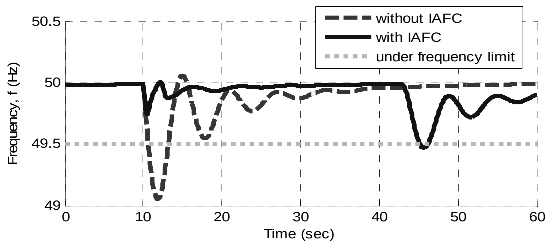

Fig. 4: Frequency response due to load increased with fixed integral gain K

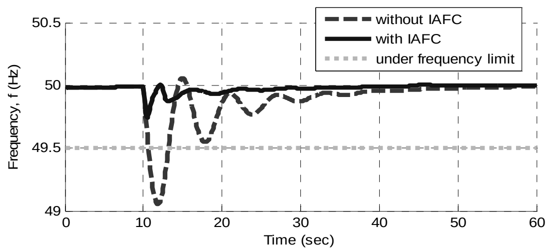

Fig. 5: Frequency response due to load increased with variable integral gain K

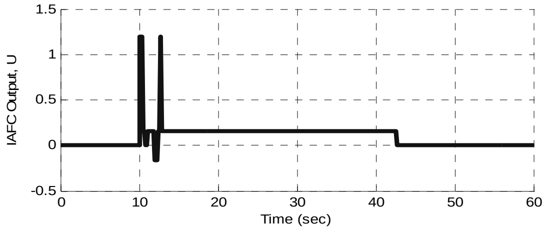

Fig. 6: IAFC output due to load increased

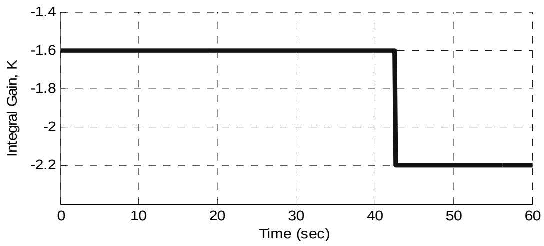

Fig. 7: Change of integral gain of AGC ($K^0 \rightarrow K^2$)

Fig. 8 demonstrates the distinction in AGC output signals determined from the computer simulations. For the first case, the AGC output without using the IAFC is obtained from fixed gain, K^0=-1.6. The signal shows that the AGC plays a major function in LFC to restore the frequency to its nominal value. It takes quite a long period to reach the steady state level. Meanwhile, the second case whereby the AGC output when using with the IAFC and obtained from the same fixed gain, describes that the value almost reach the steady state earlier than the first case at very low level. But, suddenly it increases as the IAFC is switched OFF and the AGC signal started to plays its major role to restore the frequency to its nominal value. This shows that the IAFC and the AGC are not well integrated.

Thus, the third case describes that integration by simultaneously switched OFF the IAFC and change AGC gain from K^0=-1.6 to K^2=-2.2 is the best solution. The vital point where both IAFC and AGC change synchronously is called *synchronous point* and it is required to avoid high imbalance of the system which could lead to undesired high frequency deviations and fluctuations. For that reason, there is no disturbance on the frequency deviation response when the controller is permanently switched OFF.

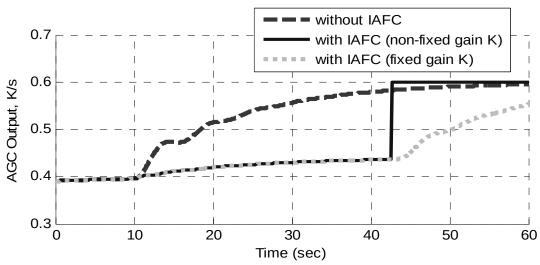

Fig. 8: Comparisons of AGC output

VI. Conclusion

The control strategy has obviously succeeded, in which the quality of frequency control substantially improved, and the major disturbances are suppressed, subsequently, load shedding and generator tripping operations can be prevented. In addition, the use of variable integral gain of AGC gives an opportunity for the frequency response to be restored to the nominal value smoothly without large ripple during the transient period. This condition can be achieved by determining the optimal value of integral gain once the *synchronous point* is reached.

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