An adaptive set-point modulation technique to enhance the performance of load frequency controllers in a multi-area power system

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Abstract

Parameters and configuration of power systems are continuously prone to change. This might negatively affect the performance of load frequency controllers. PI controllers are widely used for load frequency control (LFC) in power systems. Hence, enhancing the performance of these controllers is of great importance. In this paper, an adaptive set-point modulation (ASPM) method is proposed to enhance the performance of PI controllers. Simulation studies carried out on a two-area power system with different types of generating units and HVDC link prove the superiority of the proposed adaptive set-point modulation assisted proportional integral (ASPM-PI) over the conventional proportional integral (PI) and proportional integral derivative (PID) controllers. It has also been shown that the ASPM-PI controller is robust in case of power system parameters variations and change in the configuration.

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Keywords: Adaptive set-point adjustment; Load frequency control; Parameters variation; PI controller

1. Introduction

In power systems, load changes continuously during the day and results in power imbalance. Generated power should be controlled to retain the power balance such that the frequency would not deviate beyond the specified limits and also tie-lines power remains within the permissible constraints. These objectives can be achieved by fine tuning the load frequency controllers. Over the last decades, a large number of methods have been proposed for tuning load frequency controllers.

Internal model control was implemented in (Ibraheem et al., 2005) for tuning a unified PID load frequency controller. To design robust load frequency controllers in multi-machine power systems, a systematic method based on maximum
peak resonance specification was proposed in (Khodabakhshian and Edrisi, 2008). In (Dong et al., 2012), an active disturbance rejection control method was used in a decentralized LFC scheme. An adaptive fuzzy gain scheduling scheme has been used in (Talaq and Al-Basri, 1999) for the PI load frequency controllers. A control scheme based on artificial neuro-fuzzy inference was presented in (Abdennour, 2002) to optimize and update the automatic generation controllers’ gains according to the load variations. In (Kocaarslan and Cam, 2005), the gains of a PI load frequency controller are adaptively determined implementing a fuzzy system. Takagi-Sugeno fuzzy system has been proposed in (Lee et al., 2006) for LFC in a two area power system. In (Bevrani and Daneshmand, 2012), fuzzy logic based load frequency controllers have been implemented in a system with high penetration of wind turbines.

Evolutionary algorithms have been widely used for tuning load frequency controllers. In (Abdel-Magid and Dawoud, 1996), genetic algorithm (GA) was used for tuning the load frequency controllers of a two area non-reheat thermal power system. Actually, in (Abdel-Magid and Dawoud, 1996), several performance indices were used for tuning the PI controllers using GA. In (Pingkang et al., 2002), GA was used for LFC in a multi-area power system. A robust method for tuning the PI load frequency controllers using GA was proposed in (Huddar and Kulkarni, 2008). In (ADITYA, 2003), the load frequency controllers of a three-area deregulated power system with thyristor controlled phase shifter were tuned using particle swarm optimization (PSO). An adaptive weighted PSO is used in (Sharifi et al., 2008) for tuning multi-objective load frequency controllers. In (Bhatt et al., 2010), a hybrid PSO was implemented for tuning the gains of PID load frequency controllers of a deregulated multi-area power system. In (Stron and Price, 1997), differential evolution (DE) was used for tuning the PI load frequency controllers in a two area power system. For load frequency control in a multi-source power system including HVDC links, DE was implemented in (Mohanty et al., 2014). In (Sahu et al., 2013), a parallel 2 degree of freedom PID controller (2-DOF PID) was used for LFC in a two area power system. Imperialist competitive algorithm (ICA) was implemented in (Rakhshani et al., 2012) to find the weighting matrices for an LQR output feedback in LFC problem. In (Soheilirad et al., 2013), the performance of ICA in tuning the load frequency controllers in a multi-area power system was compared with GA. For optimizing the gains of the PID load frequency controllers in a three area power system, ICA has been used in (Shabani et al., 2013). In (Taher et al., 2014) ICA was implemented for tuning the non-integer load frequency controllers in a three area power system with reheat, non-reheat and hydraulic generating units. In (Debbarma et al., 2013) bacterial foraging algorithm was used for tuning the non-integer load frequency controllers.

Literature review shows that, due to the importance of LFC, a lot of effort has been made to introduce new load frequency controllers which are robust in case of uncertainties or parameters variation. The controllers tuned by fuzzy logic and the evolutionary algorithms have received a considerable attention in this field. However, for tuning the fuzzy logic controllers, knowledge of fuzzy logic is necessary. Also, tuning the controllers using evolutionary algorithms might be time consuming. Therefore, an alternative robust controller which does not have the aforementioned tuning difficulties seems to be necessary.

Online set-point modulation method has been newly introduced. Using this method, the performance of PI voltage and current controllers in terms of overshoot/undershoot and settling time has been improved (Mehrizi-Sani and Iravani, 2012a,b). In this paper, an adaptive form of set-point modulation method is proposed to enhance the performance of the PI load frequency controllers. It should be mentioned that, however; a PID controller might ideally have a better performance, but PI controllers are widely used for LFC in real power systems because the derivative term of PID controllers could be problematic in presence of noise. Although noise can be filtered, this might degrade the performance of PID controllers (Romero Segovia et al., 2014). Hence, upgrading the PI controllers, which are not susceptible to noise, would be a better solution in practice. The purpose of the proposed ASPM method is to enhance the performance of PI controllers widely used for LFC. Through simulation studies carried out in Matlab/Simulink, the performance of the proposed ASPM-PI controllers has been compared with the optimal PID controllers which have been tuned using DE algorithm (Mohanty et al., 2014).

2. Test system

The studied power system consists of two areas with identical generating units which are connected together via parallel AC-DC tie-lines. As shown in Fig. 1, in each area, electrical power is generated by thermal, hydro and gas turbine power plants. Although power systems are nonlinear and dynamic, the model linearized around the operating point can be used in solving the LFC problem because only small changes in load are expected during the normal operation (Mi et al., 2013). In power systems, any change in electrical loads reflects in the electrical power of the
generating units and results in a mismatch between the electrical and mechanical power. This power mismatch, in turn, brings about the rotor speed variation and consequently frequency deviation (Kundur, 1994):

$$\Delta f = \frac{1}{2Hs} (\Delta P_m - \Delta P_e)$$

Here, $H$, $\Delta P_m$, $\Delta P_e$ and $s$ represent for the equivalent inertia constant of the generating units, the change in the mechanical power, the change in the electrical power and the Laplace operator, respectively. It should be mentioned that the frequency dependency of loads will affect $\Delta P_e$ in case of frequency deviation:

$$\Delta P_e = \Delta P_L + D\Delta f$$

where $\Delta P_L$ and $D\Delta f$ represent for the change in the power of the non-frequency-sensitive and frequency-sensitive loads, respectively. Also, $D$ is load damping factor. It is clear from (1) that to control the frequency, the mechanical power should be controlled so as to retain the power balance. As shown in Fig. 1, in the primary frequency control loop, the droop characteristic ($R$) is used to decrease the power mismatch and also ensure the equitable load sharing between
the different generating units available in each area. However, decreasing the frequency deviation to zero is out of the scope of the primary frequency control and it is realized by means of the secondary frequency control. In fact, to reduce the steady state frequency error to zero and also maintain AC tie-lines power at the scheduled values, a controller is needed to be used for each power plant. As shown in Fig. 1, the area control error (ACE) is used as the input of these controllers which are responsible for changing the position of governor in order to regulate the mechanical power and consequently retain the power balance such that the frequency error and AC tie-line power error are both restored to zero. At the last frequency control stage, tertiary control which usually operates manually, activates tertiary control reserves to free up the secondary control reserves for the next disturbances. Generally, a turbine is used in power plants to convert the natural energy of steam, water, gas, etc. to the mechanical power. The amount of the mechanical power is controlled by changing the position of the governor valve. The models implemented for the power plants in this study are described as follows (Mohanty et al., 2014; Challa and Rao, 2010; Ibraheem et al., 2014). The reheater thermal unit turbine is modeled by a second order transfer function:

\[ G_T(s) = \frac{1 + K_r T_r s}{(1 + T_s)(1 + T_r s)} \]  

(3)

where \( T_s \) is the steam turbine time constant, \( K_r \) is the steam turbine reheater constant, \( T_r \) is the steam turbine reheater time constant.

The governor of the thermal power plant is represented by a first order transfer function:

\[ G_{Tg}(s) = \frac{1}{1 + T_{SG}s} \]  

(4)

Here, \( T_{SG} \) is referred to as the speed governor time constant.

Due to the water inertia, hydraulic turbines are non-minimum phase units. In fact, the water pressure response is opposite to the gate position change at first and recovers after the transient response. Thus, the transfer function of the hydraulic turbine is:

\[ G_{Hg}(s) = \frac{1 - T_w s}{1 + 0.5 T_w s} \]  

(5)

where \( T_w \) is the nominal starting time of water in the penstock.

Due to the stability concerns regarding the non-minimum phase hydraulic turbines, a transient droop is implemented which can be represented by the following transfer function:

\[ G_{Ha}(s) = \frac{1 + T_{RS} s}{1 + T_{RH} s} \]  

(6)

where \( T_{RS} \) is the hydro turbine speed governor reset time, \( T_{RH} \) is the time constant of the hydro turbine speed governor transient droop.

The governor of the hydraulic unit is modeled as follows:

\[ G_{Hb}(s) = \frac{1}{1 + T_{GH} s} \]  

(7)

\( T_{GH} \) is the time constant of the hydro turbine speed governor’s main servo.

A model of gas turbine power plants usually used in LFC studies (Mohanty et al., 2014; Challa and Rao, 2010; Ibraheem et al., 2014) has been used in this paper.

Gas turbine valve positioner is modeled as follows:

\[ G_{Vp}(s) = \frac{1}{c + b s} \]  

(8)

Here \( c \) is the positioner constant and \( b \) is the time constant of the valve positioner. The following transfer function is used to model the speed governor of the gas turbine.

\[ G_{Gg}(s) = \frac{1 + X_c s}{1 + Y_c s} \]  

(9)

where \( X_c \) and \( Y_c \) are lead and lag time constant of the speed governor, respectively.
Fuel system and combustor are modeled as follows; \( T_F \) is the gas turbine fuel time constant and \( T_{CR} \) is combustion reaction time delay.

\[
G_{Fc}(s) = \frac{1 + T_{CR}s}{1 + T_Fs}
\]

(10)

A first order transfer function is used to model the compressor of the gas turbine in which \( T_{CD} \) is the gas turbine compressor discharge volume–time constant:

\[
G_c(s) = \frac{1}{1 + T_{CD}s}
\]

(11)

It is worth noting that all power plants do not equally participate in LFC. In Fig. 1, \( K_T, K_H \) and \( K_G \) are the participation factors of thermal, hydro and gas turbine power plants, respectively.

Two areas of the studied power system are interconnected via AC and DC tie-line as shown in Fig. 1. DC tie-line is modeled as follows:

\[
G_{DC}(s) = \frac{K_{DC}}{1 + T_{DC}s}
\]

(12)

And the following transfer function represents the AC tie-line:

\[
G_{Tie}(s) = \frac{2\pi T_{12}}{s}
\]

(13)

The parameters of the studied power system are given in (Mohanty et al., 2014). It is worth mentioning that the linearized model explained above is valid for all the operating points of the power system; however, the parameters of the model might change as a result of a change in the operating point. Hence, to study the performance of control strategies in different operating points, there is no need to use the complex non-linear models and this study can be easily carried out by changing the parameters of the linearized model.

3. The proposed control strategy

Usually linear controllers such as PI or PID are used for frequency control in power systems. When the power system is in the normal condition for which the controllers are designed, these controllers can maintain the frequency near its set-point (60 or 50 Hz). But, in case of a change in the topology of system or parameters variation, the performance of these controllers might deteriorate.

In (Mehrizi-Sani and Iravani, 2012a,b) two techniques are proposed to enhance the performance of PI controllers by applying intermediate step changes to the set-point of the controllers. In fact, these works propose that when a change is going to be applied to the set point of a controller, e.g. set point of voltage or current, this change should be applied in several steps with a delay to ensure the signal stays within the permissible limits. In (Mehrizi-Sani and Iravani, 2012a) a study on change in the voltage set point in case of load energization has also been carried out.

The previous studies on set-point modulation have mainly focused on controlling the deviations when the set-point of voltage or current is changed, not when deviations are due to loads/generators power variation. The purpose of this paper is to modify the set point modulation technique in such a way that enhances the performance of PI load frequency controllers in case of power imbalance. In (Mehrizi-Sani and Iravani, 2012a,b), when a violation from the allowed limit is predicted, depending on the sign of the deviation, a 20% increase/decrease is applied to the controllers’ set-point. But, in case of frequency control, as the magnitude of frequency deviation is related to the amount power imbalance, it would not be reasonable to apply the same amount of change to the frequency set-point for all the different power imbalances. Hence, in the proposed ASPM method, the frequency set-point is adaptively altered to minimize the frequency deviations resulted from changes in load or generated power. Actually, a value with the same magnitude and the opposite sign of the frequency deviation is added to the frequency set-point. Due to the time constants of the governor and the other devices used for energy conversion, always the frequency of system tracks the changes in its set-point with a delay. Hence, it seems reasonable to predict the frequency deviation and use it for altering the frequency
set-point. In this paper, because of its simplicity and satisfactory performance, linear extrapolation is used to predict the frequency deviation (Mehrizi-Sani and Iravani, 2012b):

$$\Delta \hat{f}(t + T_{pred}) = \Delta f(t) + \frac{T_{pred}}{T_s} \times [\Delta f(t) - \Delta f(t - T_s)]$$  \hspace{1cm} (14)

where $\Delta f(t)$ and $\Delta \hat{f}(t + T_{pred})$ are the current and predicted value of the frequency deviation, respectively, $t$ is the current time, $T_s$ is the sample time and $T_{pred}$ is the prediction horizon.

Using this prediction method, the frequency set-point can be altered as follows:

$$f_{r-alt}(t) = f_r - \Delta \hat{f}(t + T_{pred})$$  \hspace{1cm} (15)

where $f_r$ is the predetermined frequency set-point, $f_{r-alt}(t)$ is the altered frequency set-point and $\Delta \hat{f}(t + T_{pred})$ is the predicted frequency deviation in $T_{pred}$ seconds ahead of the current time. In this study, $T_{pred}$ is chosen equal to 1.4 s.

Table 2
Maximum deviation (Max. dev.) and settling time (St. time) of signals in different case studies.

<table>
<thead>
<tr>
<th>Case</th>
<th>Controller</th>
<th>$\Delta f_1$</th>
<th>$\Delta f_2$</th>
<th>$\Delta P_{tie}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max. dev. (pu)</td>
<td>St. time (s)</td>
<td>Max. dev. (pu)</td>
</tr>
<tr>
<td>Disturbance in area 1</td>
<td>ASPM-PI</td>
<td>0.0112</td>
<td>11.12</td>
<td>0.0014</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0117</td>
<td>22.23</td>
<td>0.0025</td>
</tr>
<tr>
<td>Disturbance in both areas</td>
<td>ASPM-PI</td>
<td>0.0116</td>
<td>19.16</td>
<td>0.0116</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0122</td>
<td>24.63</td>
<td>0.0122</td>
</tr>
<tr>
<td>Increase in parameters</td>
<td>ASPM-PI</td>
<td>0.0102</td>
<td>10.75</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0107</td>
<td>21.97</td>
<td>0.0027</td>
</tr>
<tr>
<td>Decrease in parameters</td>
<td>ASPM-PI</td>
<td>0.0125</td>
<td>11.74</td>
<td>0.0012</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0131</td>
<td>22.74</td>
<td>0.0023</td>
</tr>
<tr>
<td>HVDC disconnection</td>
<td>ASPM-PI</td>
<td>0.0206</td>
<td>12.05</td>
<td>0.0077</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0250</td>
<td>35.28</td>
<td>0.0188</td>
</tr>
<tr>
<td>Islanded</td>
<td>ASPM-PI</td>
<td>0.0230</td>
<td>16.57</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>PID</td>
<td>0.0314</td>
<td>19.14</td>
<td>–</td>
</tr>
</tbody>
</table>
however, our studies show that for the values of $T_{pred}$ between 0.7 and 2 s, the proposed control scheme shows a satisfactory performance. The parameters of all controllers are given in Table 1.

It is worth mentioning that in the steady state, the frequency deviation equals zero. Hence, it is clear from (15) that the proposed method does not affect the steady state frequency. The schematic diagram of the ASPM-PI controller used for LFC is shown in Fig. 2. The parameters of PI controllers can be tuned using conventional methods, such as Ziegler–Nichols, or evolutionary algorithms.

Fig. 3. Change in the frequency of the first area for 0.01 pu change in demand of area1.

Fig. 4. Change in the frequency of the second area for 0.01 pu change in demand of area1.
4. Simulation results

To show the effectiveness of the proposed ASPM in improving the performance of the PI load frequency controllers in a two area power system, several comparative simulation studies are carried out. In these case studies, the impact of uncertainties, parameters variation and change in the system topology on the proposed control method is investigated. Also, the performance of ASPM-PI is compared with PID controller. The parameters of both PI and PID controllers are obtained from (Mohanty et al., 2014). The settling time and maximum deviation of the frequency of each area and tie-line power, for all the following case studies, are presented in Table 2. The nominal frequency of the system is 60 Hz and the rated power of each area is 2000 MW.

![Fig. 5. Change in AC tie-line power area for 0.01 pu change in demand of area1.](image1.png)

Fig. 5. Change in AC tie-line power area for 0.01 pu change in demand of area1.

![Fig. 6. Modulated frequency set-pint of the first area for 0.01 pu change in demand of area1.](image2.png)

Fig. 6. Modulated frequency set-pint of the first area for 0.01 pu change in demand of area1.
4.1. Step increase in the demand of the first area

In this case study, the performance of the PI, PID and ASPM-PI controllers in case of a 0.01 pu step increase in the demand of the first area is investigated. From Figs. 3 and 4 and Table 2 it is clear that the frequency deviation in both of the areas has been decreased using the ASPM-PI controllers. Also, this controller has diminished the settling time of the frequency deviation in both of the areas. Fig. 5 shows that the performance of the ASPM-PI controller in minimizing the AC tie-line power deviation is also superior to both of the PI and PID controllers. Figs. 6 and 7 show the altered frequency set-point of both the areas calculated using (15). For brevity, frequency set-points are not shown for the next case studies.

Fig. 7. Modulated frequency set-point of the second area for 0.01 pu change in demand of area1.

Fig. 8. Change in the frequency of the first area for 0.01 pu change in demand of both areas.
4.2. Simultaneous step increase in the demand of both the areas

Here, the performance of the controllers in case of a 0.01 pu step increase in the demand of both the areas is investigated. As both of the areas are identical and the same step change has occurred in them, the frequency deviation of both the areas is the same and AC tie-line power deviation is zero. Hence, only the frequency deviation of the first area is shown in Fig. 8. From this figure and the results presented in Table 2, it is clear that in comparison with the PI and PID controllers, the ASPM-PI controllers have a better performance in terms of maximum deviation and settling time.

![Graph](image1)

**Fig. 9.** Change in the frequency of the first area for 0.01 pu change in demand of area1 in case of a decrease in parameters.

![Graph](image2)

**Fig. 10.** Change in the frequency of the second area for 0.01 pu change in demand of area1 in case of a decrease in parameters.
4.3. Effect of the parameters variations

The controllers are designed based on the estimated parameters of the power system. However, due to an error in the estimation process or the low accuracy of the estimation method, the real parameters might be different from the estimated ones. Also, the parameters of power systems may vary as a result of a change in the operating point which might happen after large disturbances (Yousef et al., 2014). Therefore, the controllers should be robust in case of parameters variations. In this case study, the effect of 20% decrease/increase in $M$, $D$ and $T_{12}$ on the controllers performance in case of a 0.01 pu step increase in demand of the first area is studied. From the simulation results shown in Figs. 9–14, it can be found that, in case of power system parameters variation, all the controllers could preserve

![Fig. 11. Change in AC tie-line power area for 0.01 pu change in demand of area1 in case of a decrease in parameters.](image)

![Fig. 12. Change in the frequency of the first area for 0.01 pu change in demand of area1 in case of an increase in parameters.](image)
the stability of the power system. However, the ASPM-PI is superior to the PI and PID controllers in minimizing the frequency and AC tie-line power deviation.

4.4. Change in the topology of the power system

The controllers parameters obtained from (Mohanty et al., 2014) are tuned for the nominal operating point when the generating units and tie-lines are all interconnected. However, it is probable that AC and/or DC tie-lines are not connected. It is important that the load frequency controllers have a good performance when a disturbance occurs in such cases. $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ in case of a 0.01 pu step increase in demand of the first area when the DC tie-line is

Fig. 13. Change in the frequency of the second area for 0.01 pu change in demand of area1 in case of an increase in parameters.

Fig. 14. Change in AC tie-line power area for 0.01 pu change in demand of area1 in case of an increase in parameters.
not connected, are shown in Figs. 15–17, respectively. It can be found that in contrary to the ASPM-PI and PID, the PI controllers are not able to maintain the stability of system in this case. In addition, the performance of the ASPM-PI in minimizing the settling time and maximum deviation of frequency and AC tie-line power is superior to the PID controller.

To further study the effect of change in the power system configuration on the controllers’ performance, a 0.01 pu step increase is applied to the demand of the first area when the power system is divided into two separate islands. From Fig. 18 and the results presented in Table 2, it can be found that the ASPM-PI controllers not only could preserve the stability of the power system, but also, in comparison to the PID controllers, have a better performance in terms of maximum deviation and settling time of the frequency.

![Fig. 15](image1.png)

Fig. 15. Change in the frequency of the first area for 0.01 pu change in demand of area1 when HVDC link is not connected.

![Fig. 16](image2.png)

Fig. 16. Change in the frequency of the second area for 0.01 pu change in demand of area1 when HVDC link is not connected.
Fig. 17. Change in AC tie-line power area for 0.01 pu change in demand of area1 when HVDC link is not connected.

Fig. 18. Change in the frequency of the first area for 0.01 pu change in demand of area1 when the power system is islanded.

5. Conclusion

In this paper, an ASPM-PI controller was proposed for LFC in an interconnected power system with different types of generating units and HVDC link. It has been shown that the proposed controller is robust in case of change in the configuration and parameters of power system. Change in the parameters of power system might occur as a result of change in the operating point of the studied power system. Hence, it can be concluded that the proposed controllers work efficiently at different operating points. Also, in contrary to the other robust control methods such as fuzzy logic, tuning the proposed controller is very simple. In this paper, for the first time, the performance of ASPM-PI was compared with PID. Simulation studies showed that in comparison to the PI and PID, the performance of the ASPM-PI controller is better in terms of overshoot/undershoot and settling time. In addition, the proposed controller is based on the PI controller and unlike the PID controller it is not sensitive to noise. It was also shown that PI controller could
not maintain the stability of system when HVDC link is not connected, but adjusting the set-point of the PI controllers using the ASPM method, the stability of the power system is preserved. It was shown that the proposed ASPM-PI controller has a good performance when the topology of power system is changed; hence, this controller is expected to have an acceptable performance in multi-area power systems in which the areas are not identical.

References