Power System Restoration Assessment with Small Signal Stability Analysis in A Two-Area Interconnected Power System

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Abstract

This paper presents the assessment of existing power system network under power restoration scenario in order to ensure system stability and reliability. Generally, stability of the system can be visualized in many ways like small signal stability analysis, load scheduling, load shedding, spinning reserve deficit etc. In this connection a reality oriented simulation model of two-area interconnected thermal reheat power system using time domain simulations has been discussed for step load perturbation in both the areas under consideration. This paper deals with the small signal stability analysis assessment using Gas turbine model in the two-area interconnected thermal reheat power system to restore frequency and tie line power in a smooth way to its normal value in the shortest time. The simulation results reveal that the two-area interconnected power system incorporated with gas turbines ensure a better transient performance with smaller settling time.

Keywords: Power System Restoration, Stability Assessment, Gas turbines, Frequency Regulation, Area Control Error, Proportional-Integral controllers

Introduction

Restoration scenarios have often been made possible by carrying out load flow studies, which do not take into account the dynamical behavior of the system during the restoration process. Moreover, system black-out is an unpleasant event and the operators cannot effectively manage the system in different phases of restoration [1]. Therefore, paramount importance has to be given to take necessary decision to restore the system during frequency deviations, fluctuations, power oscillations etc., most
major power system disturbances are to be arrested prior to complete collapse and some level of interconnection assistance is available[2]. This strategy aims at providing cracking power to the system by regulating the frequency, control input and also tie line supply. The goal of restoration is achieved by taking into consideration a range of disturbances under normal operating condition, thereby optimizing the gains at different instants by incorporating Gas turbines in a two-area interconnected thermal reheat power system.

The objective of the restorative control is the speedy restoration of all customer service, which not only minimizes the restoration time but also maximization of customer load. The control variables in the restoration problem are the generation/load scheduling and switching sequences. It is always necessary to maintain the system frequency within the allowable limits imposed by turbine, system stability and with various protection setups [3]. Load pickup in small increments tends to prolong the duration. Allowable load pickups are entertained when the percentage of generation capacity is increased by any means that would help to maintain load and generation balance at acceptable frequency.

In this paper a method is proposed to restore the small signal stability so as to prevent larger frequency deviations, input control as well as tie-line loads. The research on power system restoration was activated by applications of expert systems in the mid 1980s [4]. A number of papers using expert systems are presented based upon heuristics of operators and the patterns of restorative operations [5]. Here, in this paper the following expert system is used for power system reliability considerations:

1. Optimizing gains/tuning the gains of the PI controller, used in interconnected power system and
2. Incorporating additional (economical) spinning reserves.

**Expert System Requirements**

Power systems are getting expanding day by day and its growth is tremendous. Under these circumstances, a fast and reliable restoration algorithm is required. The restorative state can be broadly divided into a state of complete collapse or to a state of complete collapse or partial collapse. In the restoration of partial outage, it is required mainly to reconfigure the networks from the restorative state to the normal state. The restoration for complete collapse relates to complicated and difficult problem such as adequate sectionalisation of blackout area, restart conditions of generators, consideration of dynamic characteristics of generator, energizing transmission lines etc., in practice blackout areas are restored by the power system operators using off-line data and their experiences. In some papers [6] the power balance state is classified into power surplus, deficit and blackout of the isolated areas.

This paper proposes a method to restore the system output parameters within the permissible limit with step load disturbances and providing initial source of power immediately and to avoid excess under or over frequency deviations. The main objective of the expert system in knowledge based restoration here in this test model is
1. To provide suitable initial power immediately by interconnection of Gas turbine,
2. By adjusting suitable gain value in the PI controller,
3. The foremost function is to restore the system due to step load perturbations in a shorter duration.

**Modeling of Two-Area Reheat Thermal Power System**

The state variable equation of the minimum realization model of the ‘N’ area interconnected power system is expressed as [7],

$$\dot{X} = AX + BU + \Gamma d$$

$$Y = CX$$

Where, the system state vector $X$ consists of the following variables as:

$$X = \begin{bmatrix} \Delta P_{1} & \Delta P_{2} & \Delta P_{3} & \Delta P_{4} & \Delta \alpha_{1} & \Delta \alpha_{2} & \Delta \beta_{1} & \Delta \beta_{2} \end{bmatrix}^T$$

System control input vector is $U = \begin{bmatrix} \Delta P_{1} \\ \Delta P_{2} \end{bmatrix}$

System disturbance input vector is $D = \begin{bmatrix} \Delta \alpha_{1} \\ \Delta \alpha_{2} \\ \Delta \beta_{1} \\ \Delta \beta_{2} \end{bmatrix}$

The state variable equation of the minimum realisation model of the ‘N’ area interconnected power system is

$$\dot{X} = AX + BU + \Gamma d$$

$$Y = CX$$

Where, $X = \begin{bmatrix} \Delta P_{1}^T, \Delta P_{2}^T, ..., \Delta P_{N-1}^T, \Delta P_{N}^T \end{bmatrix}^T$ - n-state vector

$$U = \begin{bmatrix} \Delta P_{1} \\ \Delta \alpha_{1} \\ \Delta \beta_{1} \\ \Delta \alpha_{2} \\ \Delta \beta_{2} \end{bmatrix}^T$$ - N – Control input vector

$$D = \begin{bmatrix} \Delta \alpha_{1} \\ \Delta \beta_{1} \\ \Delta \alpha_{2} \\ \Delta \beta_{2} \end{bmatrix}^T$$ - N – Disturbance input vector

$$Y = \begin{bmatrix} \Delta P_{1} \\ \Delta \alpha_{1} \\ \Delta \beta_{1} \\ \Delta \alpha_{2} \\ \Delta \beta_{2} \end{bmatrix}^T$$ - 2N – measurable output vector

$A$ is system matrix, $B$ is the input distribution matrix and $\Gamma$ disturbance distribution matrix, $X$ is the state vector, $U$ is the control vector and $D$ is the disturbance vector of load changes of appropriate dimensions. These matrix and vectors are obtained using the nominal parameters of the system. A step load has been considered as a disturbance in the two-area reheat thermal power system[8].
Gas Turbine Modelling
Gas turbine based plants (open cycle and combined cycle) can be profitably used in power system restoration for supplying power to the areas required to restore. They have the advantages like, Quick start-up/shut-down, Low weight and size, Cost of installation is less, Low capital cost, Black-start capability, High efficiency, Requires low cranking power, Pollutant emission control etc.,[9].

Gas Turbines provide the ability to rapidly restore the core path. These units provide the start-up power for those stations not equipped with local GTs or where sub synchronous synchronization would create a problem, as well as a level of the redundancy for the generating stations with local GTs. This ability to pick-up a significant number of megawatts of customer load early, while steam units are being started.

When the load is suddenly increased the speed drops quickly, but the regulator reacts and increases the fuel flow to a maximum of 100% in the same way. The modeling that has been implemented in the two-area interconnected system is GAST model as depicted below:
Maximum fuel flow depends upon ambient temperature and of compressor speed. When turbine output is limited by temperature output power is proportional to the difference in the gas flow and the power compressor consumption. In the power regulation mode, the final settling frequency depends on two factors (i.e.) Governor droop setting ‘R’ (or gain 1/R) and the amount of load rejected. However, governor systems use fuel valve opening as an indication of power output in MW of the machine [10-12].

**Controller Design**

**PI Controller**

Many investigations in the in the area of Load Frequency Control(LFC) problem of interconnected power systems have reported over the past six decades .A number of control strategies have been employed in the design of load frequency controllers in order to achieve better dynamic performance[13,14]. Among the various types of load frequency controllers, the most widely employed is the conventional proportional plus integral controller (PI).In this work optimum gain values are obtained based on the settling time of the output response of the system (especially the frequency deviation of area1) and with these gain values the performance of the system is analyzed.

**Proportional Controller**

The proportional controller is a device which produces an output signal which is proportional to the input signal. To perform the integral square error criteria and performance index is evaluated using

\[ ACE = \beta \Delta f + \Delta P_{tie} \]

Where, \( \beta = \text{Biasing factor} \).
Proportional Plus Integral Controller Design
This type of controller has received a great deal of attention in the process control areas. And here in this case study it is used as a feedback controller which drives the plant to be controlled within a weighted sum of error and integral of that value [15]. Where,

\[ U_1 = -K_p \int ACE_1 \, dt \]
\[ U_2 = -K_p \int ACE_2 \, dt \]

Where,
- \( K_p \): proportional gain
- \( K_i \): integral gain
- \( ACE \): Area control error
- \( U_1, U_2 \): Control outputs of the respective areas.

The relative simplicity of this controller is a successful approach towards the zero steady state error in the frequency of the system. When the integral term is combined with the proportional controller term it accelerates the movement of the process towards the set point and eliminates the residual steady error [16].

Fig 3. Two area-two unit interconnected thermal system with gas turbine
Simulation Results and Observations
The decentralized proportional plus integral controllers are designed and implemented in a two-area interconnected power system without and with Gas turbine as shown in figures 1 and 3. The system is simulated with the proposed controllers for various step-load disturbances in area 1 and the corresponding frequency deviations $\Delta f$, tie-line power deviation $\Delta P_{tie}$ and control input deviations are plotted with respect to time as shown through the following outputs:

![Graphs showing frequency deviations and tie-line power deviations for 0.01 p.u. MW step load change in area 1 of two-area interconnected thermal reheat power system without and with gas turbines](image)

**Fig 4.** Frequency deviations and tie-line power deviations for 0.01 p.u. MW step load change in area 1 of two-area interconnected thermal reheat power system without and with gas turbines (a) Frequency deviation of area 1, (b) Frequency deviation of area 2, (c) Tie-line power deviation of area 1
Fig 4 (d),(e). Control input deviations of two-area interconnected thermal reheat power system without and with gas turbines for 0.01p.u. MW step-load change in area 1

Table 1: Proportional plus integral controller gains and settling time of output response for 0.01 p.u. MW step-load disturbance

<table>
<thead>
<tr>
<th>Power system without Gas turbine</th>
<th>Feedback Gains</th>
<th>Settling time(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_p$</td>
<td>$K_i$</td>
</tr>
<tr>
<td>Power system with Gas turbine</td>
<td>0.85</td>
<td>0.3</td>
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<tr>
<td></td>
<td>0.8</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Fig 5. Frequency deviations and tie-line power deviations of two-area interconnected thermal reheat power system without and with gas turbines for 0.04 p.u. MW step-load change in area1 (a) Frequency deviation of area 1, (b) Frequency deviation of area 2, (c) Tie-line power deviation of area1

Fig 5(d), (e). Control input deviations of two-area interconnected thermal reheat power system without and with gas turbines for 0.04 p.u. MW step-load change in area1
Table 2: Proportional plus integral controller gains and settling time of output response for 0.04 p.u. MW step-load disturbance

<table>
<thead>
<tr>
<th>Power system without Gas turbine</th>
<th>Feedback Gains</th>
<th>Settling time(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>$K_i$</td>
</tr>
<tr>
<td>Power system with Gas turbine</td>
<td>0.8</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.15</td>
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Conclusion

This paper proposes few expert systems which are required to restore frequency deviations, tie-line power deviation in a two-area interconnected thermal reheat power system to ensure the reliable operation of the power system. The controllers are designed and implemented in a two-area interconnected thermal power system without and with Gas-turbines. The closed loop system was simulated and comparative studies of the output responses of the system without and with Gas-turbine for various step-load conditions were carried out. From the simulated results it is observed that the restoration process with the Gas turbines ensures not only reliable operation but also minimizes the peak over shoot and reduced settling time of the system output responses.

References

Appendix

Data for the two-area interconnected thermal power system with reheat turbines [7]

\[
\begin{align*}
Pr_1 &= Pr_2 = 2000 \text{MW} & Kp_1 &= Kp_2 = 120 \text{Hz/p.u} \\
Tp_1 &= Tp_2 = 20 \text{sec.} & Tt_1 &= Tt_2 = 0.3 \text{ sec.} \\
Tg_1 &= Tg_2 = 0.08 \text{sec.} & Kr_1 &= Kr_2 = 0.5 \\
Tr_1 &= Tr_2 = 10 \text{ sec.} & R_1 &= R_2 = 2.4 \text{Hz/p.u MW.} \\
a_{12} &= -1 & T_{12} &= 0.545 \text{ p.u. MW/Hz} \\
\beta_1 &= \beta_2 = 0.425 \text{ p.u. MW/Hz}
\end{align*}
\]

Gas Turbine

Data for the Gas turbine model [9]

Fuel system lag time constant \( T_1 = 10 \text{ sec} \)
Fuel system lag time constant \( T_2 = 0.1 \text{sec} \)
Load limit time constant \( T_3 = 3 \text{sec} \)
Temperature control loop gain \( K_t = 1 \)
Regulating gain \( = 0.04 \)
Damping of turbine \( D_{\text{turb}} = 0.03 \)
Maximum and minimum valve position = 1and -0.1
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