AUTOMATIC GENERATION CONTROL OF AN INTERCONNECTED POWER SYSTEM WITH CAPACITIVE ENERGY STORAGE

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Abstract: Changes in the power system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on fluctuations of voltage magnitude. So the control of the real and reactive power in the power system is dealt separately. The load frequency control mainly deals with the control of the system frequency and real power whereas the automatic Voltage regulator loop regulates the changes in the reactive power and voltage magnitude. Load frequency control is the basis of many advanced concepts of the large scale control of the power system. This paper is concerned with the application of small rating Capacitive Energy Storage units for the improvement of Automatic Generation Control of a multiunit multi area power system. Generation Rate Constraints are also considered in the investigations. Simulation studies reveal that with CES units, the deviations in area frequencies and inter-area tie-power are considerably improved in terms of peak deviations and settling time as compared to that obtained without CES units.

Keywords: Automatic Generation Control, Capacitive Energy Storage, Area Control Error(ACE)

I. INTRODUCTION

For large scale power systems which consists of inter-connected control areas, load frequency then it is important to keep the frequency and inter area tie power near to the scheduled values. The input mechanical power is used to control the frequency of the generators and the change in the frequency and tie-line power are sensed, which is a measure of the change in rotor angle. A well designed power system should be able to provide the acceptable levels of power quality by keeping the frequency and voltage magnitude within tolerable limits. A difficulty with electric energy production is that electric energy cannot be stored, except for very small quantities and short times. Therefore it must be produced at the same time at which it is consumed. The production must match the consumption at every instant. This is no easy task the power plants need to be continuously regulated to ensure that their power output matches the demand of the customers.

Electric power grids are complex interconnected systems that must be carefully controlled if they are to remain stable and secure, it should be mentioned that the tools described in this chapter are intended for steady-state operation. Short-term(less than a few seconds) changes to the system are handled by dynamic and transient system controls, which maintain secure and stable operation. The control methods are based on the fact that when the balance between power consumption and power production is upset, the system frequency starts to change. Because the total power consumption in a network cannot be measured directly (and efficiently), the balance is maintained by keeping the system frequency constant.
Generating units may have prohibited generation levels at which resonant frequencies may cause damage or other problems to the system. The impact of transmission losses, congestion, and limits that may inhibit the ability to serve the load in a particular region from a particular generator (e.g., a low cost generator) should be considered. The market structure within an operating region and its associated regulations must be considered in determining the specified demand, and in determining what constitutes economical operation. Electric power generation and consumption should perfectly go hand-in-hand if an electric energy system is to be strictly maintained in its nominal state characterized by nominal frequency, voltage profile and load flow configuration. But because of the random nature of the power demands, this power generation-consumption equilibrium, in reality, cannot be strictly met. Thus, a power deviation occurs. This imbalance, causes a deviation of system frequency and tie-power from their scheduled values. To bring back the frequency and tie-power to their respective scheduled values, most of the utilities prefer to use integral or proportional-integral controllers in their system.

Power systems consist of control areas representing a coherent group of generators i.e. generators which swing in unison characterized by equal frequency deviations. In addition to their own generations and to eliminate mismatch between generation and demand these control areas are interconnected through tie-lines for providing contractual exchange of power under normal operating conditions. One of the control problems in power system operation is to maintain the frequency and power interchange between the areas at their rated values. Automatic generation control is to provide control signals to regulate the real power output of various electric generators within a prescribed area in response to changes in system frequency and tie-line loading so as to maintain the scheduled system frequency and established interchange with other area.

II. LOAD FREQUENCY CONTROL

Power systems are used to convert natural energy into electric power. They transport electricity to factories and houses to satisfy all kinds of power needs. To optimize the performance of electrical equipment, it is important to ensure the quality of the electric power. It is well known that three-phase alternating current (AC) is generally used to transport the electricity. During the transportation, both the active power balance and the reactive power balance must be maintained between generating and utilizing the AC power. Those two balances correspond to two equilibrium points: frequency and voltage. When either of the two balances is broken and reset at a new level, the equilibrium points will float. A good quality of the electric power system requires both the frequency and voltage to remain at standard values during operation. However, the users of the electric power change the loads randomly and momentarily. It will be impossible to maintain the balances of both the active and reactive powers without control. As a result of the imbalance, the frequency and voltage levels will be varying with the change of the loads. Thus a control system is essential to cancel the effects of the random load changes and to keep the frequency and voltage at the standard values. Although the active power and reactive power have combined effects on the frequency and voltage, the control problem of the frequency and voltage can be decoupled. The frequency is highly dependent on the active power while the voltage is highly dependent on the reactive power. Thus the control issue in power systems can be decoupled into two independent problems. One is about the active power and frequency control while the other is about the reactive power and voltage control. The active power and frequency control is referred to as load frequency control (LFC).

Active power loads, which are also referred to as unknown external disturbance. Another task of the LFC is to regulate the tie-line power exchange error. A typical large-scale power system is composed of several areas of generating units. In order to enhance the fault tolerance of the entire power system, these generating units are connected via tie-lines. The usage of tie-line power imports a new error into
the control problem, i.e., tie-line power exchange error. When a sudden active power load change occurs to an area, the area will obtain energy via tie-lines from other areas. But eventually, the area that is subject to the load change should balance it without external support.

Fig 1: Schematic Diagram of Automatic Generation Control

Since the system under consideration is exposed to a small change in load during its normal operation,
a liberalized model is sufficient for its dynamic representation. Fig. 1 shows the small perturbation transfer function block diagram model of the two-area power system. The nominal parameters of the power system as well as the CES units are given in the Appendix. Area 1 consists of two reheat units and area 2 consists of two non-reheat units. Because of the thermodynamic and mechanical constraints, there is a limit to the rate at which the output power of steam turbines can be changed. This limit is referred to as Generator Rate Constraint (GRC). For the present study, a GRC of 3% per min. for reheat units and 10% per min. for non reheat units have been considered for each unit in areas 1 and 2 respectively as in. apf11 and apf12 are the ACE participation factors in area 1 and apf21 and apf22 are the ACE participation factors in area 2. Note that apf11 + apf12 = 1.0 and apf21 + apf22 = 1.0. A small rating CES unit of 3.8 MJ storage capacities is fitted to both the areas 1 and 2 to examine its effect on the power system performance.

A step load disturbance of 1% of nominal loading has been considered for the investigation. The control signal to the CES unit can be frequency deviation or the Area Control Error (ACE). In this paper, both the cases are studied. Since the power system model considered is a linear continuous-time dynamic system, it can be represented by the standard state space model as:

\[ X = AX + BU + Γp \]

Where \( X \) = state vector
\( U \) = control vector
\( p \) = disturbance vector and
\( A, B \) and \( Γ \) are constant matrices of compatible dimensions associated with them. For the system considered, the state, control and disturbance vectors are respectively given as

\[ X^T = [Δf_1, Δf_2, ΔP_{tie}^1, ΔP_{tie}^2, ΔP_{g1}, ΔP_{g2}, ΔP_{g3}, ΔP_{g4}, ΔP_{r1}, ΔP_{r2}, ΔP_{r3}, ΔP_{r4}, ΔE_{d1}, ΔE_{d2}, ΔI_{f1}, ΔI_{f2}] \]
\[ U^T = [U_1, U_2] \] And \( P^T = [ΔP_{g1}, ΔP_{g2}] \)

### III. Capacitive Energy Storage

In an interconnected power system, as the load varies randomly, the area frequency and tie-line power interchange also vary. One of the tasks of AGC is to minimize these transient deviations and to ensure zero steady state error of these variables. Application of capacitors for storing electrical energy represents one of the latest innovations in electrical energy storage technology. The low energy density and the dielectric losses of capacitors make it less attractive as a bulk energy storage device. However, a small rating CES can effectively damp out the power frequency and tie-line power oscillations caused by small perturbations to the load. CES has several advantages compared to SMES. CES units are practically maintenance free and do not impose any environmental problems unlike magnetic energy storage units. CES can be upgraded by adding extra capacitor modules to increase its capacity. The operation of CES is quite simple and less expensive compared to SMES which requires continuously operating liquid helium system. In CES, there is no need to ensure a continuous flow of current as required in SMES systems. Even for small load disturbances, frequency and tie line power oscillations persist for a long time. The use of a small capacity CES unit with the system can significantly damp these oscillations.

Capacitors are ideally suited for rapid and frequent in/out power flows. Capacitive energy storage is also important for the electric vehicles. Other energy storage applications include carry-over capability until diesel generators or fuel cell can be brought on line. Batteries are excellent for long term energy storage in terms of initial cost and high energy capacity. There is no cheaper energy storage system available anywhere. Frequent charges discharge cycles. An alternative strategy makes use of capacitors to handle the short discharge requirements of the system and batteries to handle the long-term energy supply. When capacitors handle the short recharge discharge needs, the strain
on the batteries is reduced and their lifetimes prolonged. Stretching out the time-to-replacement improves battery economics dramatically. These systems use “Maxwell-type” capacitors.

A capacitor stores the energy in its electrostatic field created between its plates in response to applied potential across it. For realizing a CES unit for converting ac to dc rectifier and dc to ac inverter system and a capacitor bank.

The capacitor bank consists of many small capacity capacitors connected in parallel. The capacity of the CES unit can be increased at time by adding capacitors in parallel to the capacitor.

![Diagram of Capacitive Energy Storage In Power System](image)

**CONSTRUCTION DETAILS OF CES UNIT:**

Figure above depicts the basic configuration of a CES unit. The storage capacitor is connected to the AC grid through a Power Conversion System (PCS) which includes a rectifier/inverter system. The storage capacitor may consist of many discrete capacitors connected in parallel, having a lumped equivalent capacitance C as shown in Fig. 2. Resistance R which is connected in parallel to the capacitor C is the equivalent resistance of the capacitor bank to represent its leakage and dielectric loss.

During normal operation of the grid, the capacitor can be charged to a net value of voltage from the utility grid. A reversing switch arrangement using gate turnoff thyristors (GTO) is provided to accommodate the change of direction of current in the capacitor during charging and discharging modes, as the direction of current through the bridge converters cannot change. When there is a sudden rise in the demand of load, the stored energy is almost immediately released through the PCS to the grid. As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the capacitor charges to its initial value of voltage. Similar is the action during sudden release of loads. The capacitor is charged immediately towards its full value, thus absorbing some portion of the excess energy in the system and as the system returns to its steady state, the absorbed excess energy is released and the capacitor voltage attains its normal value.

To examine the effect of CES on AGC, a small rating CES having 3.8 MJ storage capacities is considered. Data for CES is given in the Appendix. Assuming the losses to be negligible, the bridge voltage $E_d$ is given by

$$E_d = 2E_{ds} \cos \alpha - 2I_d R_d$$
OPERATION OF CES UNIT:

By changing the relative phase angle $\alpha$ of this pulse through a range from $0^\circ$ to $180^\circ$, the voltage across the capacitor, $E_d$ can be made to vary from its maximum positive value to the maximum negative value. The voltage pulses from the firing circuits are timed to cause each SCR to begin conduction at a prescribed time. The sequence maintains a constant average voltage across the capacitor. The exact timing of the firing pulses relative to the phase of 50 Hz ac voltage determines the average dc voltage across the capacitor. Since the bridges always maintain unidirectional current and $E_d$ is uniquely defined by $\alpha$ for positive and negative values, the power flow $P_d$ in the capacitor is uniquely determined by $\alpha$ in both magnitude and direction. Thus, without any switching operation, reversibility as well as magnitude control of the power flow is achieved by continuously controlling the firing angle $\alpha$. The firing angle of the converter is controlled by an algorithm determined by utility needs, but basically the control circuit responds to a demand signal for a certain power level, either positive or negative. Then based on the voltage across the capacitor, a firing angle is calculated and transmitted to the firing circuit.

The response time of the control and firing circuits to a new demand signal are so short that a new firing angle may be chosen for the very next SCR to be pulsed, say within a few milliseconds. This rapid response to power demands that may vary by hundreds of megawatts is a unique capability of CES relative to other energy storage systems such as pumped hydro, compressed air, flywheels etc. This ability to respond quickly allows the CES unit to function not only as an energy storage unit but also as a spinning reserve and to provide stability in case of disturbances on the utility system. The reversing switch arrangement provided accommodates the change of direction of the current in the capacitor during charging (rated load period) and discharging (during peak load period), since the direction of the current through the bridge converter (rectifier/inverter) cannot change. During the charging mode, switches S1 and S4 are on and S2 and S3 are off. In the discharging mode, S2 and S3 are on and S1 and S4 are off.

The normal operating point of the capacitor can be such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This will make the CES unit very effective in damping the oscillations created by sudden increase or decrease in load. If $E_{d0}$ denotes the set value of voltage and $E_{dmax}$ and $E_{dmin}$ denote the maximum and minimum limits of voltage respectively, then,

$$1/2CE_{dmax}^2 - 1/2CE_{d0}^2 = 1/2CE_{d0}^2 - 1/2CE_{dmin}^2$$

$$E_{d0} = \left[\frac{E_{dmax}^2 + E_{dmin}^2}{2}\right]^{1/2}$$

The capacitor voltage should not be allowed to deviate beyond certain lower and upper limits. During a sudden system disturbance, if the capacitor voltage goes too low and if another disturbance occurs before the voltage returns to its normal value, more energy will be withdrawn from the capacitor which may cause discontinuous control. To overcome this problem, a lower limit is imposed for the capacitor voltage and in the present study; it is taken as 30% of the rated value. Initially, the capacitor is charged to its set value of voltage $E_{d0}$ (less than the full charge value) from the utility grid during its normal operation. To charge the capacitor at the maximum rate, $E_d$ is set at its maximum value by setting $\alpha = 0^\circ$. At any time during the charging period, the stored energy in Joules is proportional to the square of the voltage as described by. Once the voltage reaches its rated value, it is kept floating at this value by a continuous supply from PCS, sufficient to overcome the resistive drop.

Since this $E_{d0}$ is very small, the firing angle $\alpha$ will be nearly 90°. The CES is now ready to be put into service. When there is a sudden rise in load demand, the stored energy is almost immediately released through the PCS to the grid as pulsed AC. As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the capacitor charges to its initial value of voltage $E_{d0}$. The action during sudden releases of load is similar. The capacitor immediately
gets charged towards its full value, thus absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released and the capacitor voltage attains its normal value.

The power flow into the capacitor at any instant is, $P_d = E_d I_d$

And

The initial power flow into the capacitor is, $P_{d0} = E_{d0} I_{d0}$

Where,

$E_{d0}$ = Magnitudes of voltage
$I_{d0}$ = Magnitudes of current prior to the load disturbance

When a load disturbance occurs, the power flow into the coil is

$P_{d0} + \Delta P_d = (E_{d0} + \Delta E_d)(I_{d0} + \Delta I_d)$

So that the incremental power change in the capacitor is:

$\Delta P_d = (I_{d0} \Delta E_d + \Delta E_d \Delta I_d)$

The term $E_{d0}, I_{d0}$ is neglected since $E_{d0} = 0$ in the storage mode to hold the rated voltage at constant value. The capacitor voltage should not be allowed to deviate beyond certain lower and upper limits. During a sudden system disturbance, if the capacitor voltage goes too low and if another disturbance occurs before the voltage returns to its normal value, more energy will be withdrawn from the capacitor which may cause discontinuous control. To overcome this problem, a lower limit is imposed for the capacitor voltage and in the present study; it is taken as 30% of the rated value.

Then,

$E_{d_{min}} = 0.30E_d$

$E_{d_{max}} = 1.38E_{d0}$

SYSTEM CONSIDERATIONS IN CES:

Capacitive energy storage systems are being developed as an alternative to SMES for utility power quality applications and to supplement batteries in electric vehicles. System considerations show that the low voltages of “ultra-capacitors” impose a high penalty in terms of increased component count, greater complexity in the power electronics used for charging and discharging, and large ER voltage drops. Numerous energy storage technologies have been explored to meet needs ranging from uninterruptible power supplies (UPS) to renewable energy resources to electromagnetic launchers.

The advantages of capacitors for energy storage are potentially great. Capacitors have no significant fringe fields, they are ideal for supplying voltage-sourced converter topologies, they are intrinsically modular which enhances reparability and allows capacity to be easily incremented, and there are no large forces involved during fast discharges as is the case in SMES. They also, of course, do not involve rotating machinery and are capable of high power discharge rates and fast recharge. Among the disadvantages of such capacitors in energy storage applications are high leakage currents, low energy density, and high cost.

CONTROL OF CES UNITS:

The set value of the CES voltage has to be restored at the earliest, after a load disturbance so that the CES unit is ready to act for the next load disturbance. For this, the capacitor voltage deviation can be sensed and used as a negative feedback signal in the CES control loop so that fast restoration of the voltage is achieved as shown in Fig.
CES CONTROL LOGIC:
Frequency deviation (or) area control error can be used as control signal to the CES unit
\( \Delta \text{error}_i = \Delta f_i \) (or) \( ACE_i \). \( E_{di} \) is then continuously controlled in accordance with this control signal
to CES, then deviation in current \( \Delta I_{di} \) is given by:
\[
\Delta I_{di} = \frac{1}{1 + s \tau_{DCi}} [k_{CESi} \Delta f_i - k_{vdli} \Delta E_{di}]
\]
If the tie line power flow deviations can be sensed, then area control error can be fed to CES as the
control signal \( \Delta e_i = \Delta f_i = ACE_i \). As a function of tie line power flow deviations, ACE as control
signals to CES may improve tie power oscillations. ACE of two areas is given by:
\[
ACE_i = \beta \Delta f_i + \Delta P_{tie_{ij},i,j=1,2}
\]
Where \( \Delta P_{tie_{ij}} \) is change in tie line power flow out of area i to j. Thus, if \( ACE_i \) is the control signal to
CES, then deviation of current \( \Delta I_{di} \) would be;
\[
\Delta I_{di} = \frac{1}{1 + s \tau_{DCi}} [k_{CESi} ACE_i - k_{vdli} \Delta E_{di}] ; \ i, j=1,2.
\]

<table>
<thead>
<tr>
<th>apf11</th>
<th>apf12</th>
<th>Without CES Unit</th>
<th>With CES Units</th>
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<tbody>
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<td></td>
<td></td>
<td>Frequency Deviation</td>
<td>Area Control Error</td>
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<tr>
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<td>0.90</td>
<td>0.0640</td>
<td>0.0880 1.5000</td>
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<tr>
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<td>0.50</td>
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Table 1: Optimal Integral Gain settings For Area-1
Table 2: Optimal Integral Gain settings For Area-2

IV. SIMULATION RESULTS
Dynamic Responses for $\Delta F_1$, $\Delta F_2$ and $\Delta P_{te12}$, $\Delta P_{g1}$, $\Delta P_{g2}$, $\Delta P_{g3}$, $\Delta P_{g4}$ Considering a Step load disturbance of 0.01 pu in Area-1
Dynamic Responses for $\Delta F_1$, $\Delta F_2$ and $\Delta P_{tie12}$, $\Delta P_{g1}$, $\Delta P_{g2}$, $\Delta P_{g3}$, $\Delta P_{g4}$ Considering a Step load disturbance of 0.01 pu in Area-2
To obtain the response of the two area system without ces unit, consider the load disturbance occurred on one area, i.e., area 1. This disturbance is given as unit step load disturbance i.e., 0.01 pu. Now initialize the coding which is written in the script document, save the model and simulate ones. The responses of the two-area interconnected system have been studied in detail. Fig. below shows the dynamic responses for frequency and tie-line power deviations and Fig. 5 shows the generation responses for 1% step load disturbance in area 1 considering $apf_{11} = apf_{12} = 0.5$ and $apf_{21} = apf_{22} = 0.5$ without CES units and with CES units having $\Delta f_1$ as well as $ACE_1$ as the control logic signals. From results, it is evident that the dynamic responses have improved significantly with the use of CES units. It can be observed that with the use of $\Delta f_1$ feedback to the CES control logic, the dynamic responses are better than those obtained with $ACE_1$ feedback and far improved than that without CES units. As the load disturbance has occurred in area 1, at steady state, the power generated by generating units in area 1 are in proportion to the ACE participation factors. Therefore, as in Fig. 5, at steady state, $\Delta Pg_{1ss} = \Delta Pd_1 \times apf_{11} = 0.01 \times 0.5 = 0.005$ p.u. MW and $\Delta Pg_{2ss} = \Delta Pd_2 \times apf_{12} = 0.01 \times 0.5 = 0.005$ p.u. MW. Similarly, $\Delta Pg_{3ss} = \Delta Pd_2 \times apf_{21} = 0 \times 0.5 = 0$ p.u. MW and $\Delta Pg_{4ss} = \Delta Pd_2 \times apf_{21} = 0 \times 0.5 = 0$ p.u. MW at steady state.
V. Conclusion

In this project, the responses of a two-area inter connected thermal power system with reheat and non reheat units have been studied. Small rating Capacitive Energy Storage units are fitted to both the areas and responses show that they are capable of consuming the oscillations in area frequency deviations and tie-line power deviations of the power system. Further, CES units reduce the settling time of the responses. Two different control logic for CES units are attempted and it was found that, the dynamic responses with frequency feedback to CES are better than that obtained with ACE feedback to CES units and far superior than that without CES units. Hence, it may be concluded that CES units are efficient and effective for improving the dynamic performance of AGC of interconnected power systems.

A small perturbation transfer function model of CES unit has been developed and its effect on the improvement of AGC of a two area interconnected power system has been examined. Gain settings of the integral controller have been optimized using Integral Square Error technique without and with CES units in each area. Analysis reveals that with the use of CES units, the oscillations are practically damped out and also the amplitudes of the deviations in frequency and tie-line.

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