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An Investigative Study of Generator-Load Tie-Line Model of Speed Governing System and Overview of Design of Conventional Controllers for LFC of Electrical Power Systems

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Abstract - *A real power (active power) control is an important control strategy to be performed during normal operation of the power system to meet the power generation with the continuously changing load, in order to maintain the system frequency to within ± 1%. The frequency changes due to change in system load, which leads to the change in the speed of turbine generator systems of all the units. The main purpose of operating Automatic Generation Control (AGC) or Load Frequency Control (LFC) is to keep uniformly the frequency changes during the load changes. In this paper, Automatic Load Frequency control of two area power systems using Proportional, Integral, Proportional Integral, Proportional Derivative and Proportional integral and derivative tuning technique designing method are analyzing along with generator load and tie line model. Two main objectives of LFC are to maintain the real frequency and the desired power output in the interconnected power system and, to control the change in tie line power between control areas. The advantages PID controller has the ability to provide high adaption for changing conditions and the ability for making quick decisions. The PID controller is used to improve the dynamic response as well as to reduce or eliminate the steady-state error.*

Key Words*: *Speed Governing System, Tie-line, Area Control Error (ACE), Proportional (P), Proportional Integral (PI) and Proportional Integral Derivative (PID), Load Frequency Control (LFC) or Automatic Generation Control (AGC).

1. INTRODUCTION

The need for satisfactory operation of power stations running in parallel and the relation between system frequency and the speed of the motors has led to the requirement of close regulation of power system frequency. Since the control of system frequency and load depends upon the governors of the prime movers are understand by the model of the governor. There are two types of control, Primary Control and Secondary Control. The system speed change from synchronous speed initiates the primary control action resulting in all the participating turbine-generator units taking up the change in load and stabilizes with the system frequency. The secondary control action needs to adjust the load reference set points of selected turbine-generator units and to maintain the nominal value of frequency. The objective of frequency control is the speed control of the machines in the generating stations. The system frequency is depends upon the speed at which the entire generators. The prime movers are steam or hydro turbines are coupled with speed governors which are purely mechanical sensitive device, which is to adjust the gate or control valve opening or closing for constant speed of the system. Generator synchronous speed, $N=\frac{120f}{p}$. The system frequency can be varied by changing the speed of the turbine. The frequency is closely related to real power balance of overall network. In the normal operating conditions, generators run synchronously and generate power and then meet all the loads and real power losses. Power system operation at al lower frequency than the specified maximum allowable change in frequency is ± 0.5 Hz which affects the quality of power supply. The load frequency control on a power system becomes one of changing the control valve or gate openings of the prime movers as a function of load changes in order to maintain the system frequency constant. All the generators speed up and slow down together maintaining their relative power angles, which maintains the system frequency, such system is called as a control area. The system generator unit's performances are dependent on the performance of all the auxiliary drives associated with fuel, feed water and combustion air supply system. The inter connected system, two or more areas in addition to control of frequency, the generation within each area has to be controlled and to maintain the scheduled power interchange in the power system.

II. MODELLING OF SPEED GOVERNING MECHANISM

2.1 Model of Speed Governor and Turbine

The real power in a system is being controlled by controlling the driving torques of the individual turbines of the system. The speed governor is the main primary tool for the load frequency control, whether the machine is used alone to feed a smaller system or it is a part of the most elaborate arrangement. By controlling the position of the control valve or gate, we can exert control over the flow of high pressure steam (or water) through the turbine. The speed governor is a mechanical speed sensitive device, it sense speed changes and moves through linkage point B. The speed changer provides facility to set the turbine output at desired level. A small downward movement of the linkage point A corresponds to an increase ΔP_c in the reference power setting. The hydraulic amplifier consists of low level pilot value movement is converted into high power piston movement. The input to this amplifier is the position X_D of the pilot valve. The output is the position X_E of the main piston.

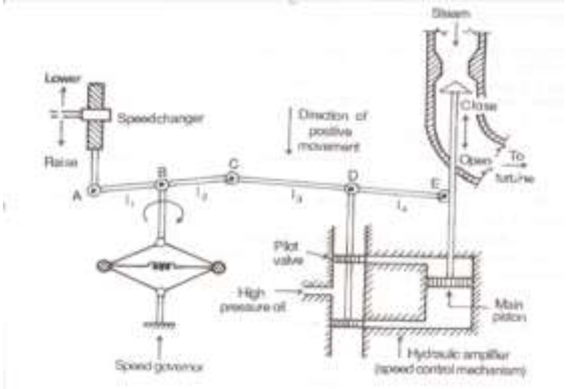

Figure 1. Functional diagram of Speed Governing System

The steam is operating under steady state and is delivering power P_G from the generator at nominal frequency. Let us assume that raise command ΔP_c to the speed changer the point A be moved downwards by a small amount ΔX_A, which causes the turbine power output to change.

$\Delta X_A = K_c \Delta P_c$ ------ (2.1)

Let us assume, that positive direction for downward movement and negative direction for upward movement.

ΔX_A = contributes $\left[\frac{-I_2}{I_1}\right]$ $\Delta X_A = K_1K_c\Delta P_c$; An increase in frequency Δf causes the fly balls to move outwards, so that point B moves downwards by a proportional amount $K_2 \Delta f$.

Therefore, $\Delta X_A = K_1K_c\Delta P_c + K_2 \Delta f$ ------ (2.2)

Then the movement of ΔX_D is the amount by which the pilot valve opens, thereby moving the main piston and opening the steam valve by ΔX_E.

$\Delta X_D = \left[\frac{-I_4}{I_3+I_4}\right]\Delta X_C + \left[\frac{-I_3}{I_3+I_4}\right]\Delta X_E$ ------ (2.3)

$\Delta X_D = K_3\Delta X_C + K_4 \Delta X_E$

As the value of oil admitted to the cylinder is thus, proportional to the line integral of ΔX_D.

$\Delta X_E = K_5 \int_0^1 (-X_D)dt$ ------ (2.4)

By taking Laplace transform,

$\Delta X_C(s) = K_1K_c\Delta P_c(s) + K_2 \Delta F(s)$ ------ (2.5)

$\Delta X_D(s) = K_3\Delta X_c(s) + K_4 \Delta X_E(s)$ ------ (2.6)

and $\Delta X_E(s) = \frac{-K_5}{s} \Delta X_D(s)$ ------ (2.7)

Substituting the above two equations,

$$\Delta X_E(s) = \frac{-K_5}{s}\,[K_3\Delta X_c(s) + K_4 \Delta X_E(s)]$$

$$\Delta X_E(s)\left[1+\frac{K_4K_5}{s}\right] = \frac{-K_5K_3}{s}\,\Delta X_C(s)$$

$$\Delta X_E(s)\left[1+\frac{K_4K_5}{s}\right] = \frac{-K_5K_3}{s}\,[K_1K_c\Delta P_c(s)+K_2\Delta F(s)]$$

$$\Delta X_E(s)\left[\frac{s+K_4K_5}{s}\right] = \left[\frac{K_5K_3K_1K_c\Delta P_C(s)-K_2K_5K_3\Delta F(s)}{s}\right]$$

$$\Delta X_E(s) = \left[\frac{K_5K_3K_1 - [\Delta Pc(s) - \frac{K_2}{K_1K_C}\Delta F(s)}{K_4K_5\left[1+\frac{s}{K_4K_5}\right]}\right]$$

$$\Delta X_E(s) = \frac{K_3K_1K_C}{K_4}\left[\frac{[\Delta P_C(s) - \frac{K_2}{K_1K_C}\Delta F(s)}{1+\frac{s}{K_4K_5}}\right] \quad \text{-----} \quad (2.8)$$

It can be written as,

$$\Delta X_E(s) = [\Delta P_C(s) - \frac{1}{R}\Delta F(s)] \text{ x } \frac{K_G}{1+sT_G} \quad \text{------} \quad (2.9)$$

Where,

Speed regulation of the governor (R) = $\frac{K_1K_C}{K_2}$ in Hz/MW

Gain of speed governor (K_G) = $\frac{K_1K_3K_C}{K_4}$

Time constant of speed governor (T_G) = $\frac{1}{K_4K_5}$

The value of T_G is less than 100 m sec.

The generating unit output at a given system frequency can be varied only due to changing its "load reference or control point" and it is integrated into the speed governing system. The reference set point is adjusted by operating the speed changer motor. This effect leads to move the speed loop characteristics up and down. A non-reheat turbine model which relates the position of the valve that controls the emission of steam into the turbine to the power output of the turbine system.

2.2. Generator Load Model

The mathematical model of an isolated generator, which can only supplying local load and is not supplying power to another area suppose there is a real load change of ΔP_D. Due to the action of the turbine controllers, the generator increases its output by an amount ΔP_G. The net surplus power (ΔP_G - ΔP_D) will be absorbed by the system in two categories.

(a) By increasing the kinetic energy in the rotor.
(b) When the frequency changes, the motor load changes being sensitive to speed.

The rate of change of load with respect to frequency is $\frac{\partial P_D}{\partial f} = B$; where B = Damping coefficient in MW/Hz. The value of damping coefficient is positive value for motoring load.

$$\Delta P_G - \Delta P_D = B\,\Delta f \qquad \text{------ (2.10)}$$

The power balance equation is

$$\Delta P_G - \Delta P_D = \frac{2HP_r}{f_0}\frac{d}{dt}(\Delta f) + B\,\Delta f \qquad \text{------ (2.11)}$$

Divide by Pr, we get,

$$\Delta P_{G\,p.u} - \Delta P_{D\,p.u} = \frac{2H}{f_0}\frac{d}{dt}(\Delta f) + B_{p.u}\Delta f \qquad \text{----- (2.12)}$$

Taking laplace transform on both sides,

$$\Delta P_G(s) - \Delta P_D(s) = \frac{2Hs}{f_0}\Delta F(s) + B\Delta f(s)$$

$$\Delta P_G(s) - \Delta P_D(s) = \Delta F(s)[\frac{2Hs}{f_0} + B]$$

$$\Delta F(s) = [\frac{\Delta P_G(s) - \Delta P_D(s)}{B[1 + \frac{2Hs)}{Bf_0}]}]$$

$$\Delta F(s) = \Delta P_G(s) - \Delta P_D(s)[\frac{K_P}{1 + sT_P}] \qquad \text{----- (2.13)}$$

Where, Power system gain (K_P) = $\frac{1}{B}$

Power system time constant (T_P) = $\frac{2H}{Bf_0}$

The combination of governor model, turbine model and generator model is the complete block diagram model of LFC of an isolated power system.

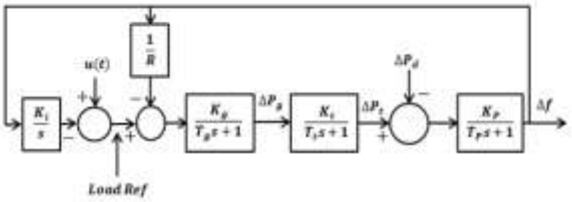

Figure 2. Model of LFC of Single Area System

III. TIE-LINE MODEL OF TWO AREA POWER SYSTEMS

A two area system consists of two single area systems, connected through a power line called tie-line. Figure.3 shows a two area power system where each area supplies to its own area and the power flow between the areas are allowed by the tie line. For two area power system, the individual areas are strong, the tie line which connects the two area is weak and a single frequency is characterized throughout.

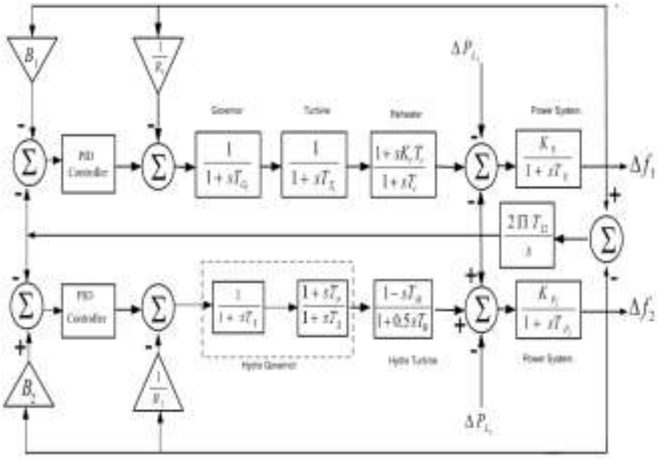

Figure 3. Simulink diagram for Two area interconnected power system

3.1 Area Control Error (ACE)

Area Control Error (ACE) of the ith area is commonly defined as

$$ACE_i = (T_{1i} - T_{0i}) - (F_{1i} - F_{0i}) \quad \text{---------} \quad (3.1)$$

Existence of Area Control Errors shows that there is excess or deficiency of generation in a control area and control is required to restore the system frequency and tie line flow to scheduled value.

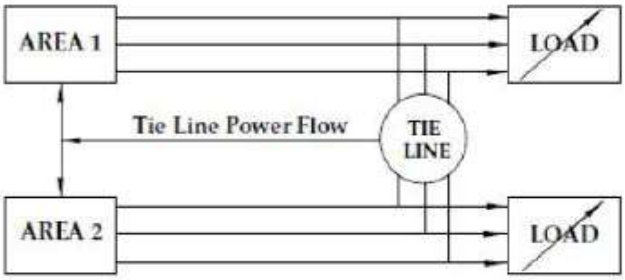

Figure 4. Two Area Power System

The tie-line equation in normal operation of power system is

$$P_{ij} = \frac{|V_i||V_j|}{X}\sin(\delta_i - \delta_j) \quad \text{------} \ (3.2)$$

There should be small deviations in the angles δ_i and δ_j. Therefore, the tie-line power equation changes with small amount.

$$\Delta P_{ij} = \frac{|V_i||V_j|}{X}\cos(\delta_i - \delta_j)(\Delta\delta_i - \Delta\delta_j) \quad \text{-----} \quad (3.3)$$

The synchronizing coefficient of a line is,

$$T^0 = \frac{|V_i||V_j|}{X}\cos(\delta_i - \delta_j) \text{ in MW} \quad \text{------} \quad (3.4)$$

The tie-line power equation becomes,

$$\Delta P_{ij} = T^0 \, (\Delta\delta_i - \Delta\delta_j) \text{ in MW}$$

The frequency deviation Δf is given is related to the reference angle Δδ.

$$\Delta f = \frac{1}{2\pi}\frac{d}{dt}(\delta^0 + \Delta\delta) \quad \text{-----} \ (3.5)$$

$$\Delta f = \frac{1}{2\pi}\frac{d}{dt}(\Delta\delta) \text{ in Hz}$$

Taking integration on both sides,

$$\int_0^t \Delta f = 2\pi \int_0^t \Delta\delta$$

$$\Delta\delta = 2\pi \int_0^t \Delta f.dt \text{ in rad}$$

Then the tie-line power deviation becomes,

$$\Delta P_{ij} = 2\pi T^0 \left(\int_0^t \Delta f_1.dt - \int_0^t \Delta f_2.dt \right) \text{in MW} \quad \text{-----} \ (3.6)$$

Taking the Laplace transformation on both sides,

$$\Delta P_{ij} = 2\pi T^0 \left(\frac{\Delta f_1(s)}{s} - \frac{\Delta f_2(s)}{s} \right)$$

$$\Delta P_{ij} = \frac{2\pi T^0}{s}\left(\Delta f_1(s) - \Delta f_2(s)\right) \quad \text{-----} \ (3.7)$$

IV. CONTROLLER

The controllers are set for a particular operating condition and they take care of small changes in load demand without voltage and frequency exceeding the pre-specified limits. If the operating conditions change materially the controllers must be re-set either manually or automatically. A Controller is a device introduced in the system to modify the error signal and to produce a control signal. The controller modifies the transient response of the system. The controllers may be electrical, electronic, hydraulic or pneumatic depending on the nature of signal and the system.

4.1 Proportional (P) Controller

The proportional controller is a device that produces a control signal u(t) proportional to the input error signal e(t).

In P-controller, u(t) α e(t)

$$U(t) = K_P \, e(t) \quad \text{------} \ (4.1)$$

On taking Laplace transform,

$$U(s) = K_P \, E(s)$$

$$\frac{U(s)}{E(s)} = K_P \quad \text{------} \ (4.2)$$

The P-controller amplifies the error signal by an amount K_P. Also the introduction of the controller on the system increases the loop gain by an amount K_P. The increase in loop gain improves the steady state tracking accuracy, disturbance signal rejection and the relative stability and also makes the system less sensitive to parameter variations. But increasing the gain to very large values may lead to instability of the system. The main drawback in P-controller is that it leads to a constant steady state error.

4.2 Integral (I) Controller

The integral controller is a device that produces a control signal u(t) which is proportional to integral of the input error signal e(t).

In I-controller, u(t) $\alpha \int e(t)dt$;

U(t) = $K_i \int e(t)dt$ ------- (4.3)

On taking Laplace transform,

U(s) = $K_i \dfrac{E(s)}{s}$ ------- (4.4)

The integral controller removes or reduces the steady error without the need for manual reset. Hence the I-controller is sometimes called automatic reset. The drawback in integral controller is that it may lead to oscillatory response of increasing or decreasing amplitude which is undesirable and the system may become unstable.

4.3 Proportional plus Integral (PI) Controller

The proportional plus integral controller produces an output signal consisting of two terms. One is proportional to error signal and the other is proportional to the integral of error signal.

In PI-controller, U(t) $\alpha \left[e(t)\int e(t)dt\right]$;

U(t) = $K_P e(t) + \dfrac{K_P}{T_i}\int e(t)dt$ ------ (4.5)

On taking Laplace transform,

U(s) = $K_P E(s) + \dfrac{K_P}{T_i}\dfrac{E(s)}{s}$ ------ (4.6)

$$\frac{U(s)}{E(s)} = \mathrm{K_p}(1 + \frac{1}{T_i s}) \quad \text{------ (4.7)}$$

The advantages of both P-controller and I-controller are combined in PI-controller. The proportional action increases the loop gain and makes the system less sensitive to variations of system parameters. The integral action eliminates or reduces the steady state error. The integral control action is adjusted by varying the integral time. The change in value of $\mathrm{K_P}$ affects both the proportional and integral parts of control action. The inverse of the integral time T_i is called the reset rate.

4.4 Proportional plus Derivative(PD) Controller

The proportional plus derivative controller produces an output signal consisting of two terms. One is proportional to error signal and the other is proportional to the derivative of error signal.

In PD-controller, U(t) $\alpha \left[e(t) + \dfrac{d}{dt}e(t)\right]$;

U(t) = $K_P e(t) + K_P T_d \dfrac{d}{dt}e(t)$ ------ (4.8)

On taking Laplace transform,

U(s) = $K_P E(s) + K_P T_d sE(s)$ ------ (4.9)

$$\frac{U(s)}{E(s)} = \mathrm{K_p}(1 + T_d s) \quad \text{------ (4.10)}$$

The derivative control acts on rate of change of error and not on the actual error signal. The derivative control action is effective only during transient periods and so it does not produce corrective measures for any constant error. Hence the derivative controller is never used alone, but it is employed in association with proportional and integral controllers. The derivative controller does not affect the steady state error directly but antipates the error, initiates an early corrective action and tends to increase the stability of the system. While derivative control action has an advantage of being anticipatory it has the disadvantage that it amplifies noise signals and may cause a saturation effect in the actuator. The derivative control action is adjusted by varying the derivative time. The change in the value of $\mathrm{K_P}$ affects both the proportional and derivative parts of control action. The derivative control is also called rate control.

4.5 Proportional plus Integral plus Derivative (PID) Controller

The PID-controller produces an output signal consisting of three terms. One is proportional to error signal, another one is proportional to integral of error signal and the third one is proportional to derivative of error signal.

In PID-controller, U(t) $\alpha \left[e(t) + \int e(t)dt + \dfrac{d}{dt}e(t)\right]$;

U(t) = $K_P e(t) + \frac{K_P}{T_i}\int e(t)dt + K_P T_d \frac{d}{dt} e(t)$ ---- (4.11)

On taking Laplace transform,

U(s) = $K_P E(s) + \frac{K_P}{T_i}\frac{E(s)}{s} + K_P T_d s E(s)$ ----- (4.12)

$$\frac{U(s)}{E(s)} = \mathrm{K_P}(1 + \frac{1}{T_i s} + T_d s) \quad \text{------} \quad (4.13)$$

The combination of proportional control action, integral control action and derivative control action is called PID control action. This combined action has the advantages of the each of the three individual control actions. The proportional controller stabilizes the gain but produces a steady state error. The integral controller reduces or eliminates the steady state error. The derivative controller reduces the rate of change of error.

4.6 PID Controller Design

A proportional integral derivative controller is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable. There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, and then choosing P, I, and D based on the dynamic model parameters. The Ki and Kd gains are first set to zero. The proportional gain is increased until it reaches the ultimate gain, Ku, at which the output of the loop starts to oscillate. The PID controller encapsulates three of the most important controller structures in a single package. The parallel form of a PID controller has transfer function. In the case of a single generator supplying power to a single service area, and consider three types of turbine used in generation. We are interested in tuning PID controllers to improve the performance of load frequency control system. In two area system, two single area systems are interconnected via tie-line. Interconnections established increases the overall system reliability. Even if some generating units in one area fail, the generating units in the other area can compensate to meet the load demand. The PID controller improves steady state error simultaneously allowing a transient response with little or no overshoot. As long as error remains, the integral output will increase causing the speed changer position, attains a constant value only when the frequency error has reduced to zero. The SIMULINK model of a two area interconnected power system using PID controller is shown in Figure 4.

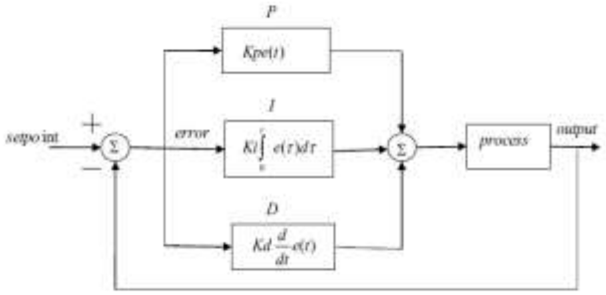

Figure 4. Block diagram of PID Controller

The PID controller improves the transient response so as to reduce error amplitude with each oscillation and then output is eventually settled to a final desired value. Better margin of stability is ensured with PID controllers. The mathematical equation for the PID controller is given as,

$$y(t) = Kpe(t) + Ki\int_0^t e(\tau)d\tau + Kd\frac{d}{dt}e(t) \quad \text{-----} \quad (4.14)$$

Where y(t) is the controller output and u (t) is the error signal. K*p*, K*i* and K*d* are proportional, integral and derivative gains of the controller. The limitation conventional PI and PID controllers are slow and lack of efficiency in handling system non-linearity. But in the case deregulated environment large uncertainties in load and change in system parameters is often occurred. The optimum controller gains calculated previously may not be suitable for new conditions, which results in improper working of controller. So to avoid such situations the gains must be tuned continuously.

V. CONCLUSION

The model of load frequency control gives relation between the changes in frequency as a result of change in generation when the load changes by a small amount. From this study it is found that if a load changes in an area, the frequency and interchange errors in that area have the same sign while these have opposite signs for the other area. Thus the relative signs of the frequency and interchange deviations help to identify the area where the load has changed. A PID controller is designed and its feasibility is studied by varying system parameters. It has been observed that responses of the system with PID controller gives better results in terms of dynamic parameters such as peak overshoot and settling time. PID gives better response by reducing settling time. The ability of two area interconnected power system of PID controller is improved as the settling time is reduced in PID as compared to PI. When compared with PI controller than PID controller of deregulated power system gives more rapidly and responsive results. Effectiveness of PID controller with the deregulated system is used to improve the stability of the system. Simulation results presented justify the connection of PID controller in deregulated system for stable and quality power.

NOMENCLATURE

KG = Gain of speed governor
TG = Time constant of speed governor
R = Speed regulation of the governor in Hz/MW
Tt = Time constant of the turbine
Kt = Gain constant
Kp = Power system gain
Tp = Power system time constant
N = Speed in rpm
F = Frequency in Hz
P = Number of poles
V1&V2 = End voltages
δ1 & δ2 = Angles of end voltages
X = Reactance
ACE = Area Control Error of i^{th} *area in MW*
T_{1i} = *Net interchange of area in MW, power output is considered positive*
T_{0i} = *Scheduled net interchange of area 1 in MW Power output is considered positive*
B_i = *Bias setting of area in MW/ Hz and is Considered Negative*
F_{1i} = *System frequency in Hz*
F_{0i} = *System frequency schedule in Hz*

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