연계계통에서 발전기 정지에 따른 주파수의 동적 변화

블라디미르 문영환 윤재영
한국전기연구원

Dynamic change of frequency after a generator outage in an Interconnection considering the primary control

Vladimir Stanojevic Y.H Moon J.Y Yoon
KERI

Abstract - Frequency is the unique physical value for all the interconnected systems. Therefore, the load frequency control is in the responsibility of all members in the interconnection. Power unbalance in one of the interconnected system can cause the problems in others. In the following text, a brief description and the role of frequency in an interconnected system will be presented. Following is the short description of the Balkan Interconnection (UCTE Second Synchronous Zone) with schematic diagram. A power-frequency (*P-f*) dynamic model of a control area will be shown. Model gives the analytical solution for frequency change versus a time after outage of a generator in the power system. This model will be applied to the Balkan Interconnection and compared with numerical approach. Advantages and drawbacks of the analytical method will be discussed. Purpose of using this model is to investigate if the pumps in reversible hydropower plant will be underfrequency shed after the outage of the biggest generator unit in the interconnection, according to (n-1) security postulate.

1. Introduction

Since the frequency presents the unique value for the whole electric power system, it is one of the most important system variables. As such, it is a good criterion for the quality of operation of the system, especially in tremendous physical systems such as interconnections, consisting of huge number of generators. Any unbalance between generated and consumed active power in the system causes the frequency deviation, which, in turn, causes the change in power flow through the network. In normal operation, frequency should be maintained precisely in a limited band in order that the power interchanges comply with scheduled ones and to prevent overloading of the national and international transmission lines.

Frequency has a dominant role in primary and secondary power-frequency control (*P-f* control). Frequency changes all the time and absolutely constant frequency is not possible to achieve, even in case of no disturbances. A good indicator of the overall system operation is synchronous time and its deviation from Coordinated Universal Time, which describes the availability of control reserve.

The objective of this paper is the application of the analytically derived equation which gives the frequency changes versus a time after an unbalance occurs in the system.

The spinning reserve also plays a very important role in order to prevent drops in frequency to be too large in magnitude and too long in duration. The spinning reserve has been taken into account by the analytical model.

2. Interconnected system

The interconnection under the study is The Balkan Interconnection, consisting of the following power pools: EKC (Yugoslavia and Macedonia), RENEL (Romania), NEK (Bulgaria), KESH (Albania) and PPC (Greece). The schematic diagram of the interconnection is given on Figure 1. This interconnection is also called UCTE Second Synchronous Zone, because two members of this interconnection are regular members of UCTE interconnection. These are EKC (**E**lektroenergetski **K**oordinacioni **C**entar) and PPC. Temporarily, this interconnection is not physically connected to UCTE due to war devastation in former Yugoslavia. The summary data of generation capacity, as well as the actual load under the study is given in Table 1.

The purpose of application of this model is to investigate if the frequency drop, followed by the outage of the biggest generator in the interconnection, will cause the underfrequency shedding of 2x300 MW pumps in the reversible hydro power plant Bajina Basta in EKC power pool. It will be discussed in detail after the model has been developed.

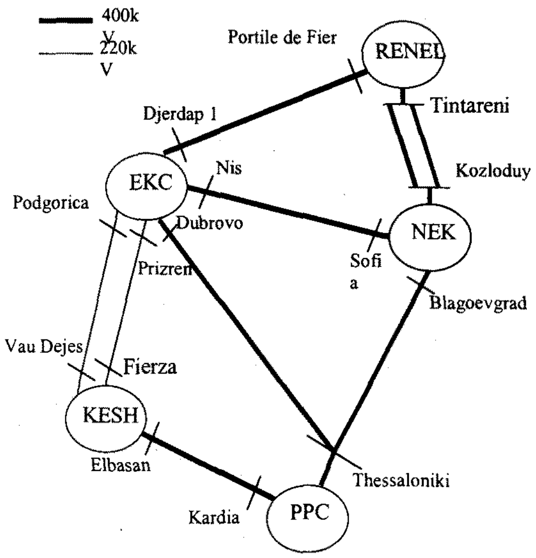

Figure 1: The Balkan Interconnection diagram

Table 1: Total installed capacity, operating capacity and actual generation of operating capacity

Power Pool	Generation Capacity [MW]		Actual Generation [MW]
	Total	Operating	
EKC	13139	4258	3541.8
RENEL	20632	4173	3127.5
NEK	12395	3558.3	2839.2
PPC	8237	2950	2409.9
KESH	1670	481	262.1

3. Analytical approach

In the following text, the average frequency for the whole system after some power imbalance ΔP will be considered. Such a case is influenced by the equivalent inertia of all the machines, by the action of the speed governors and frequency regulators. As the frequency lowers below the dead zone of the speed governors (the primary regulators), they operate and redistribute the additional load in proportion to the governors static gains. At last, the process is affected by the slow acting secondary regulators (frequency regulators) which adjust the settings of the primary regulators controlling the generation of one or more power plants so that they could compensate for power imbalance in the system. In that way, they restore the frequency in the system to its normal value provided there is enough power reserve in the system. The time response of secondary regulators is about tens of seconds, which is much slower comparing with that one of speed governors. It means, in first approximation, those two processes can be analyzed separately. In this work the secondary regulators will not be taken into account.

It can be assumed that the relationship between power change ΔP and the steady-state frequency deviation Δf is linear: $\Delta f_i = -\frac{\Delta P}{k_i}$, where k_i is the regulation in MW/Hz of the i-th generator unit. The reciprocal of k_i is the droop of the i-th unit $\sigma_i = \frac{1}{k_i}$. After the initial transient decays, the frequency will be the same for all the generators in the system, i.e. all the generators will experience the same change of speed in steady-state $\Delta\omega_1 = \Delta\omega_2 = \ldots = \Delta\omega_N = \Delta\omega$, which corresponds to the change of frequency Δf. The total change in generated power is $\Delta P = k_{g\Sigma}\Delta f$ where $k_{g\Sigma}$ is the equivalent regulation for the whole system.

Parameters needed for the analytically derived formula are as follows:

1. Rated power of each operating generator unit with exception of outaged one
2. Real power generation of outaged generator
3. Real power generation of each generator immediately before the outage
4. Inertia constants of each generator with exception of outaged one
5. Turbine droop characteristic of each generator with exception of outaged one

Frequency change dynamic model in a power system immediately after lost ΔP [MW] of generation is given by following formula (detailed derivation of this formula is given in the appendix):

$$f(t) = f_0 \cdot \left(1 - \frac{\Delta P}{(\rho k_{g\Sigma} + k_{p\Sigma}) \cdot \Sigma P_p}\right) + $$

$$+ f_0 \left[2e^{-\alpha \cdot t} \cdot \sqrt{X^2 + Y^2} \cdot \frac{\Delta P}{T_{J\Sigma} \cdot \Sigma P_{ng}} \cos(\Omega t + \theta) \right] \quad (1)$$

where:

f_0 - frequency [Hz] immediately before the outage of ΔP [MW]

ρ - real power reserve coefficient: $\rho = \frac{\Sigma P_{ng}}{\Sigma P_p}$

ΣP_{ng} - sum of rated power [MW] of all the generator units in the power system with the exception of outaged generator

ΣP_p - total load [MW] in the power system

$k_{g\Sigma}$ - equivalent regulation characteristic of the power system

$$k_{g\Sigma} = \frac{\sum_{i=1}^{N_G} P_{ng,i} \cdot k_{g,i}}{\sum_{i=1}^{N_G} P_{ng,i}} \quad (2)$$

without outaged generator

P_{ng} - nominal (rated) power [MW] of generator unit

k_g - regulation characteristic (P-f)

$$k_g = \frac{\frac{\Delta P}{P_{ng}}}{\frac{\Delta f}{f_n}} \qquad (3)$$

f_n - rated frequency [Hz]

If some generator is loaded with its rated power, or turbine governor is not operating, then $P_{ng}k_g=0$ in equation (2).

$k_{p\Sigma}$ - equivalent self-regulating coefficient for all the loads in the power system:

$$k_{p\Sigma} = \frac{\frac{\Delta P}{\Sigma P_p}}{\frac{\Delta f}{f_n}} \qquad (4)$$

$T_{j\Sigma}$ - equivalent inertia constant [s] of all the units in the power system with exception of outaged one

$$T_{j\Sigma} = \frac{\sum T_j \cdot P_{ng}}{\Sigma P_{ng}} \qquad (5)$$

T_j - inertia constant of generator unit [s]
T_{Je} - time constant of frequency change [s]

$$T_{Je} = \frac{T_{j\Sigma}}{k_{p\Sigma} \cdot \frac{\Sigma P_p}{\Sigma P_{ng}}} \qquad (6)$$

T_S - equivalent servomotor time constant [s]; it is adopted to be $T_s=5s$.

$$\alpha = \frac{1}{2} \cdot \left(\frac{1}{T_s} + \frac{1}{T_{Je}} \right) \quad [1/s] \qquad (7)$$

$$a' = k_{p\Sigma} \cdot \frac{\Sigma P_p}{\Sigma P_{ng}} \qquad (8)$$

$$\Omega = \sqrt{\frac{k_{g\Sigma}}{T_s \cdot T_{j\Sigma}} - \frac{1}{4} \cdot \left(\frac{1}{T_s} - \frac{1}{T_{Je}} \right)^2} \quad [1/s] \qquad (9)$$

$$X = -\frac{T_{j\Sigma}}{2 \cdot (k_{g\Sigma} + a')} \quad [s] \qquad (10)$$

$$Y = \frac{1}{2\Omega} \left[\frac{T_{j\Sigma} + a' T_s}{2T_s \cdot (k_{g\Sigma} + a')} - 1 \right] \quad [s] \qquad (11)$$

$$\theta = arctg \frac{Y}{X} \qquad (12)$$

Calculating all the parameters in (2)-(12) and substituting in (1), we get the frequency as a function of time.

Numerical solution, proposed by Elgerd [2], is presented in Figure 2:

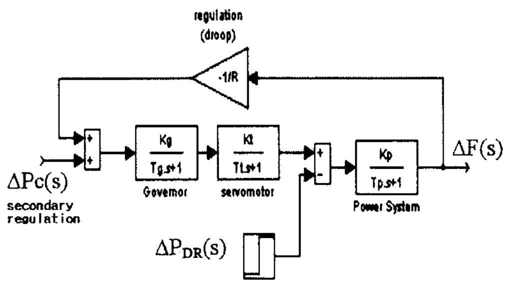

Figure 2: Block diagram representation of power system

4. Application of the model

As it was said above, the Balkan Interconnection consists of five power pools.

Reversible hydropower plant Bajina Basta is in Yugoslavia [EKC] and this is one of the worlds highest head pumped storage power station, with head exceeding 620 m. There are two synchronous machines of 300 MW each. Maximal penstock pressure is 900 m, and the problem arises if the both units runaway simultaneously. In that case, the fluctuations of the pressure overcome the designed maximal pressure in penstock. Underfrequency shedding of these synchronous machines when they operate as motors is set to 49.2Hz. From this reason, it is important to estimate the change of frequency according to (n-1) security postulate. We consider the case of outage of the biggest generator unit in the Interconnection. It is the generator in the nuclear power plant "Cherne Vode" in Romania (RENEL), rated power of which is 706 MW. Also, the largest changes in frequency appear in light load condition. This is why the summer minimum load was considered (yearly peak loads occur during winter, while they are significantly reduced during summer).

From Table 1, one can see that in the case under the study, the total generation of operating capacity at that moment was 15,420.3MW which means that 4.54% outage was happened. Also, the total power demand was 12,180.5MW. The most pessimistic case is assumed that all the units have the same servomotor time constant of $T_S=5s$ (ordinary 1-3 s). Self-regulating effect of load is estimated to be $k_{p\Sigma} =$ 0.5 (also the worst case).

After substituting the adopted and calculated parameters in the model given by equation (1) and performing the calculations, the results are plotted in Figure 3.

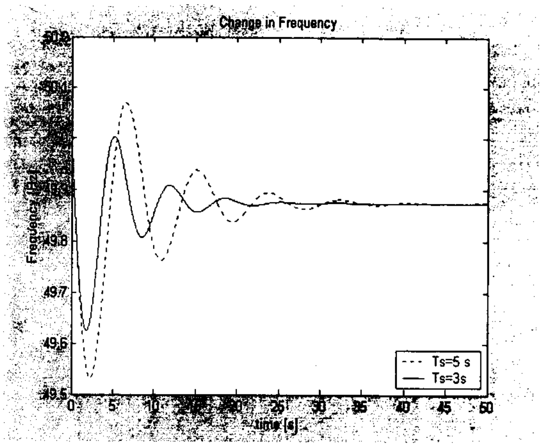

Figure 3: Frequency change after 700 MW generator outage depending on servomotor time constants

As expected, the greater time constants, the largest deviation of frequency.

Equation (1) is very convenient for analysis the effect of various parameters, such as self regulating coefficient of the loads. It is seen that the self-regulating coefficient of loads greater, the deviation of frequency smaller. In Figure 4, such analysis is shown graphically.

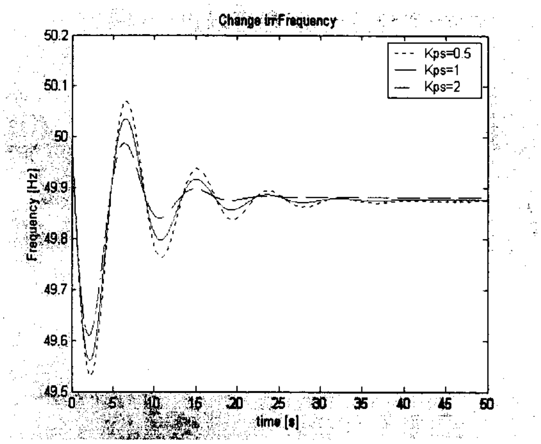

Figure 4: The load self regulating coefficient influence to change in frequency.

The steady-state value of frequency can be obtained as $\lim_{t\to\infty} f(t)$ in which case we find:

$$f_\infty = f_0\left(1-\frac{\Delta P}{(\rho k_{g\Sigma}+k_{p\Sigma})\Sigma P_p}\right)$$

This is in accordance with Figure 4, from where we can note that steady-state frequency increases as $k_{p\Sigma}$ increases.

Comparing models given by equation (1) with the model in Figure 2, one can find the results are identical. The maximal difference between the results obtained by those models is around 10^{-7}. Model given by equation (1) assumes ideal speed governors, i.e. with zero time lagging. Model from Figure 2 is capable to take into account the time constants of speed regulators, and such a case is given in Figure 5, where a speed governor time constant of 100ms was assumed.

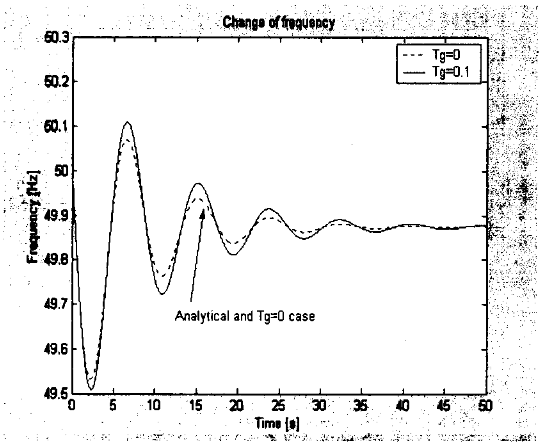

Figure 5: The influence of speed regulator time constant to the change of frequency

From Figure 5 it can be noticed that accounting for governor time constant increases the frequency deviation.

5. Conclusion

It has been shown that taking into account the largest time constants (worst case), in the case of outage of the biggest generator in the interconnection the pumps will not be underfrequency shed. Analytical model was considered since it gives a qualitative explanation of the underlying physical phenomena of power system dynamics, which cannot be obtained only by simulation results. Computer model given in form of block diagram can be readily extended to include the secondary control and governor operation. On the other hand, analytical method serves as a good reference and it can be used for very fast, yet accurate estimation of frequency changes. Comparing both analytical and numerical approaches, the same results have been obtained. Analytical model can be a good base for future researching, such as finding the prime derivative of frequency with respect to time, and the instant of time when the frequency takes its minimum value. These results can serve as a good reference to numerical finding of time derivative of frequency and its application to adaptive (selective) underfrequency load shed.

[References]

[1] V.A.Venikov : Transient processes in electrical power systems, Published by "Visaya Skola" Moscow 1977, English Translation by Mir

Publishers, 1980.
[2] Olle I. Elgerd, Electric Energy Systems Theory: An Introduction, McGraw-Hill Book Company, New York, 1971
[3] A. Kladas, I. Kabouris, G. Kontos, A. Rigos Public Power Corporation: Recent trends on interconnection of the power systems in Balkans, Second conference on the development and operation of interconnected power systems, Session 1, Report No.1.01
[4] P.Dusseiller: The quality of frequency in an interconnected system, Second conference on the development and operation of interconnected power systems, Session 2, Report No.2.07

Appendix

Swing equation $J\frac{d\omega}{dt}=T_m-T_e$ can be written as $T_jP_{ng}\frac{d\omega_u}{dt}=P_m-P_e$ where $T_j=2H$ inertia constant, $\omega_u=f_u$ per unit speed (frequency). Adding swing equations for all the generators in the system:

$$\Sigma T_{j,i}P_{ng,i}\cdot\frac{d\omega_u}{dt}=\Sigma P_{m,i}-\Sigma P_{p,i}=\Sigma P_g-\Sigma P_p \tag{A1}$$

Generation change due to change in frequency for *i*-th unit is:

$$\Delta P_{g,i}=-\frac{k_{g,i}P_{ng,i}}{1+T_s\cdot s}\Delta f_u\Rightarrow\text{adding}\Rightarrow\Sigma\Delta P_g=-\frac{k_{g\Sigma}\Sigma P_{ng}}{1+T_s\cdot s}\Delta f_u \tag{A2}$$

where $k_{g\Sigma}$ is defined in (2).

Total generation and load can be written as

$$\Sigma P_g=\Sigma P_{g0}+\Sigma\Delta P_g,\ P_p=\Sigma P_p(1+k_{p\Sigma}\Delta f_u) \tag{A3}$$

In (A3) a linear relationship between load and frequency is assumed. Substituting (A3) in (A1), we have in Laplace domain:

$$\Sigma T_jP_{ng}\cdot s\Delta f_u+\Sigma P_p(1+k_{p\Sigma}\Delta f_u)-\Sigma P_{g0}-\Sigma\Delta P_g=0 \tag{A4}$$

If we assume that a change in load power occurs at the moment t=0, then $\Delta P=\Sigma P_p-\Sigma P_{g0}$. Combining (A2) and (A4) one can find $\Delta f_u(s)$:

$$\Delta f_u(s)=-\frac{\Delta P\frac{1+T_ss}{T_s}}{\Sigma T_jP_{ng}\cdot F(s)} \tag{A5}$$

where F(s) is:

$$F(s)=s^2+s\left(\frac{1}{T_s}+\frac{k_{p\Sigma}\Sigma P_p}{\Sigma T_jP_{ng}}\right)+\frac{k_{g\Sigma}\Sigma P_{ng}+k_{p\Sigma}\Sigma P_p}{T_s\cdot\Sigma T_jP_{ng}}$$

or

$$F(s)=s^2+s\left(\frac{1}{T_s}+\frac{1}{T_{Je}}\right)+\frac{k_{g\Sigma}}{T_s\cdot T_{j\Sigma}}+\frac{1}{T_s\cdot T_{Je}} \tag{A6}$$

where $T_{j\Sigma}$ and T_{Je} have been defined in (5) and (6) respectively. Roots of (A6) are:

$$x_{1,2}=-\frac{1}{2}\left(\frac{1}{T_s}+\frac{1}{T_{Je}}\right)\pm\sqrt{\frac{1}{4}\left(\frac{1}{T_s}+\frac{1}{T_{Je}}\right)^2-\left(\frac{k_{g\Sigma}}{T_s\cdot T_{j\Sigma}}+\frac{1}{T_s\cdot T_{Je}}\right)}=-\alpha\pm j\Omega$$

with α and Ω defined in (7) and (9), respectively.

Having the roots of (A6), we can find the inverse Laplace transformation of (A5), obtaining the frequency in time domain:

$$\Delta f_u(t)=-\frac{\Delta P\frac{1}{k_{g\Sigma}}}{\Sigma P_{ng}+k_{p\Sigma}\Sigma P_p\frac{1}{k_{g\Sigma}}}+\left[(X+jY)e^{(-\alpha+j\Omega)t}+(X-jY)e^{(-\alpha-j\Omega)t}\right]\frac{\Delta P}{\Sigma T_jP_{ng}} \tag{A7}$$

where X and Y have been defined earlier, in (10) and (11).

If we write

$X+jY=\sqrt{X^2+Y^2}e^{j\theta}$ and $X-jY=\sqrt{X^2+Y^2}e^{-j\theta}$.

(A7) becomes:

$$\Delta f_u(t)=-\frac{\Delta P\frac{1}{k_{g\Sigma}}}{\Sigma P_{ng}+k_{p\Sigma}\Sigma P_p\frac{1}{k_{g\Sigma}}}+e^{-\alpha t}\cdot\sqrt{X^2+Y^2}\frac{\Delta P}{\Sigma T_jP_{ng}}\left(e^{j(\Omega t+\theta)}+e^{-j(\Omega t+\theta)}\right)$$

or, using power reserve coefficient ρ previously defined and Euler's representation of trigonometric functions, per unit frequency becomes:

$$\Delta f_u(t)=-\frac{\Delta P}{\Sigma P_p(\rho k_{g\Sigma}+k_{p\Sigma})}+2\cdot e^{-\alpha t}\cdot\sqrt{X^2+Y^2}\cdot\cos(\Omega t+\theta)\cdot\frac{\Delta P}{\Sigma T_jP_{ng}}$$

Finally, frequency changes in Hz can be easily found from the last equation:

$$f(t)=f_0\cdot\left(1-\frac{\Delta P}{(\rho k_{g\Sigma}+k_{p\Sigma})\cdot\Sigma P_p}\right)+f_0\left[2e^{-\alpha\cdot t}\cdot\sqrt{X^2+Y^2}\cdot\frac{\Delta P}{T_{J\Sigma}\cdot\Sigma P_{ng}}\cos(\Omega t+\theta)\right]$$