7. Frequency stability with RE

Frequency instability only occurs in hydro dominant islanded power system. Hydro dominant system takes shorter restoration time than thermal dominant system if once goes to blackout. Therefore, frequency stability seems not a serious problem, and the author thought to omit the chapter. However, utility employing the author has four hydro dominant subsystems that may go to frequency instability if islanded, and two among them already experienced real instability. Perhaps the instability is very rare in the other utilities. Therefore, the author rethought that the technique may fade out if the chapter is omitted, and will record the least.

Minimum model for Frequency instability is expressed as Fig. 7.1. It is classical but not familiar to most power system engineers except the author, therefore introduced here.

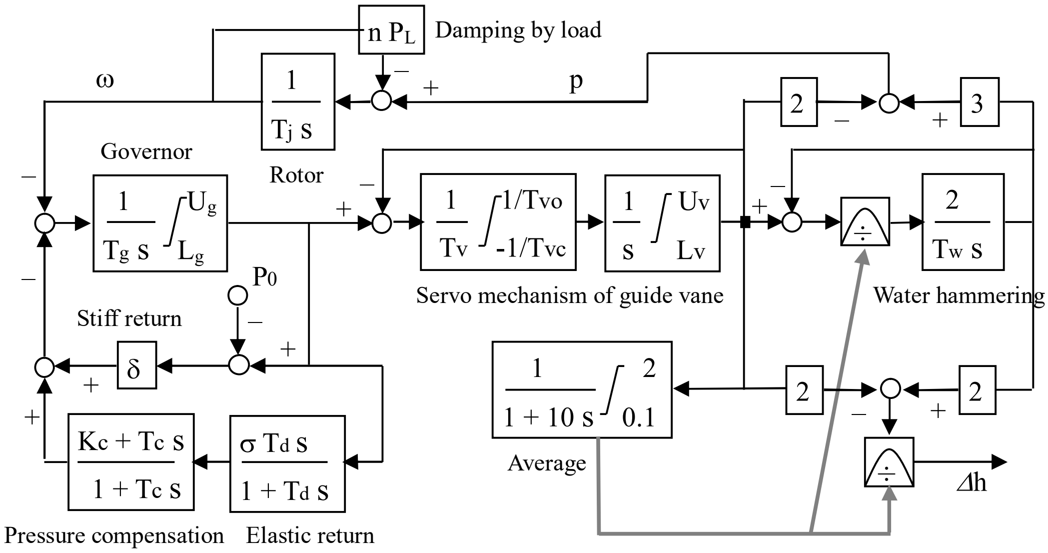

Fig. 7.1 Minimum model for frequency stability analysis in hydro islanded system

Water Hammering

When guide vane of hydro turbine moved, water flow follows at last, but is transiently affected by inertia of water included in water column. The phenomenon is called as water hammering, and may cause frequency instability. Water hammering can be observed as hydro pressure rise in load rejection (damp) test.

Physical variables are defined by symbols as follows. Suffix 0 means rated output operation. Small letters mean values at per unit expression (amount at rated output is normalized as 1). Therefore water flow is expressed $Q = Q_0 q$ as an example.

Guide vane mouth: A (m^2) Water pipe cross section: A_p (m^2) Water flow: Q (m^3/sec.)
Water pipe velocity: V (m/sec.) Head: H (m) Turbine output: P (W)

Water flow in hydro turbine is expressed as follows. "g" means acceleration of gravitation.

$$Q_0\, q = Q = A\,(2\,g\,H\,)^{1/2} = A_0\, a\,(2\,g\,H_0\,h\,)^{1/2}$$
$$Q_0 = A_0\,(2\,g\,H_0\,)^{1/2}$$
$$q = a\,h^{1/2} \qquad (7.1)$$

Water flow in water column is expressed as follows.

$$Q_0\ q = Q = A_p\ V = A_p\ V_0\ p$$
$$Q_0 = A_p\ V_0$$
$$q = v \qquad (7.2)$$

Output of hydro turbine is expressed as follows.

$$P_0\ p = P = Q\ g\ H = Q_0\ q\ g\ H_0\ h$$
$$P_0 = Q_0\ g\ H_0$$
$$p = q\ h \qquad (7.3)$$

Water hammering is expressed as follows. “s” means Laplace transform.

$$H_0\ (h-1) = H - H_0 = H_0 - \frac{L}{g}\ s\ V = -\frac{L}{g}\ s\ (V_0\ v)$$

$$h - 1 = -\frac{L\ V_0}{g\ H_0}\ s\ v$$

Here, L is length of water column (m), and water column time constant: T_w is introduced as follows.

$$T_w = \frac{L\ V_0}{g\ H_0}$$

Then, water hammering is describes as follows.

$$h - 1 = -T_w\ s\ v \qquad (7.4)$$

Every physical variable can be transformed as summation of average value in operation point and small variation (expressed by sign Δ) around the operation point. Those average values have relations as follows.

$$a = q = v = p \qquad h = 1$$

Relationships between small variations are described as follows.

$$\Delta q = h^{1/2}\ \Delta a + (1/2)\ a\ h^{1/2}\ \Delta h = \Delta a + (1/2)\ a\ \Delta h \qquad (7.1')$$
$$\Delta q = \Delta v \qquad (7.2')$$
$$\Delta p = h\ \Delta q + q\ \Delta h = \Delta q + q\ \Delta h = \Delta q + a\ \Delta h \qquad (7.3')$$
$$\Delta h = -T_w\ s\ \Delta v = -T_w\ s\ \Delta q \qquad (7.4')$$

Substituting (7.4’) to (7.1’), Δh is erased as follows.

$$\Delta q = \Delta a - (1/2)\ a\ T_w\ s\ \Delta q$$

$$\Delta q = \frac{1}{1 + (1/2)\ a\ T_w\ s}\ \Delta a \qquad (7.5)$$

Substituting (7.4’) to (7.3’), Δh is erased as follows.

$$\Delta p = \Delta q - a\, T_w\, s\, \Delta q = (1 - a\, T_w\, s)\, \Delta a$$

Using (7.5), the equation above is transformed as follows.

$$\Delta p = \frac{1 - a\, T_w\, s}{1 + (1/2)\, a\, T_w\, s}\, \Delta a \qquad (7.6)$$

Substituting (7.5) to (7.4'), equation as follows is obtained.

$$\Delta h = \frac{-T_w\, s}{1 + (1/2)\, a\, T_w\, s}\, \Delta a \qquad (7.7)$$

Thus, results: Δq, Δp, and Δh caused by Δa can be calculated by equations (7.5), (7.6), and (7.7). Those equations mean that, when guide vane reduces its area, water flow decreases with time delay, output decreases after temporary increase, and pressure increases temporary. This is the water hammering phenomenon. It appears significantly when mouth area of guide vane: a is large, i. e. full load operation. For conservative assessment, "a" that takes value of 0 to 1 is assumed as 1. CRIEPI's CPAT simulation tool takes such representation. It must be noticed that the theory introduced here regards water column as not elastic, but is sufficiently appricable in frequency instability phenomenon. For minute analysis such as determining strength of water pipe, elasticity of water column (water itself and iron pipe) must be considered.

Inconsistency on Speed Governor Setting [1]

Here, standard constants of speed governor system are assumed as follows.

$T_g = 0.1$ sec $U_g = 1.5$ $L_g = -0.5$ $\delta = 0.03$ $\sigma = 0.17$ $T_d = 10$ sec $K_c = 1$ $T_c = 1$ sec
$T_v = 0.1$ sec $T_{vo} = 10$ sec $T_{vc} = 5$ sec $U_v = 1.1$ $L_v = -0.1$
$a = 0.9$ $T_w = 2$ sec $n = 1.5$ $T_j = 7$ sec $P_L = 0.9$

T_w is very large. That means a power station newly constructed with economical design. σ is considerably large. That means dull governor setting. $K_c = 1$ means compensation is not adopted. Frequency response of hydro speed governing system under the standard constants is compared to that of typical thermal speed governing system as shown in Fig. 7.2. At o.o5Hz frequency or more, phase delay in hydro governor is much larger than that of thermal governor. Of course, the difference is derived from water hammering effect, which much spoils feedback system stability, and frequency stability becomes ill.

In hydro power station built in 1960s, T_w is 1 sec or less. In those built in 1970s, T_w is around 2 sec. The contrast is shown in Fig. 7.3. At $T_w = 0.5$ sec, phase delay becomes almost equal to that of thermal governor.

By the way, a few hydro power stations bear the task called as "trial line charging", which is the first charging to power system in blackout situation, and supply household power for thermal power stations for their rapid come back. Most hydro power stations employ "Francis hydro turbine", which is wore down severely at low output such as 30% of rated output, and therefore, needs some load. It is an important know-how that output power of hydro generator doing "trial line charging" must be kept 50% of rated power or so for avoiding frequency instability due to water hammering.

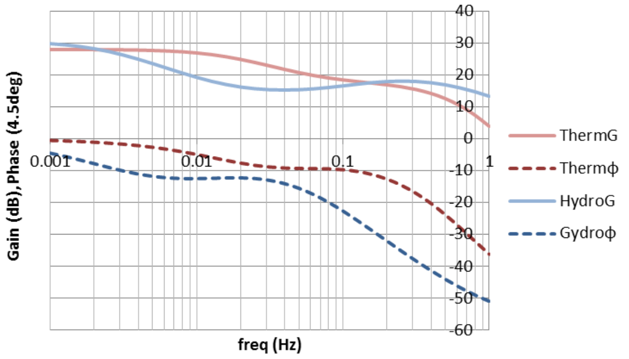

Fig. 7.2 Frequency response of thermal and hydro governors

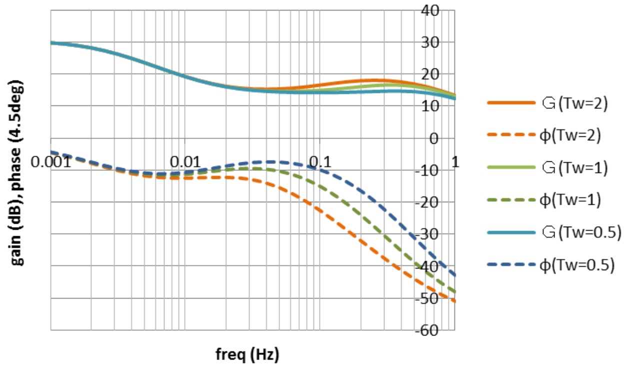

Fig. 7.3 Governor's frequency response by water hammering

Load is assumed to consist of 50% induction motor (IM), whose mechanical output torque is proportional to powered speed, and 50% constant impedance (CZ). Active power's frequency sensitivity of IM is 3, and that of CZ is 0. Therefore, active power's frequency sensitivity of total load: n is 1.5. Nyquist's trajectories with various σ are calculated as Fig. 7.4. Base case (σ = 0.17) is unstable. Only σ = 0.27 case is stable. σ = 0.07 case is quite unstable. Simulation results are shown in Fig. 7.5. In σ = 0.17 case, although swing growth seems to stop, frequency variation exceeds ordinary criterion ±3Hz and perhaps guide vane reaches its ceiling and bottom, so judged as unstable. Also, only σ = 0.27 case is stable.

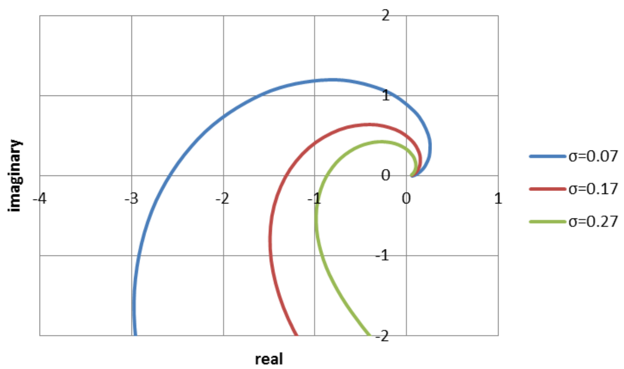

Fig. 7.4 Nyquist trajectories by elastic return σ

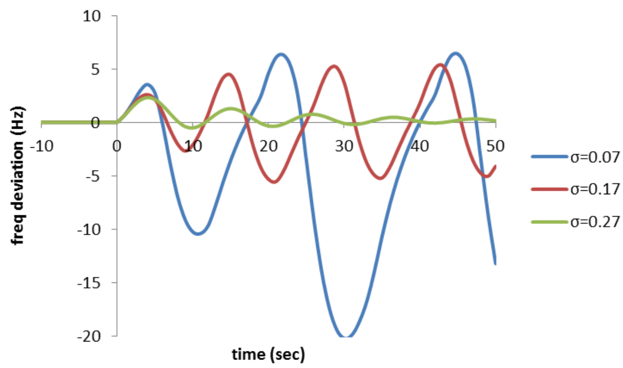

図 7.5 Simulation results by elastic return σ

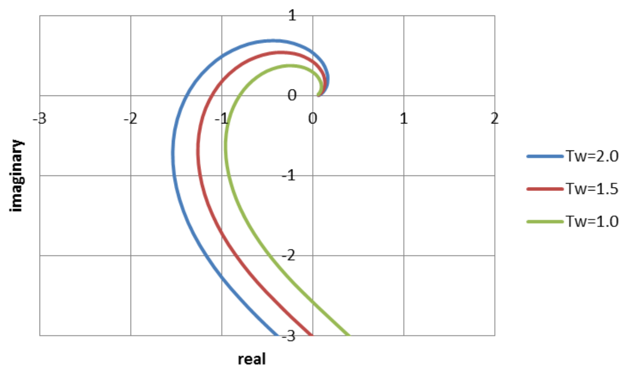

Fig. 7.6 Nyquist trajectories by water hammering Tw

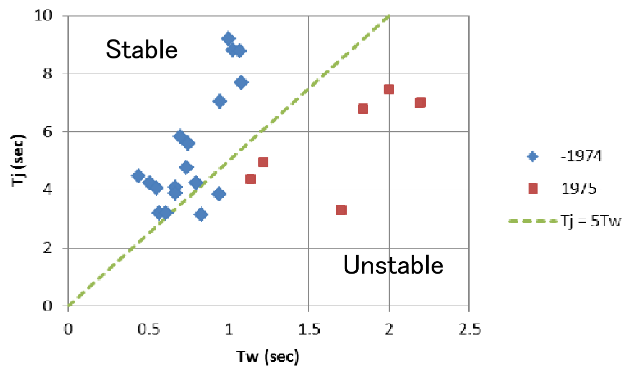

Fig. 7.7 Tj and Tw of existing hydro power stations

Assuming as a=1 (full load), frequency stability affected by T_w are shown in Fig. 7.6. Critical T_w seems to be around 1.3 sec.

T_j and T_w of existing hydro power stations are shown in Fig. 7.7. It is clear that hydro power stations constructed in 1975 or later have quite large T_w. Large T_w originates in thin and long water pipe, which enables to purchase economy. The figure tells that technology for economic design had progressed since 1975 or a little before.

Therefore, speed governors should be set dull (with large σ) if frequency stability of islanded system is regarded to be maintained, especially in modern hydropower stations having large T_w.

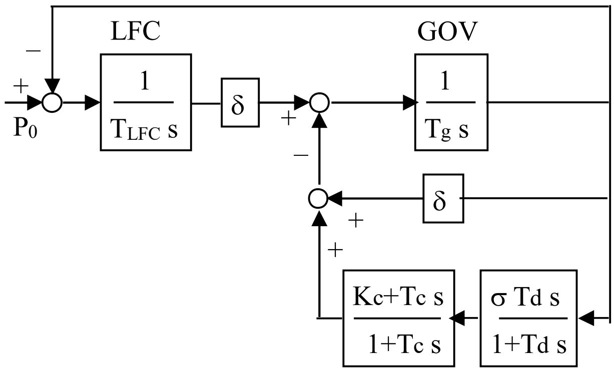

Fig. 7.8 LFC control of hydro power station

LFC (Load Frequency Control) in hydro power station is expressed as a feedback system shown in Fig. 7.8, if only governor that has the largest phase delay element.

Closed loop gain of the system is expressed as follows.

$$G_{closed} \fallingdotseq \frac{1}{1 + (T_d + T_{LFC})\, s + (1 + \sigma / \delta)\, T_d\, T_{LFC}\, s^2} \qquad (7.8)$$

Larger $1+\sigma/\delta$ value, which makes frequency stability in islanded system better, forms a peak in frequency response of the closed loop gain. That means that some overshoot will appear by step response. Closed loop gain curves calculated by assuming T_{LFC} =30 sec are shown in Fig. 7.9. In cases of σ = 0.17 and σ = 0.27, peaks appear. In case of σ = 0.07, peak is very low, and the peak disappears when Td is reduced to 5 sec. Summing up, governor should be set sensitive (small σ), if smooth LFC response is desired.

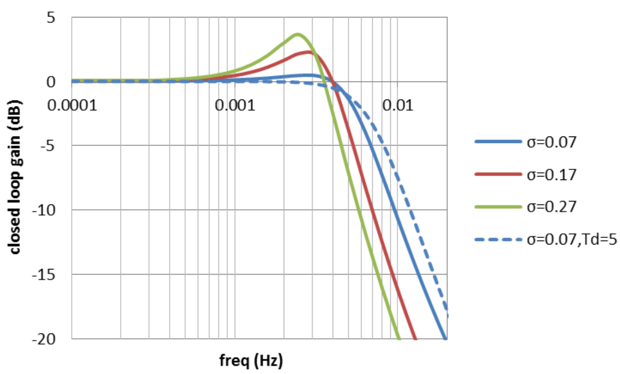

Fig. 7.9 LFC responses by governor setting

These two needs, frequency stability of islanded system and smooth LFC response are inconsistent each other, especially in modern hydropower stations having large T_w. In old days, since T_w was not so large, frequency instability hardly occurred. Nowadays, usually LFC response is tested and optimized, therefore frequency stability is very often overlooked, and the inconsistency appears as occasional frequency instability of islanded system.

Supplementary Improving Measures

As stated above it is quite difficult to solve the inconsistency by only governor setting. At first, a traditional method, "hydro pressure compensation" is introduced. It adds a gain-phase element into elastic return of speed governor as shown in Fig. 7.1, in which Kc = 1 means no compensation and larger Kc means

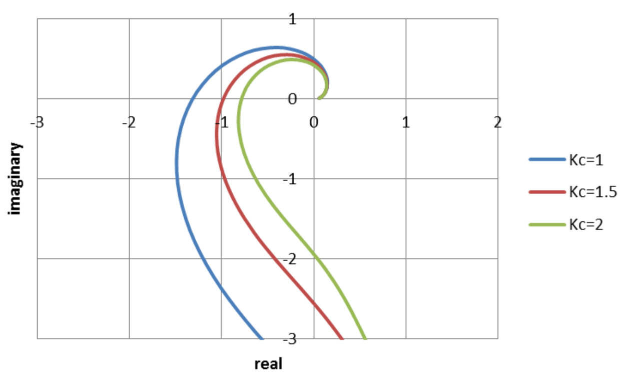

Fig. 7.10 Nyquist's trajectories by pressure compensation

stronger compensation. Analysis and simulation results on the effect of compensation are shown in Fig. 7.10 and 7.11 respectively. The compensation seems quite effective.

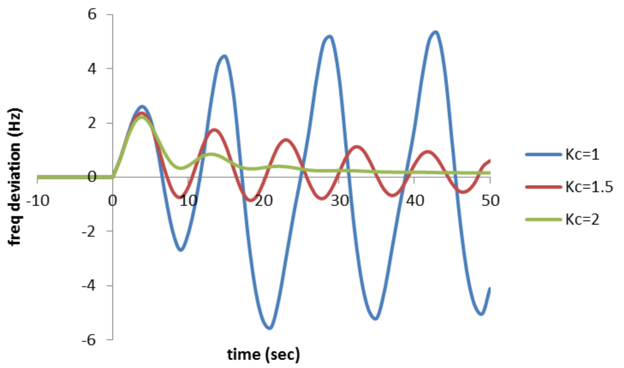

Fig. 7.11 Simulation results by pressure compensation

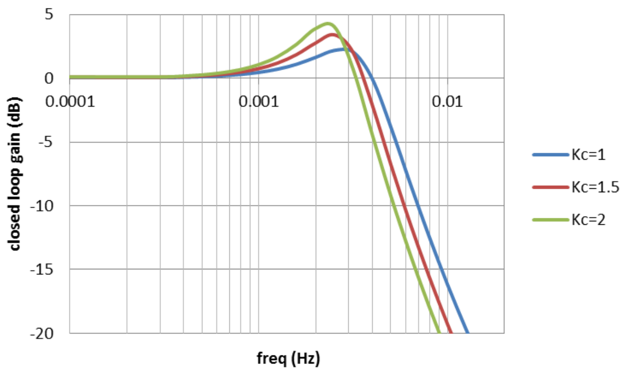

Fig. 7.12 LFC responses by pressure compensation

However, stronger hydro pressure compensation results higher peak in frequency response of LFC as shown in Fig. 7.12. It is unavoidable by reasons as follows. Pressure compensation means addition of amplifier having some phase characteristics in series to elastic return. As the result, governor becomes dull. Therefore, LFC response becomes ill.

Excitation system as shown in Fig. 7.13 is assumed. The system adopts thyristor type exciter that is very common for modern hydro generator, but uniquely wears Δf type PSS.

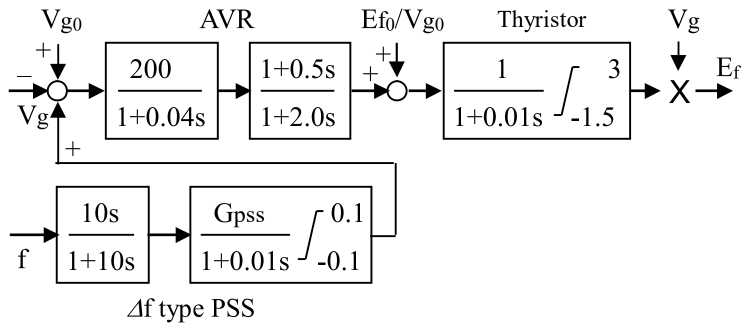

Fig. 7.13 Excitation system with Δf type PSS

Δf type PSS converts load's voltage sensitivity to frequency sensitivity. Therefore, it never spoils LFC response but improves frequency stability. Gain of thyristor type excitation is so large that generator voltage is almost equal to $1+\Delta f$. Therefore, additional load's frequency sensitivity by Δf type PSS: n^+ can be calculated approximately as follows.

$$n+ = \alpha z \; Kz \; Gpss$$

Here, αz is voltage sensitivity of CZ load (that is, αz = 2), Kz is ratio of CZ load, and Gpss is gain of Δf type PSS. For example when αz =2 and Kz = 0.5, additional load's frequency sensitivity is calculated as n^+ = 1.0 Gpss

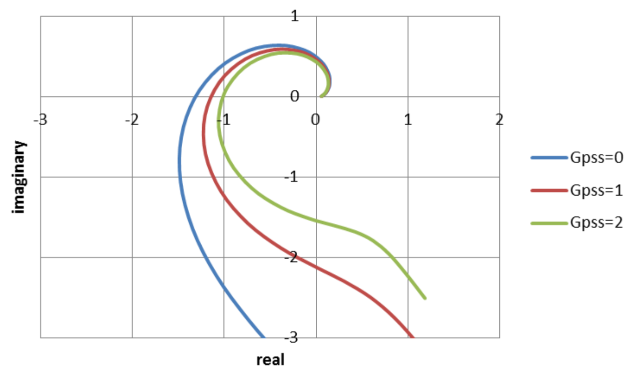

Fig. 7.14 Nyquist's trajectories by Δf type PSS gain

Analysis results assuming governor setting of base case are shown in Fig. 7.14. Gpss=1 is not sufficient but Gpss=2 is critical. Simulation results are shown in Fig. 7.15, which seems a little optimistic than analysis because of IM active power's voltage sensitivity (though small) derived from mechanical torque-speed character.

As states above, governor setting of σ = 0.07 and Td=5 sec was ideal for LFC response. The setting spoils frequency stability very much. However, if Δf type PSS can keep frequency stability, it and good LFC response are both fulfilled. Analysis results are shown in Fig. 7.16. Gpss must be 7 or more. Simulation results are shown in Fig. 7.17, which is a little optimistic because of slight voltage sensitivity of IM active load as stated above.

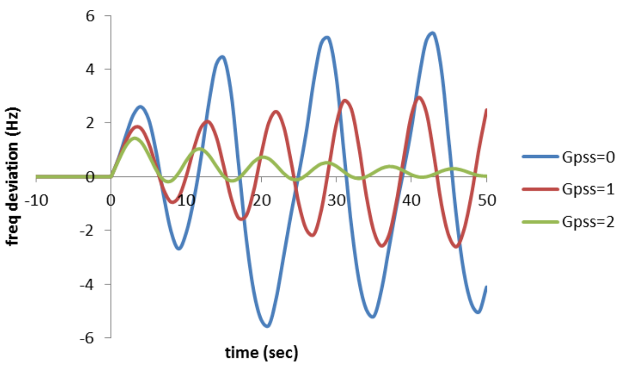

Fig. 7.15 simulation results by Δf type PSS gain

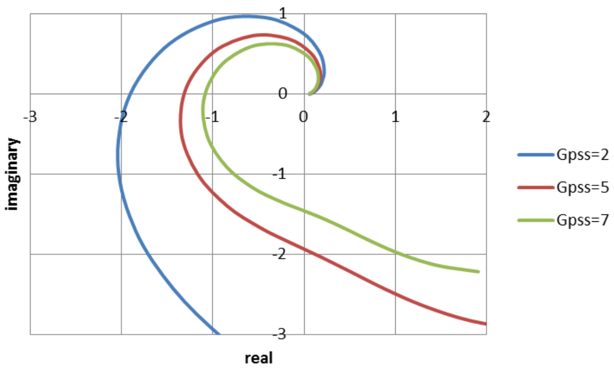

Fig. 7.16 Nyquist's trajectories employing Δf typePSS

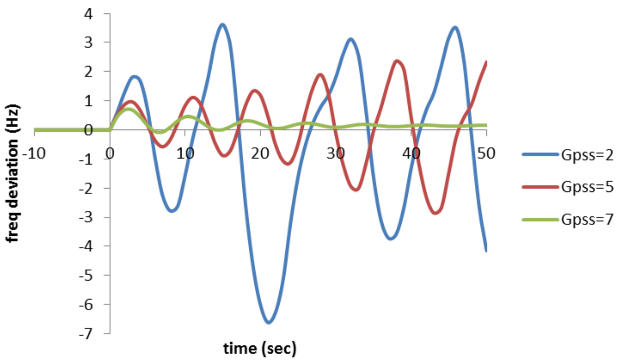

Fig. 7.17 Simulation results employing Δf typePSS

Gain of Δf type PSS and $\Delta\omega$ type PSS is usually set as 10 or less. Therefore, using Δf type PSS or $\Delta\omega$ type PSS, governor setting ideal for LFC is possible. It must be noticed that high gain of Δf type PSS causes large voltage deviation temporary. However, some voltage deviation is not considered as problem when frequency stability is threatened. $\Delta\omega$ type PSS can be easily equipped in thermal generator but cannot in hydro generator. Usually Δf type PSS is more economical but has inferior effect than $\Delta\omega$ type PSS, but has same effect in only frequency stability. It seems a very attractive supplementary measure.

Load's Frequency Sensitivity

When mixture ratio of IM and CZ varies, load's frequency sensitivity also varies, and as the result, frequency stability varies. Stability at IM0%, IM50%, and IM100% are examined. Stability is evaluated in two cases. One is $\sigma = 0.27$ (dull governor), and the results are shown in Fig. 7.18. Of course, the other constants are the same of the base case. As imagined, higher IM ratio gives better stability.

Another is Gpss = 1.5 case. The results are shown in Fig. 7.19. Although IM0% shows slight poor stability, IM ratio does not affect stability much. The reason is thought as follows. When Δf type PSS is employed, load's equivalent damping, neq is calculated as follows.

IM0%: neq = 0.0 * 3 + (1 – 0.0) * 2 * (Gpss=1.5) = 3.0

IM50%: neq = 0.5 * 3 + (1 – 0.5) * 2 * (Gpss=1.5) = 3.0

IM100%: neq = 1.0 * 3 + (1 – 1.0) * 2 * (Gpss=1.5) = 3.0

That is, load's equivalent damping does not vary by IM ratio. Δf type PSS can be recognized as a favorable supplementary measure because it gives a certain stabilizing effect without affected by load characteristics.

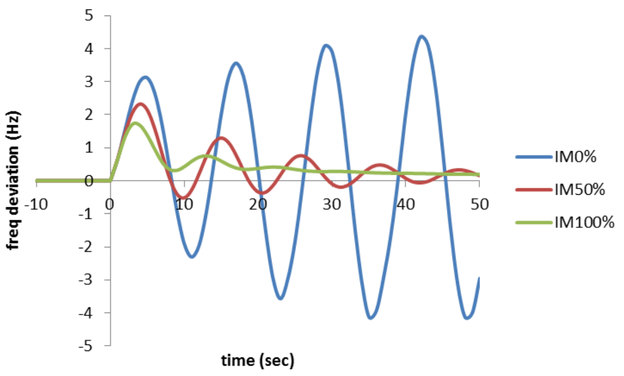

Fig. 7.18 Stability by IM ratio (σ =0.27)

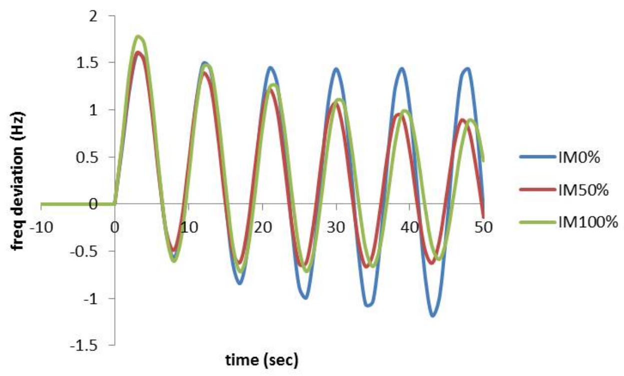

Fig. 7.19 Stability by IM ratio (Gpss =1.5)

Impact of RE Design

It is assumed that load is enlarged to 125% and renewable energy (RE) penetrates 20% of load (25% of initial load). Therefore total load seen from generator (load – RE) is not changed. If RE has voltage or frequency sensitivity on active or reactive power, frequency stability of islanded system must be affected. Here, two possibilities are considered.

At first, voltage sensitivity of RE's active power is assumed as follows.

$$P_{RE} = P_{RE0}\ (f / f_0)^{Kp}$$

The assumption indicates a kind of active anti islanding function on RE. If Kp is positive, frequency rise results RE output increases, which results further frequency rise. Thus, islanding is detected. On the contrary if Kp is negative, the character behaves like governor.

Simulation results in case of dull governor (σ = 0.27) for keeping frequency stability are shown in Fig. 7.20. Positive Kp =5 shows poorer stability than Kp =0, but still stays stable. Simulation results in case of Δf type PSS (Gpss = 1.5) for keeping frequency stability are shown in Fig. 7.21. Positive Kp = 5 shows instability. This is troublesome. Because, it was found that Δf type PSS also has some limitation due to a kind of anti-islanding on RE, although the PSS was regarded as most favorable measure that can improve frequency stability without sacrificing good LFC response.

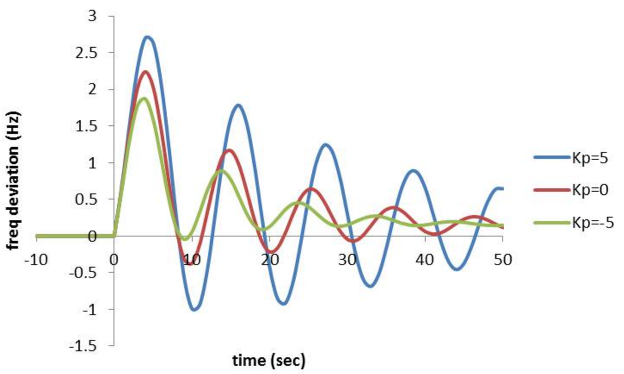

Fig. 7.20 Influence by RE's Kp (σ= 0.27)

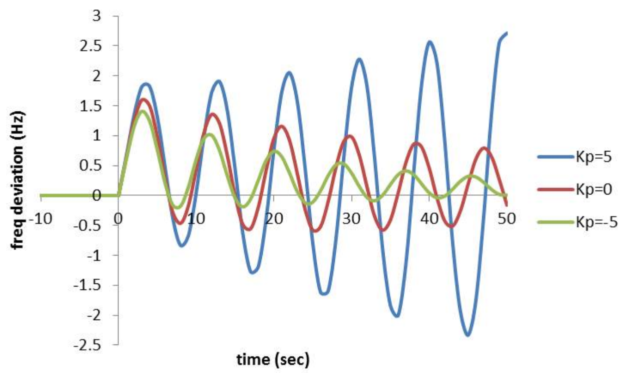

Fig. 7.21 Influence by RE's Kp (Gpss = 1.5)

Next, voltage sensitivity of RE's reactive power is assumed as follows.

$$Q_{RE} = P_{RE0}\ \{\ (V / V_0)^2 - (V / V_0)^{Kq}\ \}$$

When RE equips DVS (Dynamic Voltage Support) function, Kq becomes larger than 2, and the assumption becomes reality. Simulation results in case of dull governor (σ = 0.27) for keeping frequency stability are shown in Fig. 7.22. Even high Kq = 12 value does not affect stability much. Simulation results in case of Δf type PSS (Gpss = 1.5) for keeping frequency stability are shown in Fig. 7.23. Kq = 12 makes instability. Because, voltage is kept nearly constant by DVS, even if Δf type PSS tries to vary voltage. It is also troublesome, because it has found that DVS function on RE also has some limitation even though DVS was regarded as most favorable measure to improve voltage stability, transient synchronous stability, and oscillatory stability.

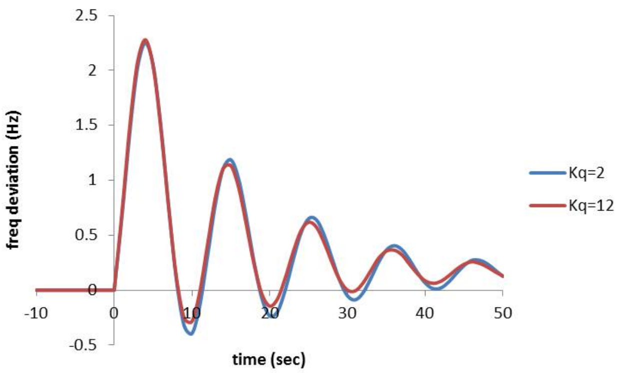

Fig. 7.22 Influence of RE's Kq (σ= 0.27)

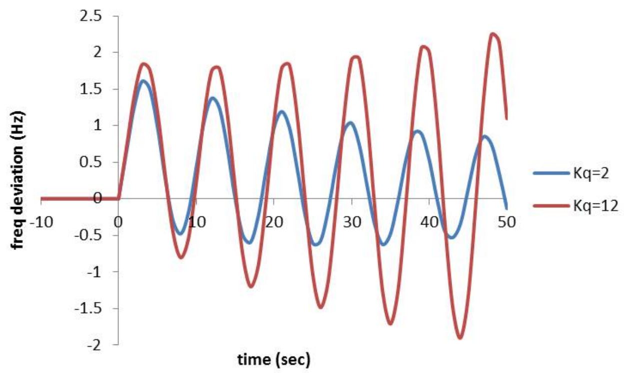

Fig. 7.23 Influence of RE's Kq (Gpss = 1.5)

However, there are many points of view. If network has sufficient capacity and restore all local loads without local generators, it is possible that islanded system is once shut down and restore load quickly. This seems as the second best way. It must be rethought that hydro islanded system necessarily keeps operation and re-interconnects to trunk system.

The chapter is not omitted to rethink old doctrine that hydro islanded system must keep operation if RE high penetration come true.

Increase of frequency varying speed by RE(3)

Such a criticism that "RE is not a respectable power source, because it has not inertia." Is very often heard but not seen such paper or article that quantitatively analyze harms due to lack of inertia are seldom seen. In chapter 5, decreasing inertia of power system due to RE integration from viewpoint of transient stability. It was shown that transient stability is not broken by fast control of turbine even if inertia is extremely small.

The author tried to verify the criticism in various ways. Nothing but only one were found. The one is increase of frequency speed when islanded system appear by network fault. For example, power receiving Hokuriku system goes to islanded by 6LO of tie line. Frequency reduces. In case of no RE frequency drops to 59.07 Hz at 6 sec, then recovers to 59.20 Hz. In case of high PV integration, inertia reduced to 66.5%, and frequency drops to 58.68 Hz at 6.5 sec, then recovers to 58.81 Hz.

In some cases, according to increase of frequency varying speed, resetting of various "power system stabilizing control" becomes necessary. Through minute study, it was found in the Hokuriku case that resetting was not necessary. Harm by reduced system inertia due to RE integration is these level at most, and is not serious issue as criticized in street.

Level governor operation

Natural inflow hydro power station has so small head tank that governor free operation brings severe water level deviation in head tank. Higher water level causes overflow (via side flow path) and lower water level causes air drawing to penstock. Therefore in most cases, level governor control is adopted to keep water level within favorable band.

However, it is not true that speed governing function is utterly locked, but governor setting such as Fig. 7.24 as example is employed. At 60Hz guide vane is full open and 110% output. As frequency rises guide vane is closed. At 63.3Hz guide vane is shut. In the example frequency regulation band is 5%, which is rather dull in hydro power station. In most hydro power station smaller band is adopted (3 to 4%). For example, 4% band results guide vane shut at 62.7Hz.

On the condition load limiter is adopted to maintain output is kept favorable to water level. For example, if output is 70% at 60Hz, operation point is A in the figure. If frequency rises, output is decreased along gray dotted arrow. This is level governor operation.

The reason why level governor operation is adopted in most natural inflow hydro power station is that frequency deviation must be kept 5% or smaller even if the power system is gone to islanded. Even natural inflow type contributes in frequency rise case. Thus usual power system frequency never exceed 105% (63Hz).

When RE highly integrated, and when excessive power cannot be absorbed, frequency rises. If RE has the same function of level governor operation of natural inflow power station, frequency rise is mitigated. If today's excessive quality: 60Hz±0.2Hz standard is abandoned, RE's preventive curtailment will be much lessened by the level governor operation.

In fact, most countries except Japan make duty for RE to equip level governor operation. Again in fact, most wind turbines have the function, but is not used because it is not written Japan grid code. Mottainai!

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