5. Transient stability and RE

Transient stability deals with synchronous generator's asynchronism caused by shock of network failure. One machine infinite bus model is used in classical analysis seen in texts. Loads nearby generator are not considered. The model is quite realistic in such a case that large and far power stations send power via long transmission line to loads in power pool. However, considering the neighboring loads(1) is indispensable in case of handling a partial system included in a large interconnection. Such a simple model as one machine infinite bus is not adequate for the use, and some extension is needed.

Mechanism destroying transient stability

Most dynamic character of load is brought by induction motor (IM) included in load. Considerable amount of induction motor is included in power system load, synchronous generator and induction motor, which are the typical rotating machines by considerable amount, make unstable each other by mechanism shown in Fig. 5.1 making system voltage decrease as common factor(2).

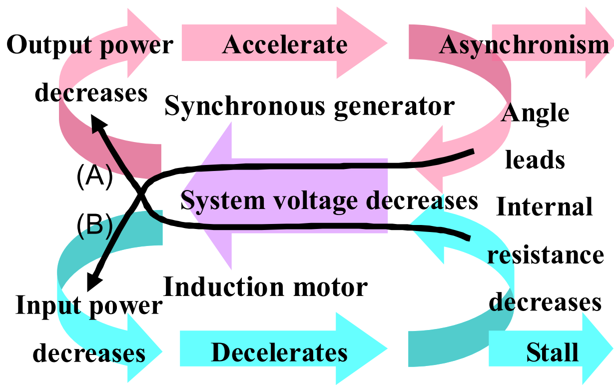

Fig 5.1 Mechanism destroying transient stability

Instability of synchronous generator is asynchronism, which is dealt by synchronous stability analysis. Instability of induction motor is stall, which is dealt by (fast) voltage stability analysis. However according to mechanism shown in Fig. 5.1, the two stabilities cannot be dealt independently, but must be dealt as unified "fast (transient) instability" or "transient voltage/synchronous stability". This is the major hypothesis in the chapter. For verifying it, existence of path (A) and (B) in the figure is shown.

Model for analysis is shown in Fig. 5.2. This is a one machine one load infinite bus system. At trunk bus sum of capacitance of trunk line and capacitor/reactor in trunk substation Bb is modeled. At 66kV class medium bus considerable amount of really installed capacitor Bm is modeled. Load branch impedance Zt that is considered in Y-connection aggregation(3) is modeled. At load bus locate constant impedance load Zcz and induction motor load whose initial impedance is Zim by 50% and 50%. Power factor is Q/P = 0.1, which reflects the fact that motor's no-load reactive power is just compensated by capacitor. Renewable energy (RE) is modeled as admittance Yre, its output is set as 30% of load power, and its power factor is set as Q/P = -0.2, which reflects constant leading power factor operation mainly adopted in PV mitigating voltage rise. Generator is modeled as voltage source behind Xd'. Generator branch impedance Zg includes reactance of main transformer (15% at generator capacity base) and Xd' (30% at same).

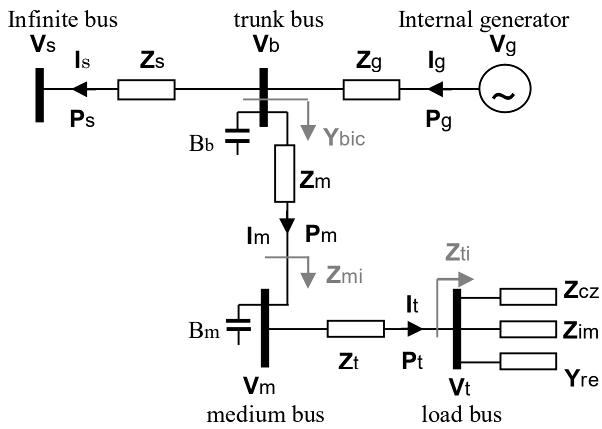

Fig. 5.2 Model for transient stability analysis

Initial flow condition of example power sending system (Sen.) and power receiving system (Rec.) is shown in Table 5.1, in case of no RE, at generator capacity base. Angle is radian value. Sending system shows large Xs, which means loose interconnection. Reactive power is excessive, so absorbed at trunk bus. Receiving system shows negative angle at internal generator. Reactive power is in short and large amount of capacitor is equiped at trunk bus and medium bus. Load angle takes a large negative value.

Network impedance is modeled not only by reactance but includes resistance . The reason is that power consumed in the resistance when large current due to fault and motor stall appeared can mitigate generator ' s acceleration. If ignored, synchronous stability is optimistically assessed.

However modeling resistance, initial condition cannot be analytically solved. Therefore by Excel repeated calculation is used as follows. Variables for conversion are **Vb**'s angle Ab , **Vg**'s angle Ag, capacitor at trunk bus B_b , capacitor at medium bus B_m. Giving tie line power Ps, generator output P_g, and load' Q/P ratio, load's active and reactive power absorb error. Equations for conversion are adopted as follows. Suffix "ref" means reference value. Definite values as 0.3 are acceleration/deceleration coefficients. Of course, Ps and P_g are real part of **Ps** and **Pg**.

Table 5.1 Initial flow condition of example trunk system

	Zs	**Z**g	**Z**m	**Z**t
Sen.	0.0896+j3.2302	0.0063+j0.2058	0.0040+j0.3591	0.0099+j0.2701
Rec.	0.0283+j1.3167	0.0153+j0.5812	0.0015+j0.1125	0.0018+j0.1204

	Vs	**V**b	**V**g	**V**m	**V**t
Sen.	1.∠0	1∠0.2054	1.1∠0.3448	1∠-0.0454	0.9547∠-0.2398
Rec.	1∠0	1∠-0.6529	1.1∠-0.2058	1∠-0.7151	0.9694∠-0.9548

	Ps	Pg	Pm	Pt	Bb	Bm
Sen.	0.0629	0.7601	0.6902	0.6851	-0.3271	0.3039
Rec.	-0.4645	0.8274	1.2726	1.2695	0.2769	0.4435

$$\left.\begin{aligned}
&\text{next } A_b = A_b + 0.3\ X_s\ (P_{sref} - P_s)\\
&\text{next } A_g = A_g + 0.7\ X_g\ (P_{gref} - P_g)\\
&\text{next } B_b = B_b - 0.1\ (V_{mref} - V_m)\ /X_m\\
&\text{next } B_m = B_m + 0.5\ (Q_{tref} - Q_t)
\end{aligned}\right\} \quad (5.1)$$

In calculation of P-δ curve and T-ω curve, from motor speed ω internal resistance R_{im} = real(**Zim**) is calculated by equation as follows. Here, ω_0 and Rim0 are initial speed and internal resistance.

$$R_{im} = R_{im0} \frac{\omega_0}{\omega} \quad (5.2)$$

Then, load side admittance seen from trunk bus **Ybic** is calculated.

Generator internal voltage **Vg** is expressed as follows. V_g is its magnitude, and δ_g is its angle.

$$\mathbf{V}_g = \text{complex}\ (V_g \cos \delta_g + V_g \sin \delta_g) \quad (5.3)$$

Using factors above **Vb** is calculated as follows.

$$\mathbf{V}_b = \frac{\dfrac{\mathbf{V}_s}{\mathbf{Z}_s} + \dfrac{\mathbf{V}_g}{\mathbf{Z}_g}}{\dfrac{1}{\mathbf{Z}_s} + \mathbf{Y}_{bic} + \dfrac{1}{\mathbf{Z}_g}} \quad (5.4)$$

Thus, the other variables are calculated one by one.

P-δ curve Power-angle curve (P-δ curve) is drawn on one machine infinite bus model as texts, but can be drawn in cases having load at midway. The analysis method was already introduced in Ref. (2). Then load was assumed as variable resistance behind fixed reactance, and some P-δ curves was drawn by varying internal resistance 100% to 40%. Here different from Ref. (2), not internal resistance but motor speed ω is taken as parameter, and impact of motor deceleration is directly expressed.

First, initial motor speed ω is assumed as 0.977 (that is, slip is 0.023) P-δ curve is drawn. Next, setting motor speed lower value, some P-δ are drawn. Thus several P-δ curves are drawn on the same plane. Those of sending system are shown in Fig. 5.3, and those of receiving system are shown in Fig. 5.4.

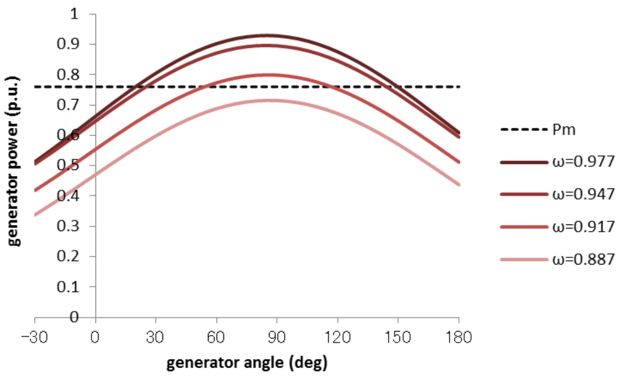

Fig. 5.3 P-δ curves by motor speed (Sen.)

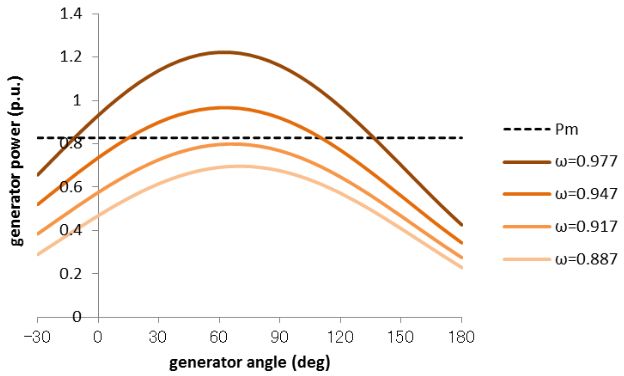

Fig. 5.4 P-δ curves by motor speed (Rec.)

In both, when motor decelerates, its internal resistance in reduced, and P-δ curve becomes lower. The tendency is more significant in receiving system. Then, synchronous generator's decelerating power $P_d = P_e - P_m$ becomes important. Here, Pe is electric output power varies by δ and ω, and P_m is mechanical input power kept constant.

By interpolation on parabolic curve approximation, speed ω_c that makes peak of P-δ curve is equal (P-δ curve touches P_m line) is identified as 0.898 in sending system and as 0.917 in receiving system. Endurance of motor deceleration is weaker in receiving system. If motor speed is reduced to ω_c or less during 1 sec or so, synchronous generator cannot keep stability. Thus, deceleration of motor promotes generator's asynchronism, that is, path (A) is verified.

T-ω curve Analysis method of induction motor's stall phenomenon was already introduced in Ref. (4), but was one load infinite bus (that is, for pure load system), therefore, cannot assess impact of generator angle δ. Here, the method is extended to one machine one load infinite bus system, and assessment how generator angle δ affects on motor's T-δ curve is enabled.

First, supposing initial generator angle is equal to value in Table 5.1, T-ω curve is drawn. Next, setting angle δ as larger value, some T-ω curves are drawn. Thus, several T-ω curves are drawn on a same plane. Those in sending system are shown in Fig. 5.5, and those of receiving system are shown in Fig. 5.6. In both, T-ω curve becomes lower when angle δ leads. Thus, acceleration of generator promotes motor's stall, and path (B) in Fig. 5.1 is verified.

Motor's acceleration torque $T_a = T_e - T_m$ becomes important. Here, Te is electrical input torque varies by δ and ω, T_m is mechanical torque varies by ω. Peak accelerating torque in high speed range: Ta-max and bottom of that in middle speed range: Ta-min can be identified. By interpolation on parabolic curve approximation, δ at which

Ta-max becomes zero and δ at which Ta-min becomes zero are obtained.

In sending system Ta-max is always positive, and Ta-min is positive at δ is 78.6 deg. or less. Also in case of fault in trunk system cleared by main protection, motor's deceleration is at most 5% (speed is 0.927), at the speed Ta is positive even if δ goes to 180 deg. That is, in the sending system, motor never goes to stall in trunk system failure cleared by main protection, and transient stability is never lost triggered by motor's stall. However impact by larger disturbance, generator accelerates much, slightly promoted by motor's deceleration, may go to asynchronism. In such a situation, motor may drop into condition like stall.

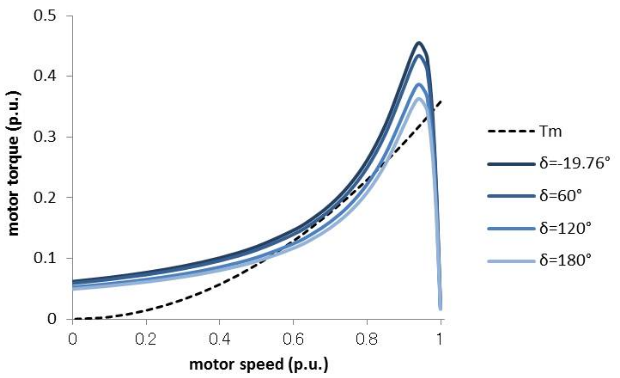

図 5.5 T-ω curve by generator angle (Sen.)

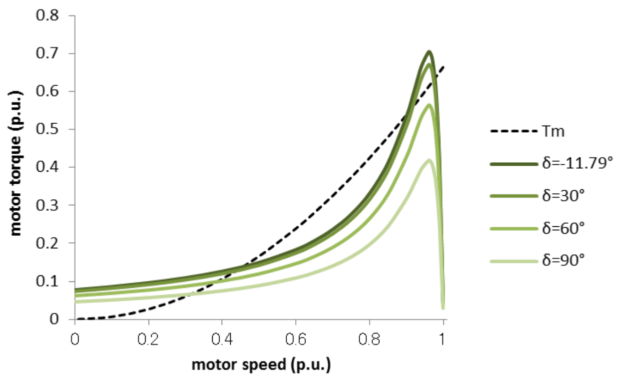

Fig. 5.6 T-ω curve by generator angle (Rec.)

In receiving system, Ta-min is always negative. If impact of fault is sufficiently large, motor decelerates beyond unstable equilibrium and go to stall. Ta-max becomes smaller when generator's angle δ leads. If δ exceeds 51.1 deg. Ta-max turns to negative. Initial value of δ is -22.8 deg. Angle increase from initial condition to 51.1 deg. Is 73.9 deg. This is possible in transient stability. In the receiving system, decrease of P-δ curve's height due to motor deceleration and decrease of T-ω curve due to generator's angle leading are simultaneously proceed, and generator's transient instability is caused by motor's transient instability as trigger.

Simulation in sending system Simulation is performed in original system before aggregation. Because fault to be modeled locates inside of the aggregation object. In such a case, no fault in Fig. 5.2 can be the fault to be modeled. Structure of the original system before aggregation is shown in Fig. 5.7, which has 7 generators and 5 loads.

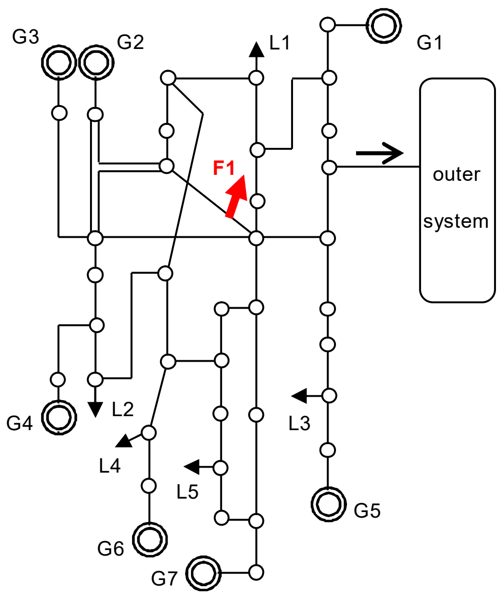

Fig 5.7 Structure of sending system before aggregation

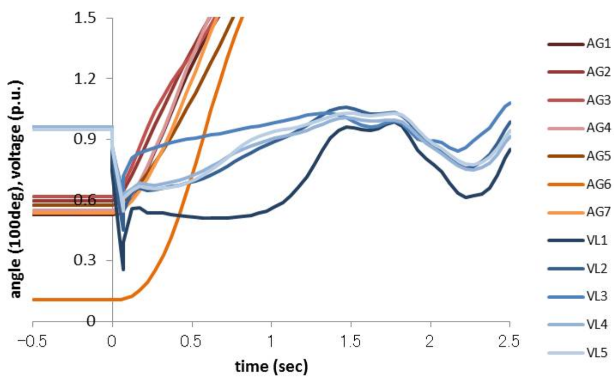

Fig. 5.8 Simulation of sending system before aggregation

One circuit 3LG-O on double circuit transmission line is modeled at F1, Fault clear time is 0.07 sec. Time variation of generators' angle and loads' voltage are shown in Fig. 5.8. All generators go to asynchronism in 1 sec., but all loads once recover by 1.5 sec. Transient instability of the sending system is caused mainly by generators' asyncuronism, motors only promote generators' asynchronism but never go to stall by themselves.

In existing system 40% of impedance load (20% of total load) stops due to voltage sag. Therefore, load's voltage instability is mitigated, and never goes to transient voltage/synchronous instability. But here, partial load drop is not modeled, because observing behavior of motor and generator in process to instability.

Simulation in receiving system Structure before aggregation is shown in Fig. 5.9. Five generators with number go to unstable.

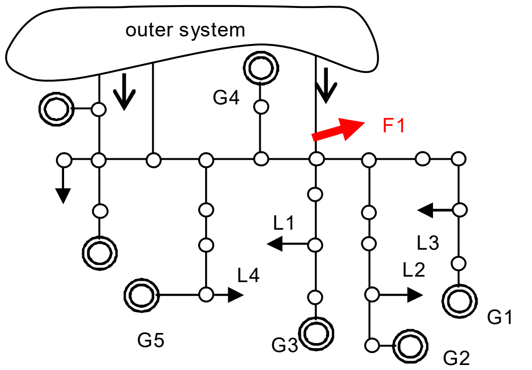

Fig. 5.9 Structure of receiving system before aggregation

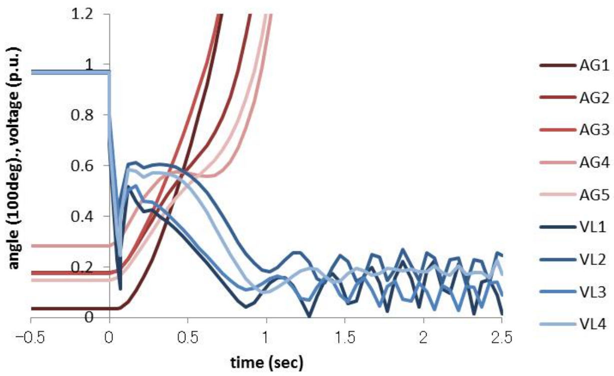

Fig. 5.10 Simulation on receiving system before aggregation

Two circuit 6LG-O fault on double circuit transmission line at F1 is modeled. Fault clear time is 0.07 sec. Time variation of generators' angles and loads' voltages are shown in Fig. 5.10. As the first group, loads L1 and L3 soon go to voltage collapse, and neighboring generators G1 and G3 soon go to asynchronism. As the second group, loads L2 and L4 go to voltage collapse, and neighboring generators G2, G4, and G5 go to asynchronism. The fact that instability is classified to first and second steps means that motor's transient voltage instability and generator's transient synchronous instability are simultaneously proceeding. Considering the truth that transient synchronous instability hardly appears, trigger is motor's voltage instability.

Thus, it is obvious that induction motor's stall and synchronous generator's asynchronism are promote each other, however, it is matter of degree. If strength of unstable tendency is smaller than system's self-stabilizing ability, instability does not appear. To appear instability, some major change must introduced into present power system. As one of the major change, unfavorable design of highly interconnected renewable energy (RE) is thought. In the next section, Highly integrated RE is considered.

Highly integrated RE

RE output is 30% of load power. Load power factor is Q/P = 0.1. RE power factor is Q/P = -0.2. Some thermal generators stop corresponding RE output, and also capacities of generator and main transformer are reduced, therefore proportionally, reactance of generator branch **Zg** increases. As result, initial flow condition becomes as Table 5.2.

Three type design on RE concerning disturbance as follows are assumed.

(1) Drop type (drRE); stops due to voltage sag.

(2) Constant impedance FRT type (czRE): does not stop due to voltage sag, and is constant impedance during low

voltage.

(3) Constant current FRT type (ciRE): does not stop due to voltage sag, and is constant current during low voltage.

As number of cases is large, P-δ curve and T-ω are represented by ciRE with medium ability.

Table 5.2 Initial flow condition of the example trunk systems with RE

	Zs	Zg	Zm	Zt			
Sen.	0.0896+j3.2302	0.0063+j0.3730	0.0040+j0.3591	0.0099+j0.2701			
Rec.	0.0283+j1.3167	0.0153+j0.9656	0.0015+j0.1125	0.0018+j0.1204			
	Vs	Vb	Vg	Vm	Vt		
Sen.	1.∠0	1∠0.2054	1.1∠0.3925	1∠-0.0292	0.9548∠-0.1074		
Rec.	1∠0	1∠-0.6529	1.1∠-0.2089	1∠-0.6848	0.9694∠-0.8661		
	Ps	Pg	Pm	Pt	Bb	Bm	Wg
Sen.	0.0629	0.5541	0.4877	0.4850	-0.1650	0.2329	0.7290
Rec.	-0.4645	0.4463	0.8997	0.8980	0.3076	0.3719	0.5393

P-δ curve P-δ curve of sending system is shown in Fig. 5.11, and that of receiving system is shown in Fig. 5.12.

ωc value at which P-δ curve touches Pm line is 0.877 in sending system and 0.896 in receiving system. Comparing no RE case (0.898 and 0.917), motor deceleration margin increases by 0.021 (sending) and 0.014 (receiving). That is, transient synchronous stability is improved by reduced power flow from trunk bus to load because of RE power.

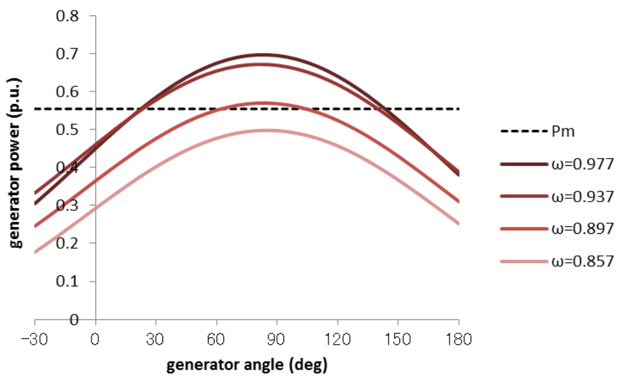

Fig. 5.11 P-δ curve by motor deceleration (Sen.)

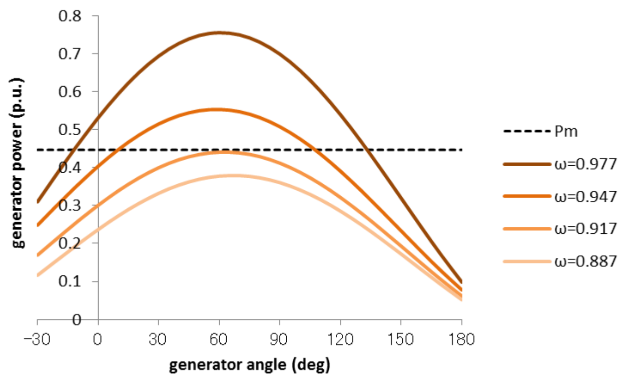

Fig. 5.12 P-δ curve by motor deceleration (Rec.)

T-ω curve T-ω curves in sending and receiving systems are shown in Fig. 5.13 and 5.14 respectively. In sending system, motor's peat accelerating torque $Ta = Te - Tm$ in high speed range was always positive in no RE case, but in czRE case it turns negative at 130.7 deg. δ or more. Bottom accelerating torque in medium speed range was always negative in no RE case, and is still always negative also in czRE case. Thus in highly integrated czRE case, motor stall can occur more easily in sending system.

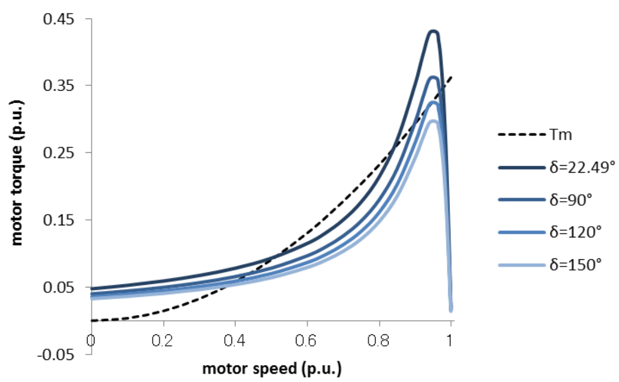

Fig. 5.13 T-ω curve by generator angle (Sen. czRE)

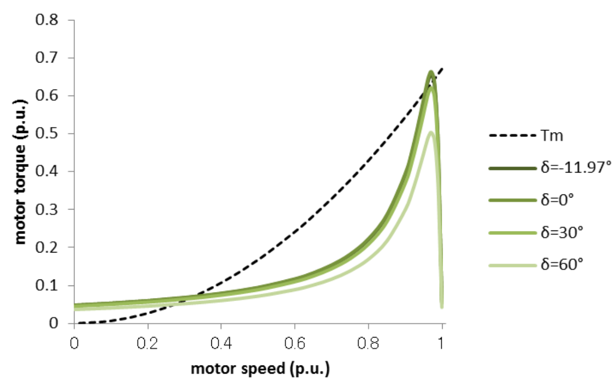

Fig. 5.14 T-ω curve by generator angle (Rec. czRE)

In receiving system, motor's peak acceleration torque Ta = Te – Tm in high speed range was negative at 51.1 deg. δ or more in no RE case , and is negative even at 34.0 deg. δ or more in czRE case. Bottom acceleration torque in medium speed range was always negative in no RE case, and still is negative in czRE case. Thus in highly integrated czRE case, motor stall can occur more easily also in receiving system.

The results are understood as follows. On one hand reduced power flow toward load Pm and Pt lessens stall possibility. On the other hand reduction in generator capacity reduces system's voltage support capability. Since influence of the latter exceeds that of the former, motor becomes stall more easily.

Difference in RE design P-δ curve and T-ω curve with highly integrated RE in the other two design are calculated. In P-δ curve, motor speed ωc at which decelerating power Pd = Pe – Pm turns to negative. Corresponding ωc, slip Sc = 1 – ωc is calculated. Larger Sc means better transient synchronous stability. In T-ω curve generator angle δc at which motor's peak accelerating torque Ta = Te – Tm in high speed range turns negative. Larger δc means better transient voltage stability.

Comparison of no RE and with RE in three design cases in 10Sc and δc/100 (by convenience in graduation) are shown in Fig. 5.15 (sending) and 5.16 (receiving). If Ta never go negative until δ reaches 180 deg., δc is expressed as 180 deg. If Ta never come positive in assumed δ range, δc is expressed as 0 deg.

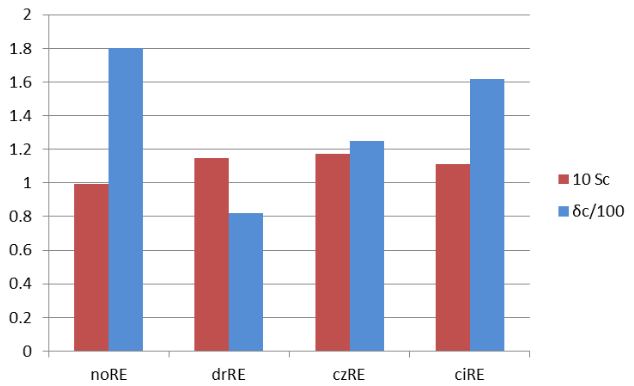

Fig 5.15 Sc and δc by RE design (Sen.)

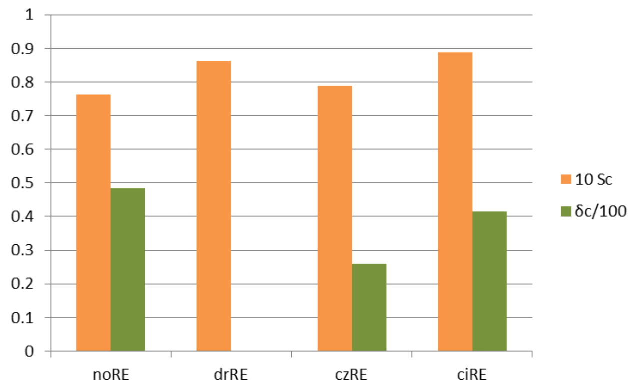

Fig. 5.16 Sc and δc by RE design (Rec.)

Omitting load branch

In models for analysis and simulation now practiced in Japan, loads are directly connected to 66kV secondary bus of primary substation. Of course load cannot be connected such a high voltage as 66kV, but be connected in stepped down voltage such as 6.6kV or 100/200V that fit load equipment via transmission and distribution network, in which considerable impedance exists. It is load branch (LB) that models the impedance. If LB is omitted, considerable difference must appear in analysis and simulation results.

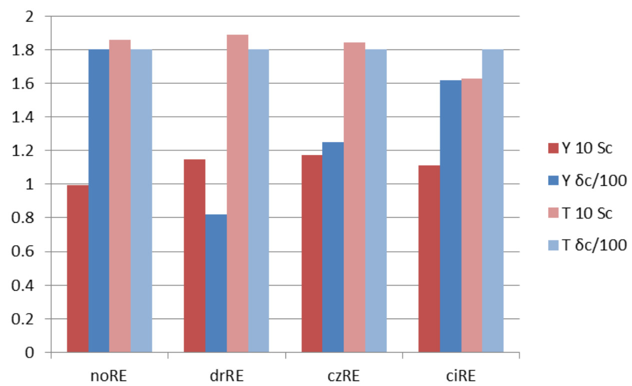

図 5.17 Impact on Sc and δc by omitting LB (Sen.)

Analysis Adding results of omitting LB case into Fig. 5.15 and 5.16, the results are shown in Fig. 5.17 (sending) and 5.18 (receiving). "Y" means Y-connection (that is, considering LB), "T" means traditional (that is, omitting LB). In both system, index of transient synchronous stability Sc and index of transient voltage stability δc become larger by omitting LB, that is, transient stability becomes optimistically assessed by omitting LB.

Simulation Simulation results corresponding to Fig 5.8 and 5.10 are shown in Fig. 19 (sending) and 5.20 (receiving). Those cases that were unstable when LB is considered become stable by omitting LB, and transient synchronous and voltage stability are optimistically assessed.

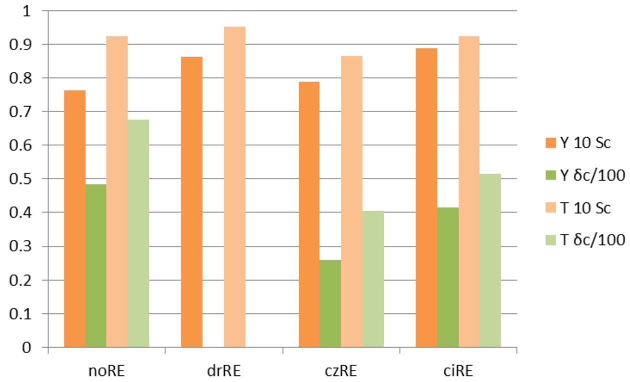

Fig. 5. 18 Impact on Sc and δc by omitting LB (Rec.)

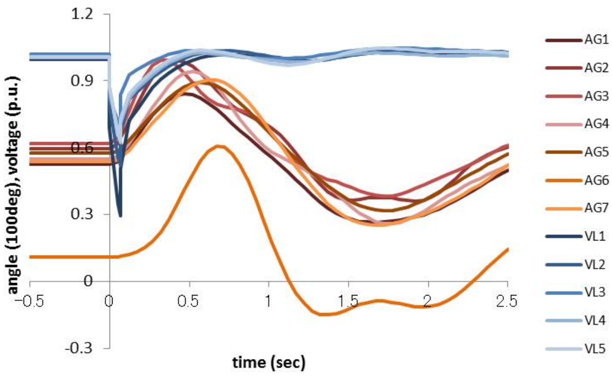

Fig. 5.19 Simulation of sending system before agg. (w/o LB)

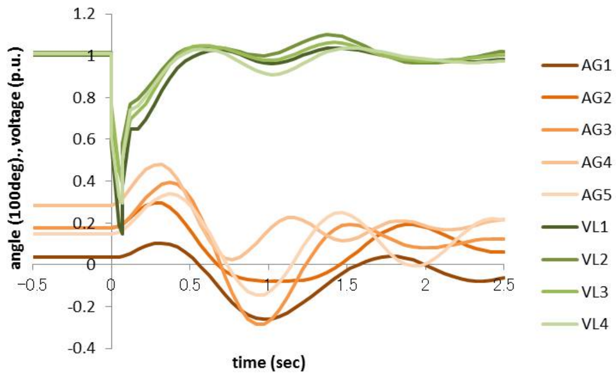

Fig. 5.20 Simulation of receiving system before agg. (w/o LB)

Summing up

From existing trunk power system one sending system and one receiving system having ill transient stability are chosen. Induction motor load and load branch (feeder equivalent) from 66kV class bus to load are considered. Thy are aggregated by Y-connection method into one machine one load infinite bus system and analyzed.

By varying induction motor's speed ω, P-δ curves of synchronous generator are drawn. By varying synchronous generator's angle δ, T-ω curves of induction motor are drawn. Thus mutual influence of δ and ω is shown. In some cases simulations are performed. The tendency agree with what analysis theory shows.

As additional cases, highly integrated RE (Renewable Energy) in various design during disturbance are studied. Transient synchronous stability tends to be improved by RE integration, and transient voltage stability tends to be poorer by RE integration. As to RE design, transient stability is better in constant current FRT type RE, next better in constant impedance FRT type RE, and the worst in drop type RE.

When motor decelerates generator output is suppressed and generator acceleration is promoted. When generator accelerates motor input is suppressed and motor deceleration is promoted. In sending system transient synchronous stability of generator is dominant, and in receiving system transient voltage stability is dominant.

As fast instability, generator's transient synchronous instability and motor's transient voltage instability progress simultaneously and mutually promote. In general, it is not adequate to study generator's transient synchronous instability and motor's transient instability independently, but is adequate to consider the two simultaneously.

In analysis without modeling induction motor load, impact by motor deceleration on transient synchronous instability never appears, and analysis without modeling load branch, the impact is not assessed adequately. In case of assessing transient synchronous and voltage stability with highly integrated RE, not only adequate modeling of RE but also adequate modeling of network such as motor load and load branch are indispensable.

Is inertia indispensable for generator?

Since most renewable energy (RE) interconnects via inverter, does not have large inertia as synchronous generator. Opinion that RE cannot be recognized as proper generator because it has not inertia is often heard. The opinion is not verified nor disproved falsified yet. To not verify or falsify proposition although it can be verify or falsify is an attitude of “pseud science”. Therefore the author will falsify and solve misunderstanding.

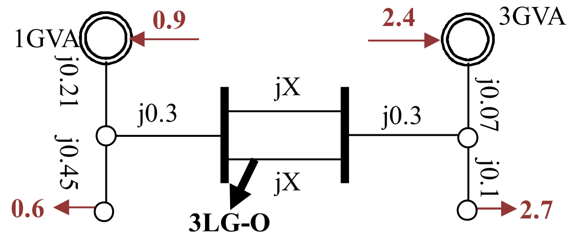

図 5.21 例題系統の構造と定数

As minimum model Fig. 5.21 is employed. Two subsystems interconnect via a double circuit tie line. The two subsystems are aggregated by Y-connection method[3] where impedance from medium bus to load is considered. For simplicity resistance in impedance is omitted, and only reactance is considered as approximation. Load is expressed mix of 50% induction motor and 50% resistance reflecting reality. Smaller subsystem at left side is sending power to larger subsystem at right side. 3LG-O fault on one circuit at smaller system side of the tie line. Fault clearing time is assumed as 0.1 sec.

表 5.3 系統電源の定数

Xd	Xd’	Xd”	Td’	Td”	Xq	Xq’	Xq”	Tq’	Tq”	Ta
1.7	0.3	0.25	1.0	0.03	1.7	0.6	0.25	0.3	0.03	0.19

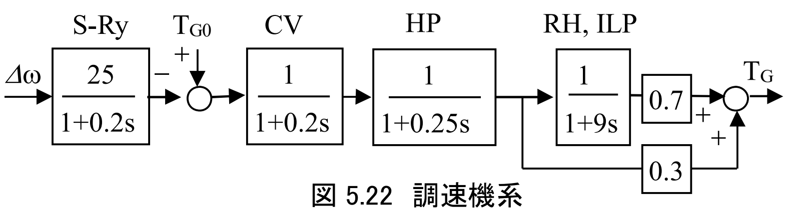

図 5.22 調速機系

Generators are modeled as synchronous generators, whose constants are shown in Table 5.3. Inertia is assumed as 7.0 sec. Speed governing system is shown in Fig. 5.22 and excitation system in Fig. 5.23. Simulation is held by CRIEPI Y-method. Increasing reactance of the tie line X, instability is produced.

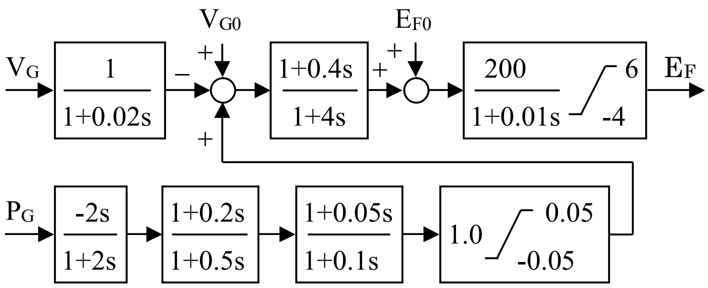

図 5.23 励磁系

Usual synchronous generator When X is increased to 0.7, instability appears as Fig. 5.24. In smaller system 1, although generator output (PG1) largely decreases, turbine torque (TG1) hardly varies. As esult excessive energy is stored in inertia, and generator angle leads. In the example the first swing is endured but go to asyncronism in the second swing.

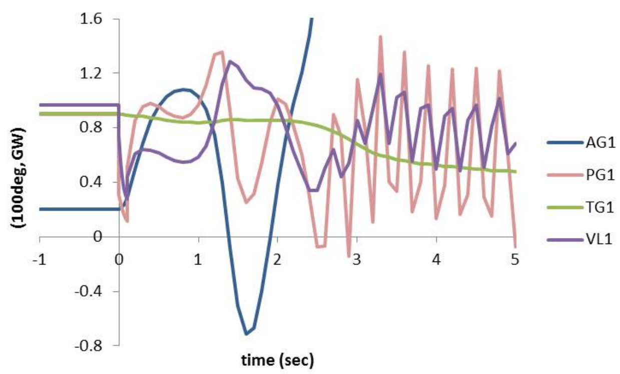

Fig. 5.24 Stability limit of usual synchronous generator

Super light generator Here, generator inertia is changed to vary small. The other generator constants, excitation system, tie line reactance X are kept, but sped governing system is changed as Fig. 5.25 by reason as follows. In large disturbance generator cannot send power from turbine to system. So in a short time, turbine torque (TG) follows generator output (PG). Therefore, a part of turbine power is thrown away. In reality, when AC output of photovoltaic generation (PV) decreases, DC voltage rises, and DC output from solar panel decreases. Therefore, the assumption is sufficiently realistic.

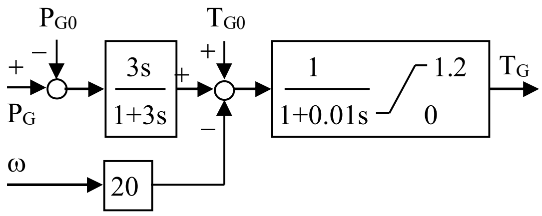

Fig. 5.25 Speed governing system for superlight generator

Inertia at stability limit was as small as 0.02 sec. (Fig. 5.26). During low voltage due to voltage sag, turbine torque (TG1) follows generator output (PG1) well, and turbine throws off excessive power and does not supply to generator. Therefore, even then inertia is very small, generator's angle lead is suppressed small. Due to small inertia, power swing after fault clear hardly seen.

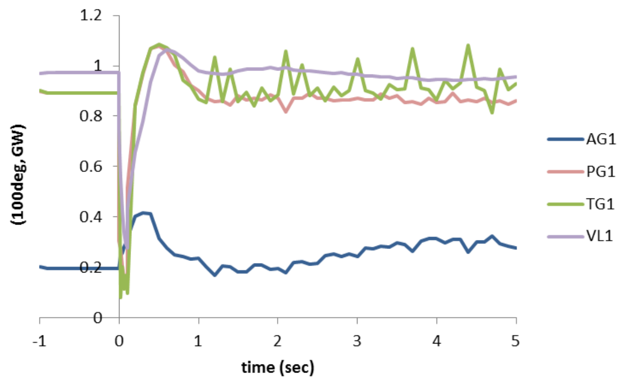

Fig. 5.26 Stability limit of super light generator

Since some time delay exists in speed governing system, some inertia (or equivalent) covering it is necessary. In PV, DC capacitor play the role. Since 0.02 sec. inertia is stability limit, following of turbine torque (TG1) is somewhat insufficient, but becomes sufficiently smooth with 0.1 sec. inertia.

Inverter power source with synchronous condenser Synchronous generators are replaced to inverter power sources. Inverters are assumed to be controlled as follows (Here, W is inverter capacity). As active power control fast speed governing is assumed with around half sensitivity of usual generator. As reactive power control so called DVS (Dynamic Voltage Support) like SVC character is assumed. The both are easily realized in inverter. These control are expressed as follows.

Active power $P \propto V^2 f^{-10}$

Reactive power $Q = W (V^2 - V^{12})$

However only by DVS function, voltage support ability of system is slightly in short. Therefore, rotary condenser (RC) with 30% capacity of inverter is added, and perform soft AVR (Automatic Voltage Regulator) function. The other condition is same of the former section.

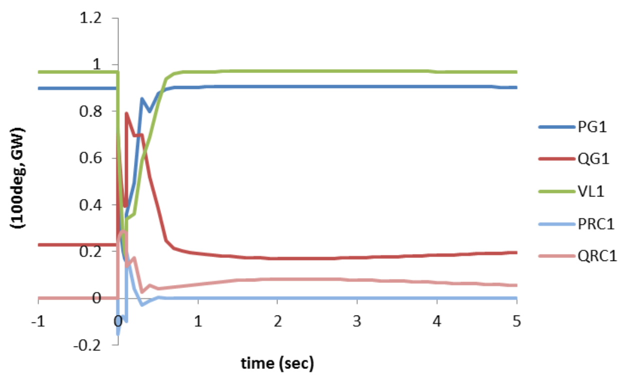

Fig. 5.27 Stability limit of inverter power source with RC

By reducing RC inertia, the system goes to unstable. In the case 0.5 sec. is stability limit (Fig. 5.27). Transient disturbance calms down eithin 0.5 sec., and stability is better than very light generator case. RC in subsystem 1 generates slightly increases reactive power after fault clear for compensating increased reactive power loss in tie line.

As stated above, due to network fault some imbalance occurs between turbine output (that is, generator input) and generator output, and to absorb the imbalance is role of inertia (or equivalent). Necessary inertia is different by physics of turbine and generator. In conventional turbine and generator system, the imbalance is very large, so large inertia is needed. On the contrary in PV panel and inverter system, the imbalance is very small, so only small inertia is needed. It is proper that generator must have some inertia, but the necessity is different by two figures by physics of the system. Therefore, it is unfair to assert that RE cannot be recognized as proper generator because it has not inertia.

Possibility of asynchronism

In the author’s duty as electric engineer during 40 years or more, only one incident of asynchronism had been seen. The incident was that, due to 77kV bus fault cleared by so long as 1 sec. by poor protection system in those days, a thermal generator in 154kV network went to asynchronism. However, the asynchronism cannot occur in the same condition in analysis and simulation. Why asynchronism occurred?. The offender was OEL (Over Excitation Limiter) setting. Since synchronous generator’s field winding is wound on a large forged iron rotor, temperature does not rise easily if large excitation current occurs. Therefore, some tens second time delay is prepared. However, OEL time delay of the generator was set as instant (0 sec). So, as soon as bus fault occurred, OEL operated, field current was reduced, field flux was weakened, and synchronous stability was broken. After the affair, a rule that OEL setting must be checked by power system department was established.

The demonic physical phenomenon that generator and motor load mutually promote their instability tends to appear in case that three-phase fault brings large deceleration in motor. Then, is three-phase fault may occur on transmission line due to lightning strike? Since usually minus charge falls in lightning, phases having positive electric potential discharges easily. Since one of the three phases must have negative electric potential, usual lightning strike (except ultra large lightning strike) cannot cause three-phase fault on transmission line. Especially in trunk system line that has high phase voltage three-phase fault is quite rare. Besides, fault location is usually far from line end (substation bus). The fault is seen from bus a fault through line impedance, which is lighter than bolted short circuit, and it is not probable that generator easily go to instability.

If asynchronism is assumed to occur in trunk system, the cause must be bus fault. Two scenario are thought. The first is internal fault of three-phase in one type GIS (Gas Insulated Switchgear). Even though only one-phase fault occurs at first, it extends to three-phase fault within half cycle (8 msec.). The second is charge without removal of temporary grounding for safety during work. That is a human error. These two scenario have considerable reality. Human error may be reduced by training to some extent, but GIS aging never stops and fault possibility will increase. In near future engineer7s ability will be declined, and the author thinks that really asynchronism can occur in trunk system.

If asynchronism may occur due to faults on transmission line, the faults are two-circuit faults shown in Fig. 5.28 until fast reclosing is performed. Among them, 2ϕ3LG is severe to synchronous stability, because one phase is lost during reclose time. 2ϕ4LG causes two-circuit trip. This is out of range of synchronous stability, if not loop system.

During reclosing time phase A and C offer electric energy to phase B through electric and magnetic induction. This current is called as “secondary arc current”, and is especially large in 1ϕ2LG case. By that arc by the fault tends to not extinct. When reclosing is performed before arc extinction, the fault reappear and reclosing goes to failure. One more reclosing is impossible by circuit breaker’s design, so go to two-circuit trip. Secondary arc current has cross relationship with transmission line’s voltage and length. 0.833 sec. reclosing tome (50cycles in

60Hz) is sufficient for 100km 500kV line.

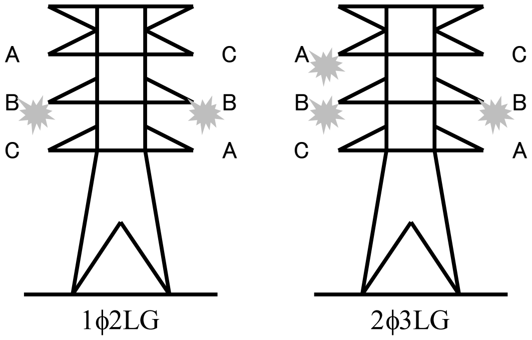

Fig. 5.28 Typical two-circuit fault on EHV transmission line

Decelerating asynchronism(5)

Usually asynchronism appears as "accelerating asynchronism". Unstable generator increases its angle by time and goes to step out. The phenomenon tends to occur when the system sends much power to outer system. As the dual concept, "deceleration asynchronism" can be thought. Unstable generator decreases its angle by time and goes to step out. The phenomenon tends to occur when the system is receiving much power from outer system. However, does such a phenomenon exist? Condition that results decelerating asynchronism is, by mechanism shown in Fig. 5.1, alike to condition that accelerating asynchronism occurs when much induction motors exist in load.

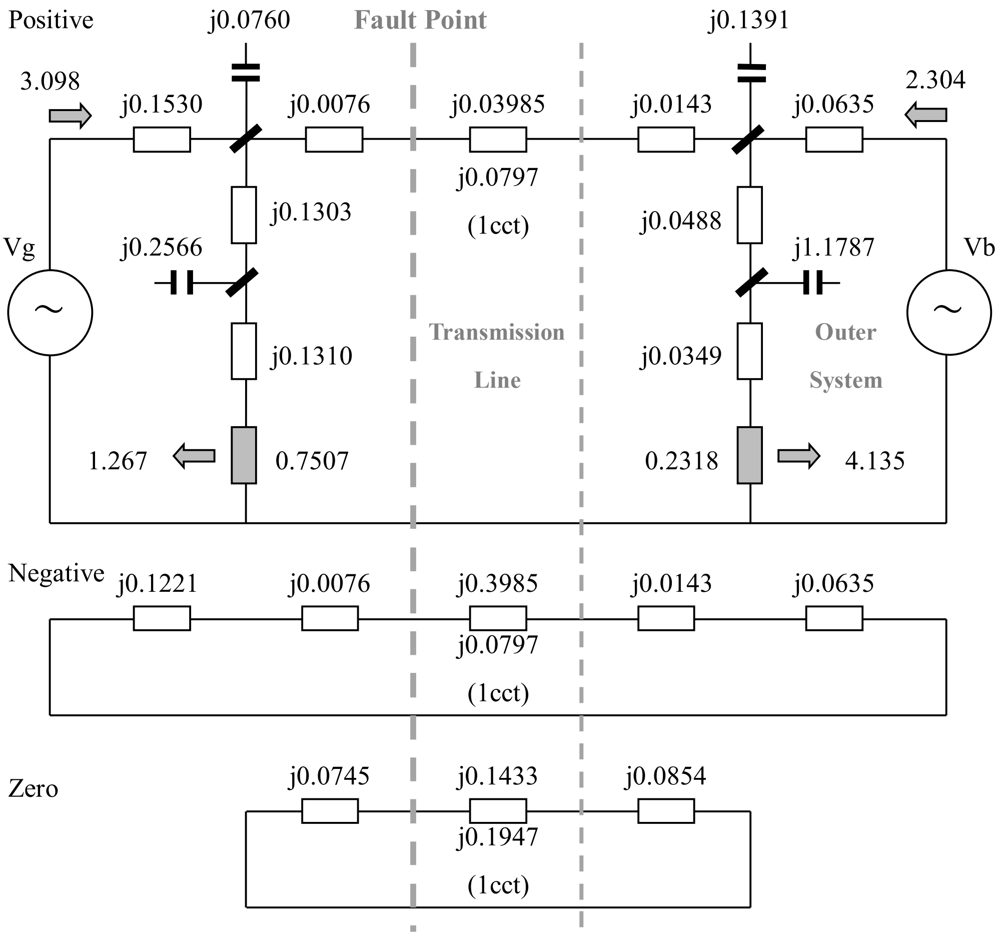

Fig. 5.29 Equivalent symmetry circuit of theexample system

Conditions that deceleration asynchronism are listed up as follows.

1) Receiving power is suppressed long and largely.

2) Load's consumption power increases when its internal resistance is reduced.

Condition 1) realizes when two-circuit fault causing two-phase operation occurs on transmission line. Condition 2) realizes when rich near and local power source exists. Load's voltage is supported by local power source, therefore, consumption power increases when internal resistance is reduced. Therefore, decelerating asynchronism can exist. However, really exists in existing system? By investigation the author discovered an example.

Equivalent symmetric circuit of the example is shown in Fig. 5.29. The system has rich local power source and voltage stability is good, interconnects to outer system via one route double-circuit line. The heaviest fault not resulting two-circuit shutdown is 3f4LG-O-C.

Demand supply balance was kept in the system till end of 20th century, but new power source appeared in outer system, local power source with high fuel cost included in the system become to stop. Thus, the system becomes to suffer from heavy receiving power flow especially during lightning attack. As countermeasure lightning arresters were equipped in two phases among six phases of two circuits. However, very severe lightning strike really cause 3ϕ4LG fault.

Assuming load as constant impedance (CZ), P-δ curves under various conditions are calculated as Fig. 5.30. Deceleration asynchronism seems not to occur in two- phase operation. However in dynamic load case, risk of decelerating synchronous increases as load's internal resistance is reduced as shown in Fig. 5.31. Load's consumption power increases as its internal resistance is reduced as Fig. 5.32.

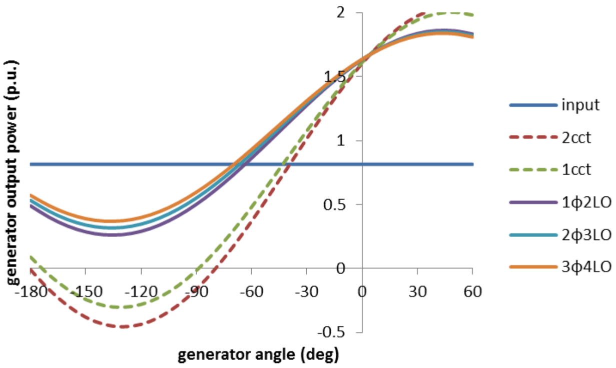

Fig. 5.30 P-δ curves (static load)

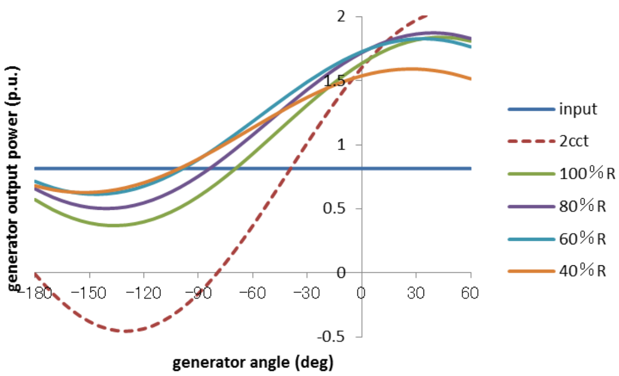

Fig. 5.31 P-δ curves (dynamic load)

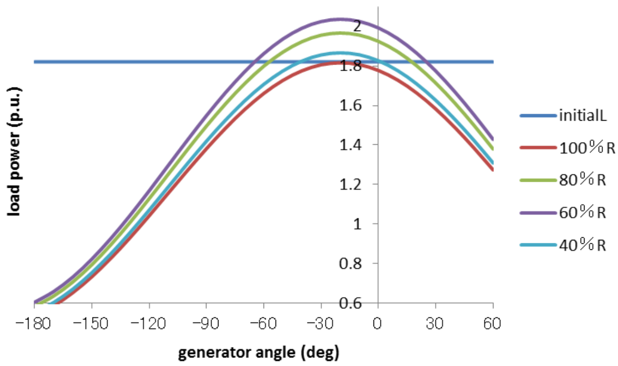

Fig. 5.32 Load's P-δ curves (dynamic load)

Also generator's forcing in excitation system must be considered. Forcing has improves usual (accelerating) asynchronism. What effect is brought in decelerating asynchronism? To examine the effect load's electromotive power is enlarged to 1.15 times. P-δ curves become as Fig. 5.33. Transient stability is broken and decelerating asynchronism occurs. Load's P-δ curves become as Fig. 5.34. Load's consumption power significantly increases as load's internal resistance is reduced.

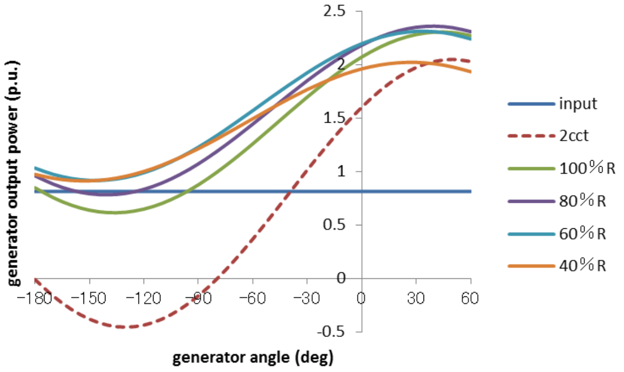

Fig. 5.33 P-δ curves (dynamic load, forcing)

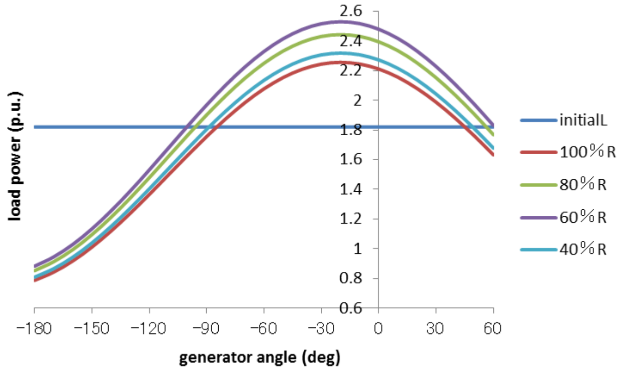

Fig. 5.34 Load's P-δ curves (dynamic load, forcing)

To verify analysis results above, simulation under the three cases as follows are performed.

1. constant impedance load (CZ)
2. constant current load, never changes to 定 CZ at low voltage (CI)
3. mix of 50% induction motor and 50% CZ (IM50%)

The results are shown in Fig. 5.32. Fault is 3ϕ4LG-O, reclosing is performed 2 sec. after fault clear. In CZ load case, transient stability is maintained. In CI load case, decelerating asynchronism occurred. In 50% IM load, decelerating asynchronism occurred but later than CI load case. The reason why asynchrponism appears earlier in CI lad case is that load's internal resistance is reduced at the instance of voltage drop in CL load, but by inertia some time is needed for reducing internal resistance in 50% IM load.

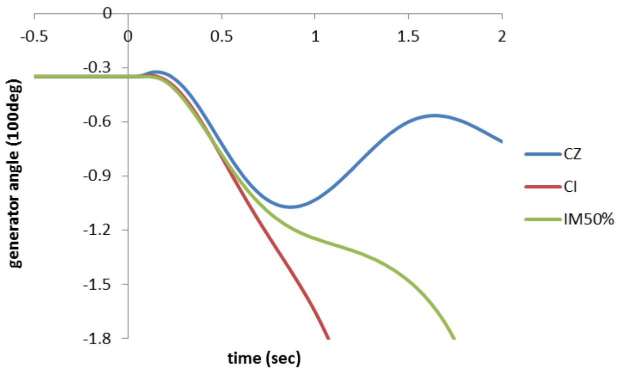

Fig. 5.35 Difference in simulation result by load model

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