5. Transient Synchronous Stability and RE Design

In chapter 4, voltage stability is studied. Next in the chapter, the next theme, transient synchronous stability is studied. This deals with the phenomena that a part of synchronous generators in power system lose synchronism with the others due to shock of fault. In classic analysis written in text, one machine infinite bus model is employed. Loads near the generator in question are ignored. Therefore, the model is realistic in such a case that large remote power source sends power to power pool feeding to much load, but is not applicable to analyze stability of a partial power system included in a large interconnection, because to consider mechanism of nearby loads (1) becomes indispensable. An extended theory is needed.

Extended Theory of Asynchronism

Load's dynamic character is mainly derived from induction motor (IM). Considerable amount of IMs exist in Loads. Therefore, two types of rotating machines, that is, synchronous generators (SG) and IMs exist in power systems, and the two mutually make transient voltage and synchronous stabilities worse bay having system voltage decrease as the common phenomenon as shown in Fig. 5.1.

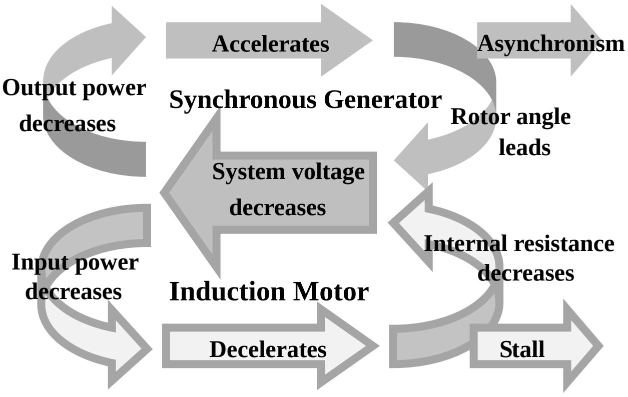

Fig. 5.1 Mechanism of Asynchronism

Instability of SG appears as asynchronism, which is analyzed by synchronous stability analysis. Instability of IM appears as stall, which is analyzed by fast voltage analysis. However according to the figure, the two instability are cannot analyzed independently but should be analyzed as a synthesized fast instability.

To deal with the synthesized fast instability, power system model must include elements as shown in Fig. 5.2. The structure is already introduced in chapter 3 where power system aggregation is studied. At trunk bus capacitor C_B exists. Capacity in cable of underground transmission lines operates like C_B. At 66kV class midway bus a considerable amount of capacitor C_M exists. Load is represented as a variable resistance R_L behind a fixed impedance Z_L. By measured data, in case of deep voltage sag, R_L drops to around 60% of before fault. By simulation, R_L drops to around 40% of before fault when IM goes to stall.

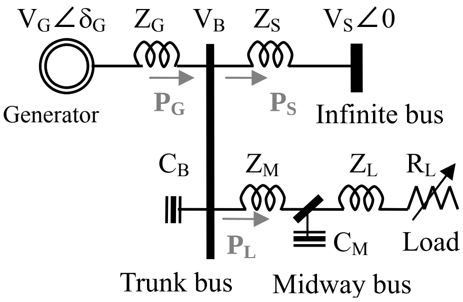

Fig. 5.2 Minimum model for fast instability analysis

The power system model is further more complex than 1 machine infinite bus model, but analysis is still possible. Influence of dynamic load with variable internal resistance R_L can be recognized by drawing multiple power-angle (P-δ) curves for some values of R_L as parameter.

On one hand, load branch impedances Z_M and Z_L hinder power consumption in resistance R_L when system voltage decreases. Reduced power consumption in load produces excessive power, which accelerates SG. On the other hand, load is obstructed to receive power, and as the result, IM decelerates. Thus, SG and IM go to instabilities. These unstable phenomena are hardly represented by traditional aggregation ignoring load branch impedance, and as the result, such inadequate aggregation will inadequately assess stability optimistically.

Partial load drop due to voltage sag has a negative effect that reduced load consumption power accelerates SG and makes synchronous stability worse, and has a positive effect that fast load voltage recovery also recovers load consumption power and makes voltage stability better. Which effect is stronger must be studied by minute simulation.

Main theme of the chapter is what impacts on transient synchronous stability become serious when renewable energy (RE) highly penetrates. Since RE (especially PV) locates near load, load's dynamics such as IM and accurate aggregation of load system become indispensable.

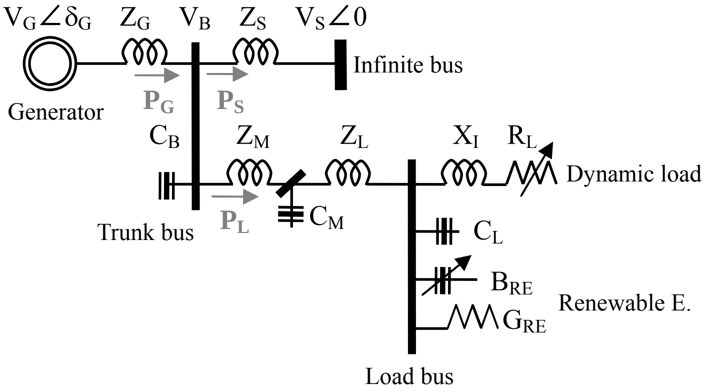

Fig. 5.3 Minimum model of fast instability considering RE

Minimum model for fast instability study considering RE is shown in Fig. 5.3. RE is expresses as negative constant conductance G_{RE} and variable susceptance B_{RE} in parallel to load terminal. Of course expressions by constant current, constant power or voltage source are possible. However, it is convenient for power system that RE output decreases when system voltage becomes low, negative conductance model is adopted that has the effect most. RE penetrates by 20% of load. Some thermal generators stop because of demand supply balance. Three types of RE design are assumed.

"Drop type" RE once shuts down due to voltage sag. Until it reintegrates, voltage collapse may occur.

"FRT (Fault Ride-Through) type RE never shuts down due to voltage sag, but never support system voltage recovery.

"DVS (Dynamic Voltage Support) type RE never shuts down due to voltage sag, and supports system voltage recovery.

Power-voltage characters of DVS type RE are assumed as follows. Here, Y_{RE0} is admittance at rated power output.

$$\begin{aligned} P_{RE} &= G_{RE0} \left(\frac{V_{RE}}{V_{RE0}}\right)^2 \\ Q_{RE} &= Y_{RE0} \left[\left(\frac{V_{RE}}{V_{RE0}}\right)^2 - \left(\frac{V_{RE}}{V_{RE0}}\right)^{12}\right] = B_{RE} \left(\frac{V_{RE}}{V_{RE0}}\right)^2 \end{aligned} \qquad (5.1)$$

When stabilities are calculated using power system model made from viewpoint of fast instability that synthesizes classic asynchronism and fast voltage collapse, unstable cases appears one after another, which were recognized as stable in traditional analyses. Those cases may become reality in today's power system. But further comments are postponed.

Is Inertia of Generator Indispensable?

Most RE interconnects through inverter, which has not large inertia such as SG. Taking is as reason RE is very often remarked as inferior power source. However, the remark is not verified or falsified yet, although it is possible. The attitude is that of pseudo-science. Therefore, the author as representative does it and solves misunderstanding in electric engineering field.

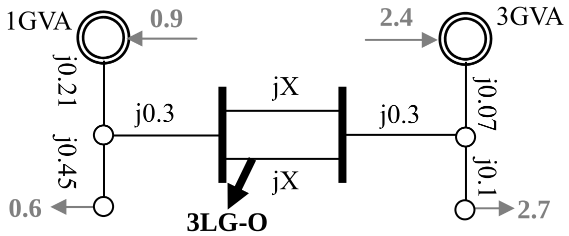

Fig. 5.4 Structure and constants of the example system

As minimum mode for verification/falsification, model system shown in Fig. 5.4 is employed. Two subsystems interconnect through a 2-circuit tie line. Two subsystems are aggregated by Y-connection method, and all network impedances are considered. But they are, for simplicity, modeled as pure reactance without resistance. Load is modeled as 50% IM and 50% CZ (constant impedance) for realistic expression. Small subsystem at left sends some power to large subsystem at right. A 3LG-O fault is assumed on a circuit of the tie line at small subsystem end. Fault duration time is set as 0.1 sec.

System power sources are SGs, and their constants are shown in Table 5.1. Unit inertia constant of SGs is 7.0 sec. Speed governing system is shown in Fig. 5.5. Excitation system is shown in Fig. 5.6. Unstable phenomenon is performed on simulation using CRIEP Y-method by enlarging tie line reactance X (for 1 circuit).

Table 5.1 Constants of the SGs

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

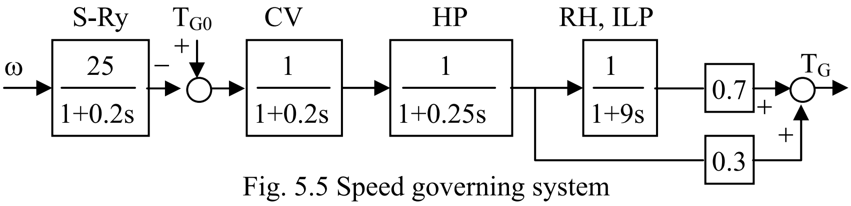

Fig. 5.5 Speed governing system

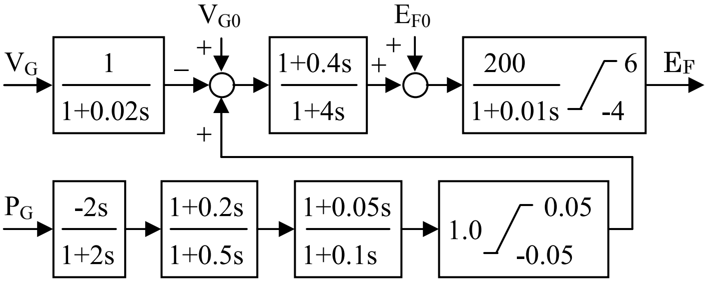

Fig. 5.6 Excitation system

[Synchronous Generator] Increasing X up to 0.7, unstable phenomenon appears as shown in Fig. 5.7. Although Generator output in subsystem 1 (PG1) considerably decreases sue to voltage sag during fault, Prime mover torque in subsystem 1 (TG1) hardly varies. As the result, excessive power is accumulated in inertia and phase angle (AG1) leads. In the example the first swing is still within stability but the second swing goes to instability.

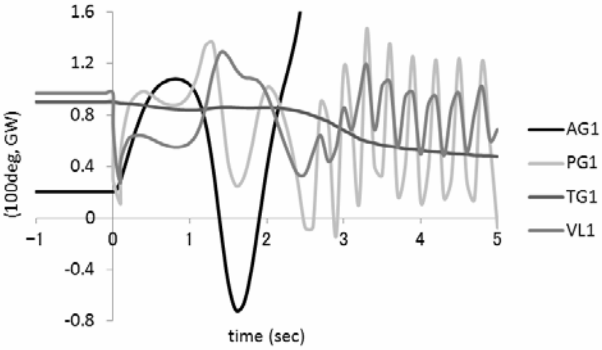

Fig. 5.7 Stability limit of SG

[Very Light Synchronous Generator] Inertia of SGs are set as very small. SG constants, excitation system, and tie line reactance are same of normal inertia case. However, speed governing system is changed as Fig. 5.8. The reason is as follows. When large contingency occurs, generator cannot send power from prime mover. For solving the problem, a control that makes prime mover torque (TG) follow generator output in a short time. As the result, some part of prime mover power is abandoned. In truth, when AC output of PV decreases, DC voltage rises, and solar panel output decreases. Therefore, the control is sufficiently realistic.

Inertia at stability limit is found as 0.02 sec (Fig. 5.9), which is incredibly small. During voltage sag due to fault prime mover torque (TG1) follows generator output (SG1) well, and prime mover abandons excessive power and does not supply to generator. Since inertia is very small, large power swing after fault hardly appears.

Since 0.01 sec control delay exists in speed governing system, some inertia (or something like it) is needed. In PV, DC capacitor works like inertia. In case of 0.02 sec inertia, some ripple remains on prime mover torque. However, the ripple will disappear if inertia is 0.1 sec.

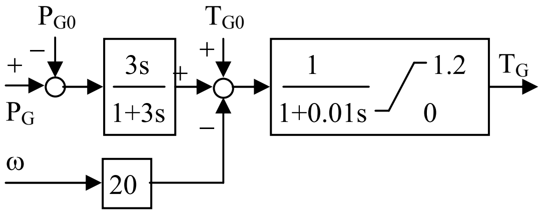

Fig. 5.8 Governing system for very light SG

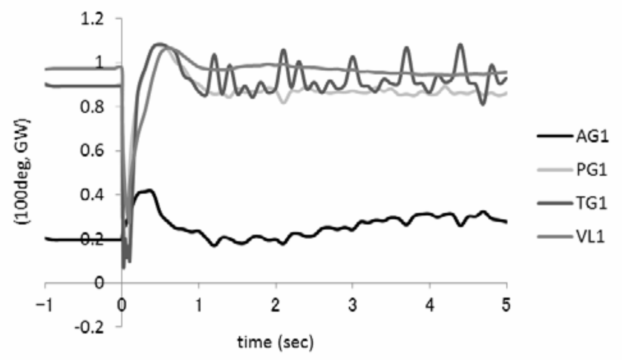

Fig. 5.9 Stability limit of very light SG

[Inverter and Synchronous Condenser] Inverter power sources are employed instead of SGs. Inverters are assumed to be controlled as follows. Here, W is rated capacity of inverter. For active power control, fast speed governing system with around half gain of governor for SG is employed. For reactive power control, SVC like character, that is, DVS (dynamic Voltage Support) is given. The two are easily realized on Inverter.

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

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

However, system voltage support ability is slightly weak only by DVS. Therefore, synchronous condenser with 30% capacity of inverter is equipped in parallel and controlled by gently set AVR (Automatic Voltage Regulator). The other conditions are kept unchanged.

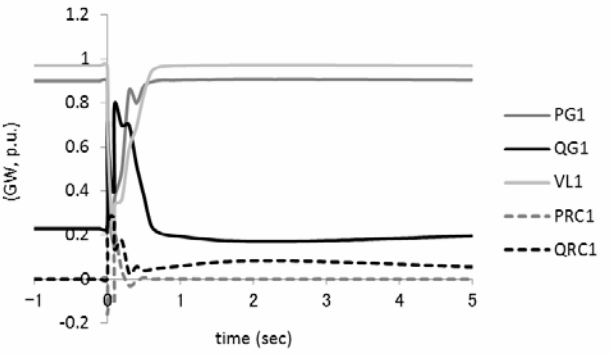

Fig. 5.10 Stability limit of inverter

As making RC inertia small, the system becomes unstable. In the case, 0.5 sec inertia is the stability limit (Fig. 5.10). Transient fades out within 0.5 sec, and stability seems better than very light SD case. RC in subsystem 1 near fault shows a small power output after fault. This is caused for compensating loss increase in tie line.

Thus by fault on power system, some mismatch between prime mover output and generator output appears, which is absorbed into something like inertia. Therefore, necessary amount of something like inertia is decided by physical law of prime mover and generator system. In turbine and synchronous generator system, the mismatch is so large that inertia of the system must be very large. In solar panel and inverter system, the mismatch is so small that necessary inertia like element is very small. It is certain that any generator needs something like inertia, but necessary amount of it varies 100 times or so. As the conclusion, it is falsified to regard PV as not regular power source because of small inertia like element.

Poor voltage support ability of RE (such as PV) is rather more serious issue on RE integration. SGs are powerful voltage sources. But, Inverters are only current sources because so controlled that over current due to system fault does not hurt inverter. Voltage support ability of current source is inferior to that of voltage source. Therefore, if SG is replaced by RE, voltage support ability of whole system decreases, voltage stability decreases, and as the result, transient synchronous stability also decreases. To mitigate the problem, giving DVS (Dynamic Voltage Support) ability is effective.

To verify the theory above, analyses results of an example of sending power system and an example of receiving power system are introduced among many studied cases.

Example of Power Sending System

Structure of the system is shown in Fig. 5.11. The system locates at the edge of a large interconnection, and sends slight power to outer system. Usually asynchronism occurs by leading generator angle, and called as “accelerating asynchronism”. In sending system possibility of the asynchronism becomes large. As the dual concept “decelerating asynchronism” can exist.

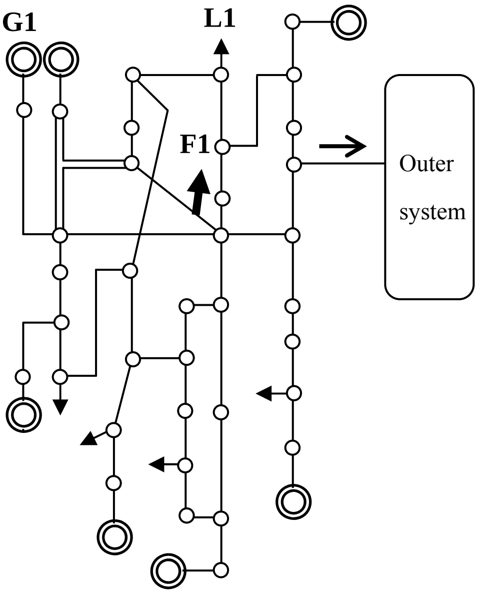

Fig. 5.11 Structure of power sending system

A 3LG-O fault on a circuit of two-circuit transmission line at F1 is assumed. Fault duration time is set as 0.07 sec. Constants by aggregating the system to 1 generator and 1 load by traditional method and Y-connection method are compared in Table 5.2.

Table 5.2 System constants (after fault, aggregated generator capacity base)

	Z_g	Z_s	Z_m	Z_L
Traditional	0.00603+j0.50124	0.08982+j3.23466	0.00698+j0.21163	0.00000+j0.00000
Y-connection	0.00625+j0.50575	0.08959+j3.23015	0.00404+j0.35907	0.00992+j0.27011

	V_g	δ_g	V_b	V_s	P_g	P_L	P_s	C_b	C_m
Traditional	1.15	0.52607	1.02	1.02	0.76007	0.68992	0.06290	0.00000	0.05000
Y-connection	1.15	0.52885	1.02	1.02	0.76007	0.68648	0.06291	0.00000	0.27000

Power-angle curves (P-δ curve) are drawn by 100%, 80%, 60%, and 40% load resistance (R_L) of normal condition. That considers rotating speed down of IM. The results are shown in Fig. 5.12. For simple, partial load drop due to voltage sag is ignored.

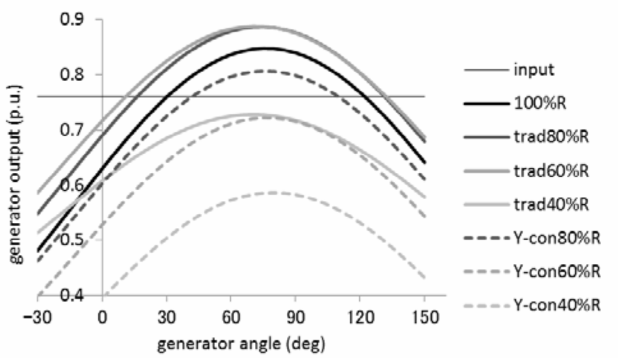

Fig. 5.12 P-δ curve by load resistance (Send)

In case of Y-connection method, height of P-δ curve becomes considerably smaller by lower load resistance compared to traditional aggregation method case. The scenario that excessive energy accelerates generator to asynchronism becomes realistic.

Simulation results are shown in Fig. 5.13 by generator angle and in Fig. 5.14 by load voltage.

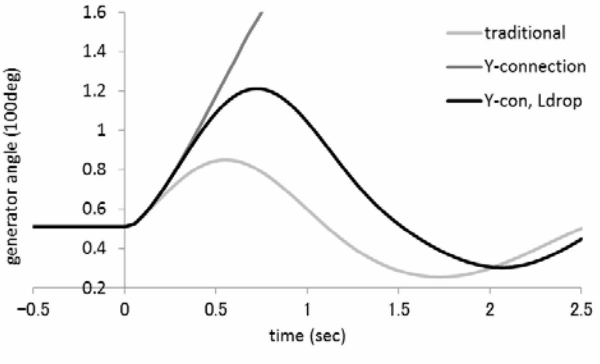

Fig. 5.13 Stability of generator (Sending)

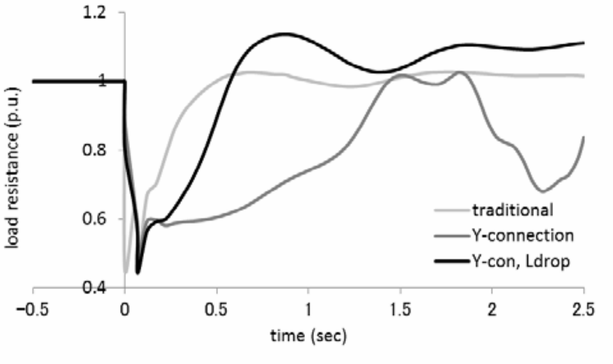

Fig. 5.14 Stability of load (Sending)

Load resistance is calculated as follows from total active and reactive power consumed by all loads

Psum , Qsum , and weighted average load voltage Vave.

$$R_L = \frac{\mathrm{Vave}^2\ \mathrm{Psum}}{\mathrm{Psum}^2 + \mathrm{Qsum}^2}$$

In case of traditional aggregation, generators keep easily stability even if neglecting partial load drop, and load voltage recovers within 0.3sec. No sign of instability are seen. On the contrary in case of Y-connection aggregation, 1.5 sec is needed for voltage recovery when neglecting partial load drop, and during the period generators go to accelerating asynchronism. By considering partial load drop, recovering time reduces to 0.6 sec and stability of generators is maintained. But slight over voltage due to load drop appears after fault clear. Load resistance is around 60% of normal. At the resistance, top of P-δ curve is lower than input in case of Y-connection (which means completely unstable), but higher than input in case of traditional aggregation (which means possibility of stable operation).

Impacts of RE penetrated by 20% of load are assessed. Simulation results are shown in Fig. 5.15 and 5.16. Partial load drop is considered. In case of drop type RE, generator goes to accelerating asynchronism and load goes to stall. Stability is quite ill. Impacts due to RE drop seem to be dominant in load voltage recovery delay rather than in generator acceleration. In case of FRT type RE, stability is kept but voltage recovery becomes slightly slower than no RE case. In case of DVS type RE, generator acceleration is suppressed very small and load voltage recovery is very fast. Stability is quite sound.

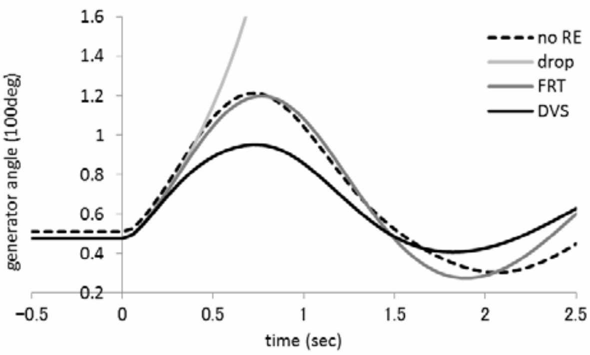

Fig. 5.15 Generator stability by RE design (send)

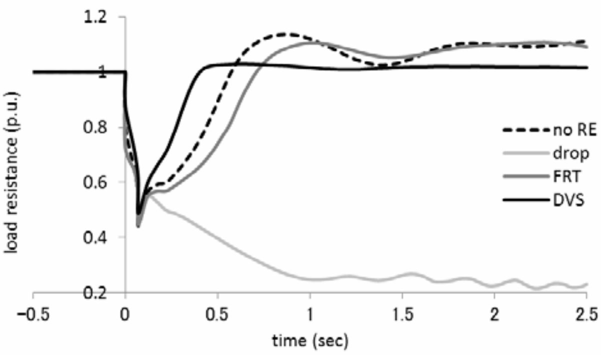

Fig. 5.16 Load stability by RE design (send)

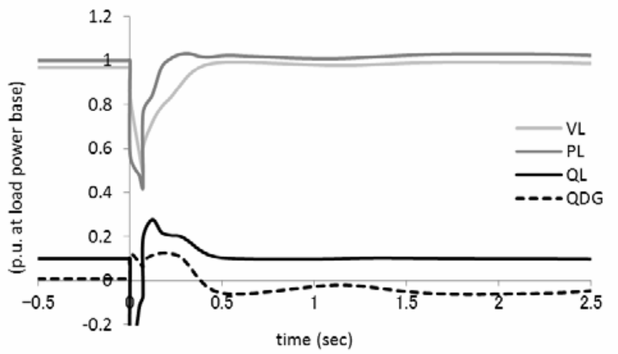

Fig. 5.17 Effective operation of DVS type RE (send)

Effective operation of DVS type RE is shown in Fig. 5.17. Load consumes much reactive power for recovery around 0.3 sec after fault. The reactive power is almost compensated by DVS type RE, because

RE locates near load. In addition DVS absorbs excessive reactive power after load recovery and mitigates over voltage of system.

As stated above, IM load operates as making load voltage unstable, and as the result, transient synchronous stability is worse than ever believed even in case of power sending system. The risk of instability cannot be assessed without employing 50% (or so) IM load and Y-connection aggregation. RE improves (DVS type) or spoils (drop type) stability according to its design.

Example of Power Receiving System

Structure of the system is shown in Fig. 5.18. The system locates at the center of a large interconnection, and receives much power from outer system via three tie lines. It seems a common sense that generators in power receiving system hardly go to asynchronism, because those phase angles are lagged from those of outer system. But is it true?

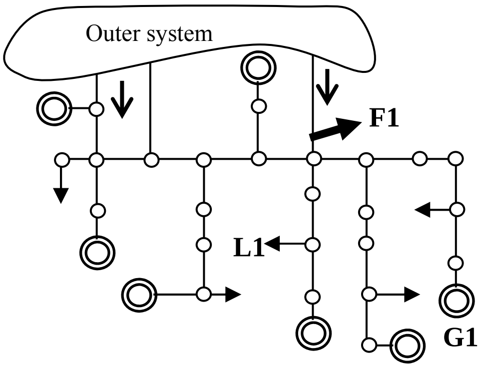

Fig. 5.18 Structure of receiving system

A 6LG-O fault on 2-circuit 500kV line at F1 is assumed. Although the system falls into a severe condition receiving much power via only two tie lines, asynchronism hardly appears according to traditional common sense. Fault duration time is set as 0.07 sec. Constants of aggregated system by traditional method and Y-connection methods are shown in Table 5.3.

Table 5.3 System constants (after fault, aggregated generator capacity base)

	Z_g	Z_s	Z_m	Z_L
Traditional	0.01529+j0.58088	0.02829+j1.31708	0.00067+j0.02183	0.00000+j0.00000
Y-connection	0.01531+j0.58121	0.02827+j1.31674	0.00144+j0.11252	0.00182+j0.12039

	V_g	δ_g	V_b	V_s	P_g	P_L	P_s	C_b	C_m
Traditional	1.10	-0.20638	1.00	1.00	0.82745	1.27476	-0.46452	0.36000	0.00000
Y-connection	1.10	-0.20583	1.00	1.00	0.82745	1.27062	-0.46447	0.28000	0.46000

Power-angle curves (P-δ curves) are drawn by varying load’s internal resistance as 100%, 80%, 60%, and 40% of normal condition as shown in Fig. 5.19. The reduced resistance represents rotating speed down of IM. For simple, partial load drop due to voltage sag is ignored. Y-connection aggregation shows much more decreased generator output due to reduced load’s resistance than traditional aggregation, and scenario that excessive energy accelerates generator toward asynchronism becomes realistic.

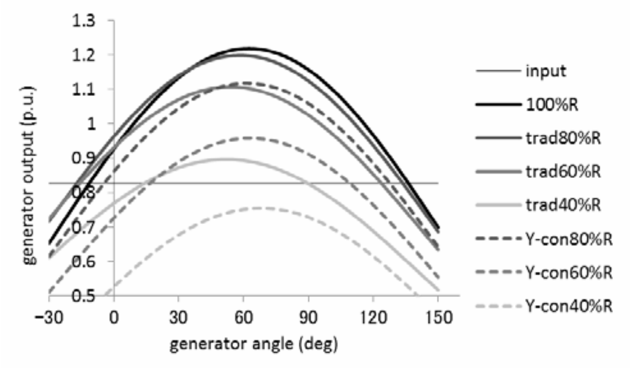

Fig. 5.19 P-δ curve by load resistance (Receive)

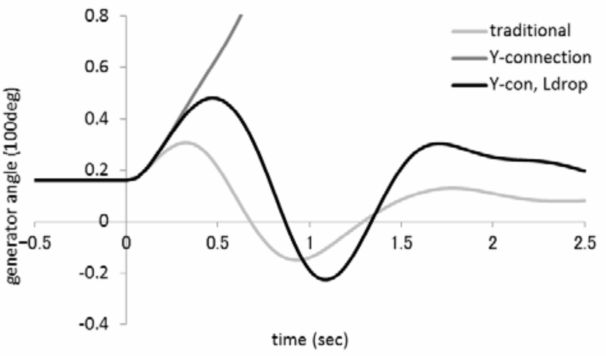

Fig. 5.21 Stability of generator (Receiving)

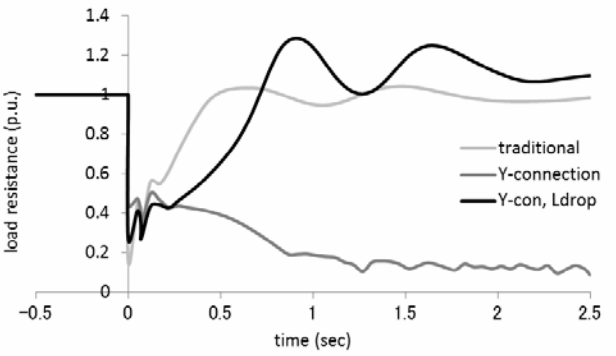

Fig. 5.22 Stability of load (Receiving)

Simulation results of generator angle are shown in Fig. 5.20, and those of load voltage are shown on Fig.5.21. In case of traditional aggregation, generator easily keeps stability, load recovers within only 0.4 sec, and no signs of instability are seen, even if partial load drop is ignored. On the contrary in case of Y-connection aggregation, load resistance does not recover and generator goes to asynchronism, if partial load drop is ignored. If it is considered, load resistance recovers by 0.8 sec and generator can keep stability. However, due to load drop, considerable over voltage appears. Load resistance becomes around 40% of normal in every case. At the load resistance, P-δ curve by traditional aggregation has some region at which generator output is larger than input. However by Y-connection aggregation, such region does not exist.

Impacts of RE penetrated by 20% of load are assessed. Simulation results are shown in Fig. 5.22 and 5.23. Partial load drop is considered.

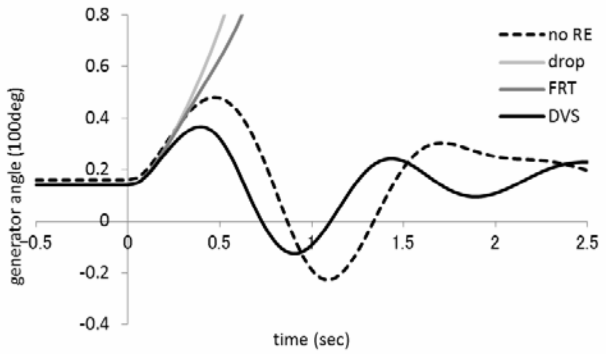

Fig. 5.22 Generator stability by RE design (receive)

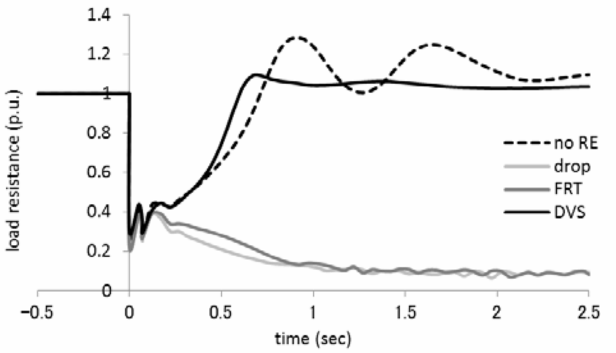

Fig. 5.23 Load stability by RE design (receive)

In case of drop type RE, generator goes to accelerating asynchronism and load goes to stall. Stability is quite ill. In case of FRT type RE, stabilities are also quite ill like drop RE case. In case of DVS type RE, generator acceleration is suppressed very small and load voltage recovery is very fast. Stability is quite sound.

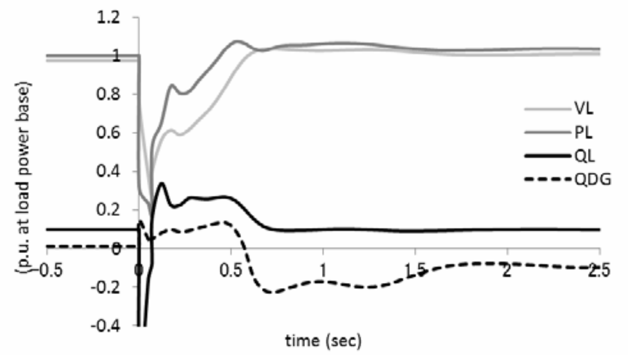

Fig. 5.24 Effective operation of DVS type RE (receive)

Effective operation of DVS type RE is shown in Fig. 5.24. Load consumes much reactive power for recovery around 0.6 sec after fault. The reactive power is almost compensated by DVS type RE, because RE locates near load. In addition DVS absorbs excessive reactive power after load recovery and mitigates over voltage of system.

As stated above, even in case of power receiving asynchronism may occur triggered by IM load stall. That is quite different from old common sense. The risk of instability cannot be assessed without employing 50% (or so) IM load and Y-connection aggregation. RE improves (DVS type) or spoils (drop type) stability according to its design.

Possibility of Transient Synchronous Instability

The author has only once seen transient synchronous instability in his 30 years of engineering life or more. The instability occurred due to 77kV bus fault. For clearing the fault, around one sec is needed because of primitive protection equipments in those days. During the time, a generator connecting to 154kV system went to asynchronism. But true criminal was another, which was OEL (Over Excitation Limiter) setting. Usually OEL has several tens sec time delay, because field winding of synchronous generator is wound on gigantic large iron rotor and temperature of the winding rises very slowly even if over current occurs. It was astonishing that OEL of the generator was set as zero! As the result, by voltage drop due to the 77kV bus fault field current increased, and OEL operated instantly. Field current of the generator was quite reduced. Magnetic flux was also reduced. Thus, synchronism was lost. After the accident, OEL setting has become ruled to be checked by power system engineering section.

A nightmare that SG and IM mutually make stabilities worse will come true when 3-phase-to-ground fault (3ϕG fault) occurs and IM largely decelerates. However, 3ϕG fault can occur on trunk transmission lines? Usually, lightning attacks transmission line with negative electric charge. Therefore, phases having positive voltage against the earth tend to go flashover. Since at least one phase has negative voltage against the earth. Only very large lightning will result 3ϕG fault especially in extra high voltage transmission lines. In addition in case of transmission line fault, the fault locates considerably far from substation bus usually.

Considerable impedance exists from the bus to the fault. Shock by the fault must be easier than fault on the bus itself. Therefore, synchronism is thought to be hardly lost by transmission line faults.

Transient synchronous instability can occur by fault on busses if it occurs. Two scenarios can be thought. One is internal fault of 3-phase-type GIS (Gas Insulated Switchgear). Even if the fault occurs on a phase conductor, it spreads to the other phase conductors within a half cycle (around 8 msec). Another is to charge a bus having temporary grounding for safe working. That is a human error. The temporary grounding must be put away before charging the bus. The two scenarios seem realistic. Human error can be reduced by training and so on. However, fault possibility becomes in aged GIS. Low level of diagnosis technique can cause GIS fault and following transient asynchronism, the author thinks.

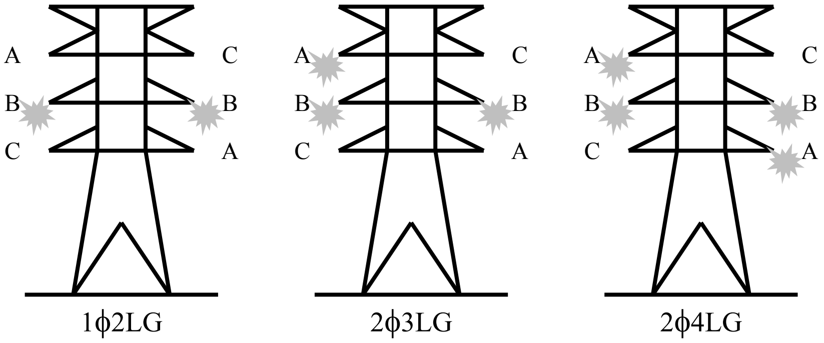

Fig. 5.25 Typical 2-circuit faults on EHV transmission lines

As transmission line fault causing transient asynchronism, 2-circuit faults shown in Fig. 5.25 on EHV line that employs high speed reclosing can be thought. Among them 2ϕ3LG is a severe case. In case of 2ϕ4LG, fast reclosing is not performed and the line (both 2 circuits) once shut down. Therefore, the case stands out of consideration of stability if the line does not form loop system.

By the way, especially in case of 1ϕ2LG, since sufficiently large power can be fed from survived phases through electrostatic and electromagnetic induction for obstructing arc extinction, high speed reclosing sometimes fails and results shut down of the circuit. Therefore, there is a relationship between adequate reclosing time and line length. By author's calculation, 0.833 sec (50cycles in 60Hz system) reclosing time enables 100km length of 500kV transmission line.

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