4. Voltage Stability and RE Design

In chapter 2 and 3, it was concluded that traditional power system model cannot represent real phenomena and that dynamic load model considering IM and Y-connection aggregation are indispensable for representing the real phenomena. Real phenomena to be represented were instantaneous voltage sags that very often appear in power system. To tell the truth, it is various power system stabilities that need correct power system model, because stabilities most strongly limit power system operation.

Power system stabilities are classified into three categories. The first is voltage stability of load, the second is transient synchronous stability of generator, and the third is oscillatory stability of generator. Hereafter it will be demonstrated that power system model much affects to the three stabilities. It is also demonstrated that design of renewable energy (RE) also much affects to the three stabilities. In this chapter 3, voltage stability is studied at first.

Voltage Stability without Voltage Sag (Steady State Voltage Stability)

Load voltage may drop significantly and never recover. The phenomenon sometimes called as “voltage collapse”. It is shocking words. Here at first voltage stability without voltage sag is studied. West Kanto large blackout in 23 July 1987 is included.

Two kinds of voltage collapse exist. The first is “slow voltage collapse” due to “reverse effect” of on-load tap changer (LTC) of transformer, and the second is “fast voltage collapse” due to stall of induction motor (IM). The simplest power system model that can represent the two kind of voltage collapse is shown in Fig. 4.1.

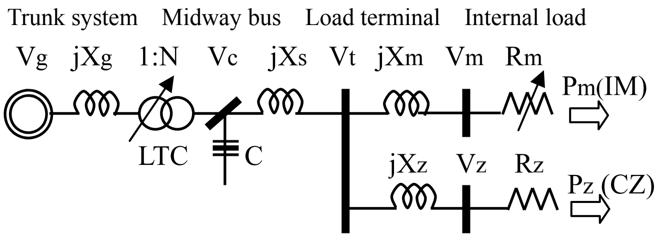

Fig. 4.1 The simplest model for the two kinds of voltage collapse

Trunk system is represented by a voltage source Vg and internal reactance Xg, induction motor (IM) load is represented by a variable resistance Rm behind a series constant reactance Xm, and constant impedance (CZ) load is represented by series composite of constant reactance Xz and constant resistance Rz. Transformer with LTC (on-Load Tap Changer) is represented by ideal variable tap ratio 1:N, and reactance of transformer is included into Xg. Considerable amount of capacitors exist at midway bus.

Two dynamic elements exist in the system. One is variable tap of LTC, and another is internal resistance of IM. The former causes slow voltage collapse due to unstable of tap control, and the latter causes fast voltage collapse due to IM stall. The two voltage-unstable phenomena are seen in real power system, and both phenomena can be represented by the model of Fig. 4.1.

At first limit in which slow voltage collapse does not occur is calculated. Usually secondary voltage rises when tap ratio rises. However, if power system is highly stressed, tap ratio causes secondary voltage reduction. This is “reverse effect” of LTC. Here as an example of local system, a primary substation fed by two-circuit 154kV transmission line is studied. Stop of one of the two-circuit line is assumed as contingency. Structure is same of Fig 4.1, and constants are shown as follows. The example is notorious as poor voltage stability in the utility employing the author.

$V_g = 1.01$ $X_g = 0.8132$ (2 circuits) $X_g = 1.318$ (1 circuit),
$N_0 = 1.0$ $V_c = 1.0$ $C = 0.313029$ $X_s = 0.5578$,
$X_m = 0.09/P_m$ $R_m = 1.675036$ $X_z = 0.09/P_z$ $R_z = 1.675036$

Transmission line becomes 2 circuits to 1 circuit, which is represented by increasing of X_g, midway bus voltage V_c varies by change of LTC tap ratio N. Assuming that power consumed by load is not affected by load terminal voltage (constant power character), relation between tap and midway bus voltage are calculated as Fig. 4.2. This is one of an elegant solution, and is called as “N-V curve”. It must be noticed that voltage rises by tap ratio rise to a certain voltage, but by much higher tap ratio voltage begins to decline. Voltage once drops by contingency. If voltage can recover to 1.0 that is the value before contingency by rising tap ratio, tap change stops and voltage stability is maintained. However, if voltage cannot recover to 1.0, tap rises in vain and cynically voltage continues to decline. This is “slow voltage collapse”. In the example 0.44GW load is stable, and 0.46GW load is unstable by N-V curve.

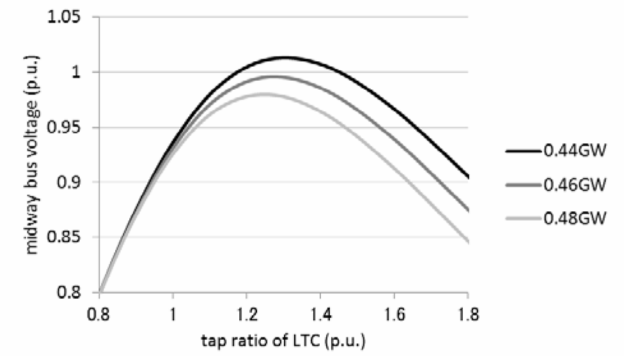

Fig. 4.2 N-V curve with 1 circuit line

In the Figure N range is set 0.8 to 1.8. There are no LTC covering such a wide range. Around 0.9 to 1.1 is reality. However, LTC of distribution transformer exists in series of LTC of interconnection transformer. Therefore, around 0.8 to 1.2 tap ratio can be realized by the series two LTCs. If LTCs reach upper limits, tap rise end and voltage will be decided by voltage sensitivity of the load itself.

Of course muscling solution, that is, simulation is possible. Typical simulation tool is CRIEP V-method. It is also called as “long term voltage analysis program”. The program repeats power flow calculation by around 1 sec time interval, considers tap change on transformers, and considers load’s static voltage and frequency sensitivity as follows.

$$P = P_0 (V / V_0)^{\alpha} (f / f_0)^{\gamma} , Q = Q_0 (V / V_0)^{\beta} (f / f_0)^{\delta}$$

The load representation is sometimes called as “exponential load”, is a kind of static load model, and is generally adopted in Japan. In local system analysis frequency sensitivity γ and δ are need not consider. Usually α is set as 1.0 and β is set as 2.0. These are obtained through measurement of small voltage change due to tap change and so on. The static load model will work well in slow voltage collapse analysis.

As to the same example, long term voltage simulation was made and the results are shown in Fig. 4.3. In the example, generally used α = 1.0 resulted ill conversion, therefore α = 1.2 is employed. The ill convergence is rare, but in the example reactance from midway bus to load terminal X_s is taken into account. The reactance is usually neglected in daily work.

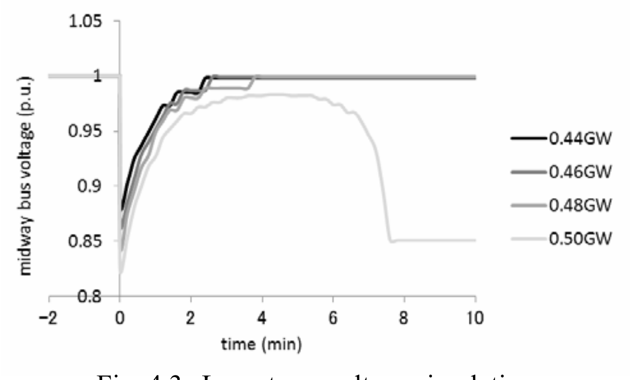

Fig. 4.3　Long term voltage simulation

Stability limit is 0.48GW in load amount. This is slightly larger than N-V analysis result. The first reason of the difference is that load has positive voltage sensitivity (α = 1.2, β = 2.0) although in N-V analysis the sensitivity is not given. By the sensitivity, lower voltage slightly reduces load consuming power and system become slightly easier. The second reason is dead band in tap control for avoiding frequent tap change. By the dead band tap does not change by small voltage shortage. By the two reasons, 0.46GW and 0.48GW load cases that were unstable in N-V curve analysis turn to stable in simulation.

In case of 0.50GW load, slow voltage collapse appears. Speed of the phenomenon is minutes order. Therefore it is called as slow. Although named as collapse, voltage does not drop lower than around 0.85, because tap ratio reaches to its upper limit. If LTC of distribution transformer is considered, voltage will drop further.

Next, limit in which fast voltage collapse does not occur is calculated. Most elegant method is P-V curve. Load is classified into IM and CZ as shown in Fig. 4.1. Relationship between IM terminal voltage and IM consumption power is calculated. Results about the same example are shown in Fig. 4.4. Vertical lines in the figure mean IM mechanical loads, which are independent from voltage. If P-V curve and load line have cross points, they are equilibriums. There are two equilibriums if exist. One with higher voltage is called as “high voltage equilibrium” and the other as “low voltage equilibrium”.

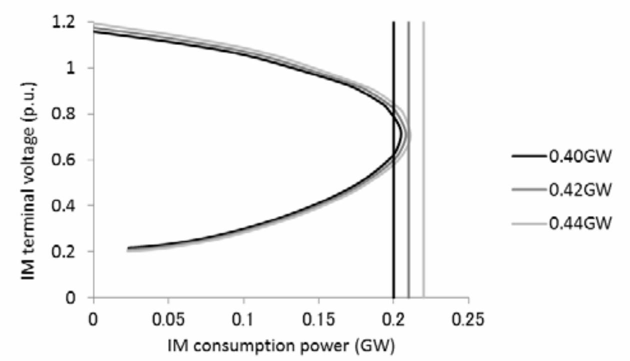

Fig. 4.4　Load voltage stability shown by P-V curve

The example assumes that 50% of load power is consumed by IM. Since 0.40GW load case has two equilibriums, it is stable. 0.42 GW case has no equilibriums. That means unstable. IM decrease internal resistance so that it can draw much power from system and fulfill demand of mechanical load, but fails. IM further decrease resistance, and fails. At last IM voltage becomes very low, and rotating speed is very slow then. This is so called stall. The example shows poorer stability than N-V curve and long term simulation, because internal reactance X_m is taken into account.

Explanation above is going beyond information that P-V curve can give, and is compensated by knowledge of electric engineering about IM mechanism. Since those who are not experts in the field will not able to imagine, the author will make deeper explanation.

IM's mechanical load torque T_m is expressed as proportional to n times powered rotating speed ω as shown as follows. In most cases n is 2. Here, T_{m1} is the mechanical load torque at synchronous speed (ω = = 1). Usually IM rotates at slightly slower speed than synchronous speed.

$$T_m = T_{m1}\ \omega^n$$

IM's internal resistance R_m varies by speed ω as follows. This is the knowledge by electric engineering. Here, R_{m0} means the internal resistance at rated speed ω_0 .

$$R_m (1 - \omega) = R_{m0} (1 - \omega_0)$$

Thus, IM's internal resistance R_m is obtained. Therefore, electric input power that flows from system to IM can be calculated. Excessive torque deducting T_m from T_e is used to accelerate IM rotating speed. IM's inertia M_m prevents the speed up. Thus, the mechanism is expressed as follows.

$$M_m\, d\omega = T_e - T_m$$

To solve the equation strictly some simulation methods must be employed. However, considerable results are obtained without simulation. Relation between IM's acceleration torque and speed tell much as shown in Fig. 4.5.

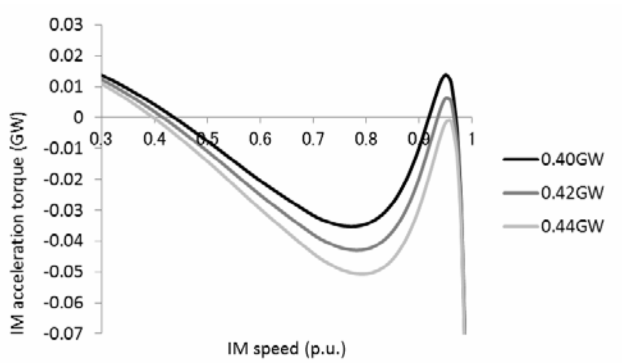

Fig. 4.5 IM's acceleration torque and speed

In cases of 0.49GW load and 0.42GW load, three equilibriums at which acceleration torque becomes zero exist. Among them, one at the center is unstable equilibrium, which is sometimes called as saddle point, and at which slight speed up will bring positive acceleration torque and further speed up. On the contrary, the other two at the edge are stable equilibrium. One at right means normal operation. The other at left means stall. In cases of 0.40GW load and 0.42GW load, equilibriums indicating normal operation exist and are stable. In case of 0.44GW load, two equilibriums indicating normal operation and addle point vanish away, and only one equilibrium indicating stall remains. In such condition, however initial condition is, IM goes to stall. This is instability of IM load itself, that is, fast voltage collapse.

The phenomenon can be performed by short term simulation. Although it is usually used for synchronous and oscillatory stability of synchronous generator, it also prepares IM load model, and as the result, it can also perform fast voltage collapse. CRIEPI Y-method is a typical tool. The results are sown in Fig. 4.6. In cases of o.40GW load and 0.42GW load, voltage considerably drops due to stop of one circuit, but does not drop so much as called collapse. However in case of 0.44GW load, voltage becomes extraordinary low. It means extraordinary low rotating speed, that is, stall. Since the phenomenon proceeds fast in seconds order, it is called as “fast voltage collapse”. Simulation results just agree with torque-speed analysis.

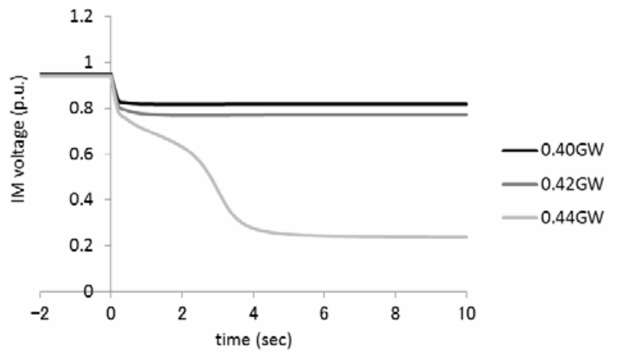

Fig. 4.6 Short term simulation

Using the same local pure load power system data, two kinds of slow voltage collapse analyses (dark gray) and three kinds of fast voltage collapse (light gray) analyses were performed, and summarized and compared in Fig. 4.7 in maximum stable load, which is smaller in fast voltage collapse. In Japan, slow voltage collapse is sometimes analyzed, but fast voltage collapse is very rarely. However, since IM 50% or more power is consumed by IM, it is not slow voltage collapse due to tap operation but fast voltage collapse due to IM stall. If a phenomenon seems to be a slow voltage collapse, it will be IM that triggers the instability.

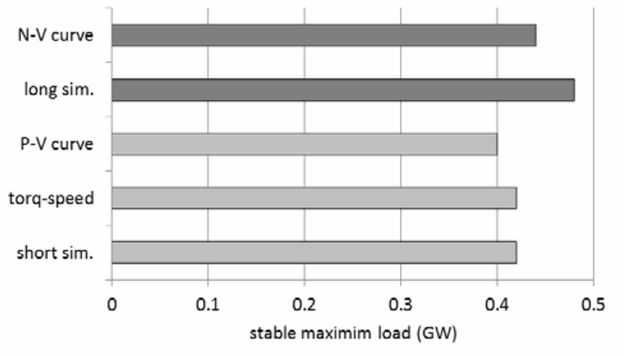

Fig. 4.7 Stability limits by various analyses

Voltage Stability with Voltage Sag (Transient Voltage Stability)

Up to here 1 circuit stop on 2-cicuit transmission line is assumed. In the section it is assumed that the 1 circuit stop is caused by 3-phase-to-groung fault on the circuit. By 3-phase-to ground fault, voltage sometimes drops to nearly zero. Then, IM in load cannot receive power from system at all. But, mechanical load consumes certain power. IM solves the inconsistency by supplying its rotating energy to mechanical load. For example it is assumed that mechanical load is 50% of IM capacity, that inertia of IM is 0.5 sec, and that 100% depth sag lasts for 0.1 sec. Then, IM will decelerate due to the sag as follows.

$$\frac{0.1\text{sec}}{0.5\text{sec}/50\%} = 10\%$$

If rotating speed was 0.977 (p.u. at synchronous speed base) before sag, it decreases to 0.877 at the instance of fault clear. The speed down makes stability of IM load itself worse. Usually stop of circuit of transmission accompanies some fault, and practical stable maximum load must be smaller than that without fault.

At first, torque-speed curve is taken about the same local system model. It is assumed that IM's rotating speed is 0.877 at just after fault. IM will recover to normal operation, if acceleration torque at 0.877-speed is positive. IM will stall if the torque is negative. Calculation results are shown in Fig. 4.8. In cases of 0.32GW load and 0.34GW load, the torque is positive and the IM load is stable. In case of 0.36GW, the torque is slightly negative and the IM load is unstable. As result, stable maximum load becomes considerably smaller by considering voltage sag due to fault.

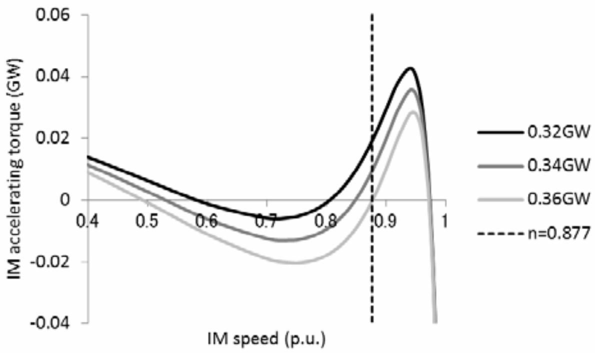

Fig. 4.8 Torque-speed curve

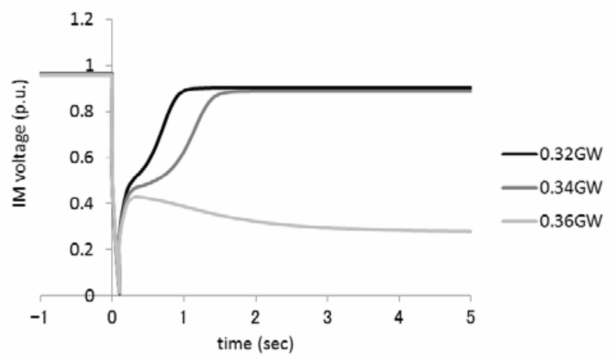

Fig. 4.9 Short term simulation (IM, Y-con)

In the same example, short term simulation is made. The results are shown in Fig. 4.9. In case of 0.32GW load and 0.34GW load, IM voltage recovers. In case of 0.36GW case, IM cannot recover its voltage and goes to stall. Stable maximum load is just same of the result of torque-speed analysis.

Analyses results will be different if system models are different. As system model, cases as follow are considered. Number of cases is 2 by to equal 4.

Load: IM load vs. Static load

Aggregation: Y-connection vs. traditional

Combination of IM load and Y-connection is already shown in Fig. 4.9. The other 3 cases are shown in Fig.4.10 to 4.12. In case of static load and y-connection, stable maximum load becomes very large as 0.48GW. In case of IM load and traditional aggregation, the limit also becomes very large as 0.46GW. In case of static load and traditional aggregation, the limit becomes further large as 0.64GW and exceeds limit by tap operation stability. Of course, only IM load and Y-connection is truth, and the other three are false, which show quite good voltage stability and quite overlooking. Their optimistic assessment must be doubted seriously.

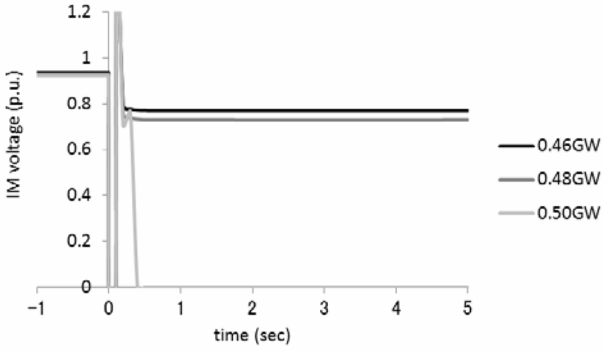

Fig. 4.10 Short term simulation (Stat, Y-con)

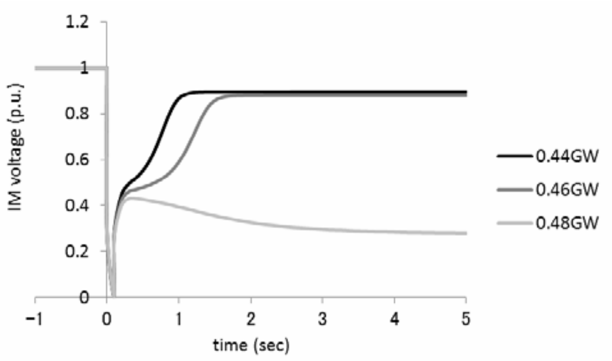

Fig. 4.11 Short term simulation (IM, Trad)

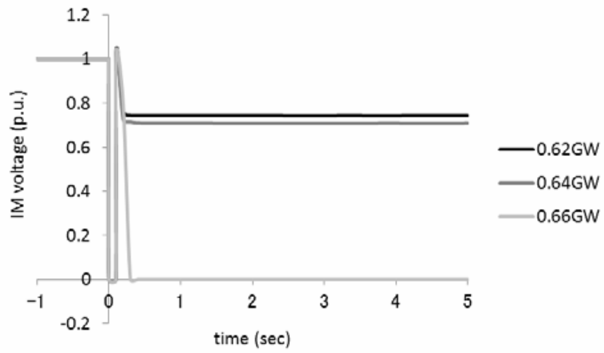

Fig. 4.12 Short term simulation (Stat, Trad)

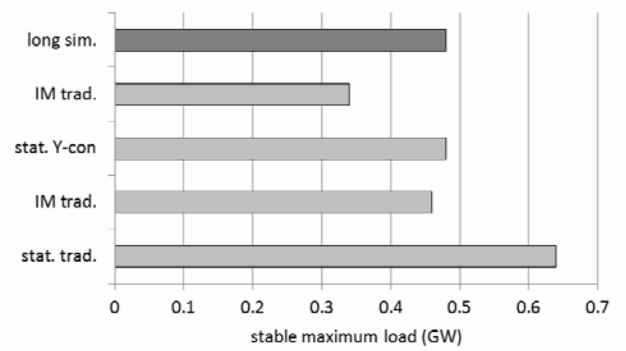

Fig. 4.13 Voltage stability limit by system model

Voltage stability limits assessed by stable maximum load are quite different by power system model as shown in Fig.4.13, with limit by slow voltage collapse (by long term simulation) as contrast. Limit load amount by voltage stability with voltage sag will be wrongly assessed as almost equal to limit by slow voltage collapse without voltage sag, if static load model or traditional aggregation is used. For correct assessment, IM load model and Y-connection aggregation are indispensable. However, since those correct methods are not employed in Japan even now, risk of voltage stability with voltage sag (transient voltage stability) has been overlooked for a long time.

Another factor may affects to transient voltage stability. It is the fact that almost 30% load may drop by sufficiently deep voltage sag by chapter 2. It is not IM but CZ that drops due to sag. If some part of CZ loads drops, perhaps IM stall can be avoided in some cases.

By voltage sag 60% of CZ load (it is 30% of total load because IM ratio is 50%) are assumed to drop. Then, torque-speed curves are calculated as Fig. 4.14. IM rotating speed is assumed to decrease to 0.877 just after sag. In cases of 0.38GW load and 0.40GW load, acceleration torque at the speed is positive and the load is stable. In case of 0.42GW load case, the torque is negative and the load is unstable. Stable maximum load becomes considerably larger than without considering partial load drop.

Results of short term simulation are shown in Fig. 4.15. In case of 0.40GW load or less, IM voltage recovers to normal. In case of 0.42GW load, IM goes to stall. The results just agree with the results of torque-speed curve analysis.

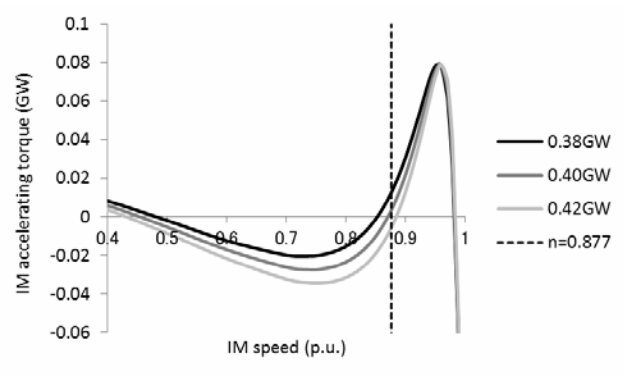

Fig. 4.14 Acceleration torque with partial load drop

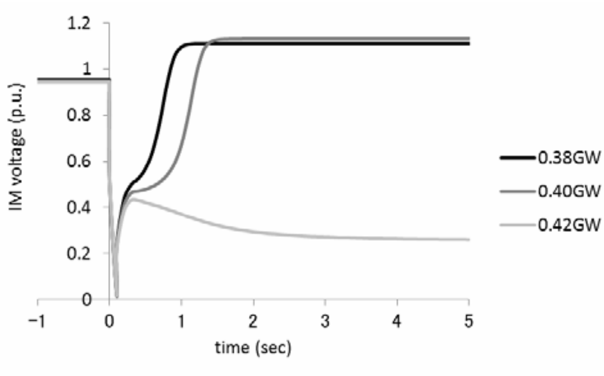

Fig. 4.15 Short term simulation with partial load drop

If these phenomena are solved by P-V curve analyses, the results will become as shown in Fig. 4.16. All cases show quite stable results, but they are not true. From the beginning, P-V curve is a method that cannot handle IM deceleration due to voltage sag and cannot assess whether IM can recover or not. Although it is certainly true that P-V curve is one of excellent analysis methods, it is not true P-V curve can explain everything as to voltage stability.

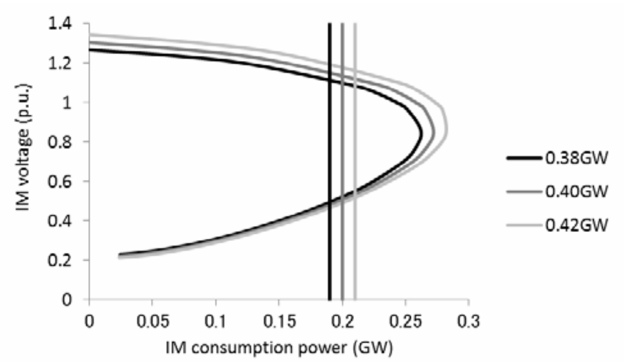

Fig. 4.16 P-V curve with partial load drop

Thus, voltage stability on local pure load system is analyzed by various approaches. Voltage stability limit by load amount through four approaches are compared in fig. 4.17. Stability limit by slow voltage collapse was 0.48GW. That by fast voltage collapse without voltage sag was reduced to 0.42GW. That with voltage sag is further much reduced to 0.34GW. 10% rotation speed down of IM due to voltage made voltage stability very much. By considering 30% load drop due to voltage sag, the stability limit recovered to 0.40GW.

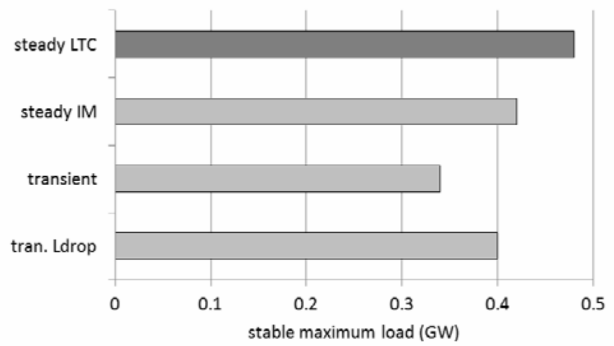

Fig. 4.17 Summary of voltage stability in local system

Voltage Stability as Affected by RE Design

Thus finally, conditions for correct calculation of voltage stability have been realized, and impacts of highly penetrated RE onto power system have become possible. As design of RE, three types as follows 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.

Dynamic characters of RE that never shuts down due to voltage sag are expresses as follows here as negative load having voltage sensitivity.

$$G_{RE} = G_{RE0},$$
$$B_{RE} = Y_{RE0}\ \{(Vc / Vc_0)^2 - (Vc / Vc_0)^{2+K}\ \}$$

As to active power, conductance G_{RE} is assumed as constant. Of course, constant current and constant power character are also possible. However, there is certainly some difficulty to be constant power even if voltage sag is deep. On the contrary, constant conductance control has no difficulty in any cases.

Reactive power is assumed as susceptance varying by voltage. Y_{RE0} means admittance at rated output. Vc is RE voltage and Vc_0 is its initial value. Resulted reactive power is shown in Fig. 4.18. $K = 0$ means FRT type. Reactive power is always zero. In DAV type, K is larger than 0, and by larger K voltage support capability is highly demonstrated. However, K is set as 5 to10 so that excessive reactive power does not generated by small voltage deviation. To say the truth, the DVS design does not thoroughly use current capacity of PCS (Power Conditioning System). Of course thorough and more effective design is possible. However, the author intends to show that such slight DVS has dramatic positive effect.

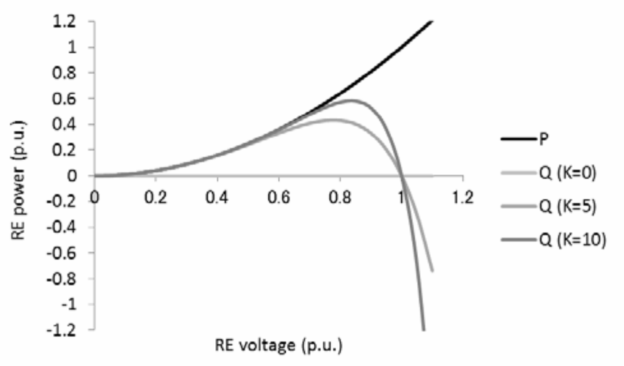

Fig. 4.18 Power-voltage character of DVS type RE

RE is connected to load terminal in parallel considering photovoltaic (PV) that are expected to much penetrate to low voltage residential customers. RE output is assumed as 20% of load power. Load is assumed as 50% IM and 50% CZ mixture. A 3LG-O fault on two-circuit transmission line is assumed. Fault clear time is set as 0.1 sec. 30% of load (60% of CZ load) is assumed to drop due to voltage sag caused by the fault. Result in case of no RE is already shown as Fig. 4.14 and 4.15.

Short term simulation results with 20% RE of drop type, FRT type, and DVS type are shown in Fig. 4.19, 4.20, and 4.21. Since it can be highly hoped that results of torque-speed analysis and simulation agree very well, only the latter is shown here.

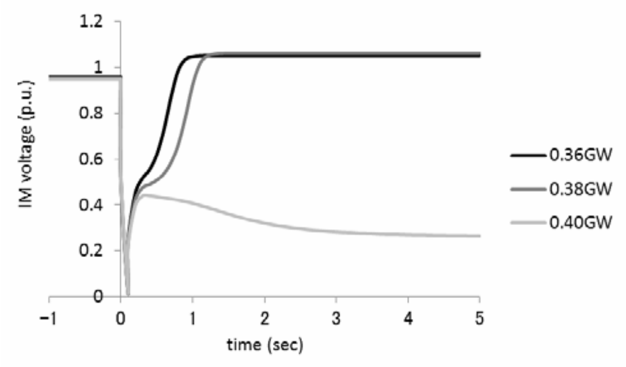

Fig. 4.19 Short term simulation (drop-RE)

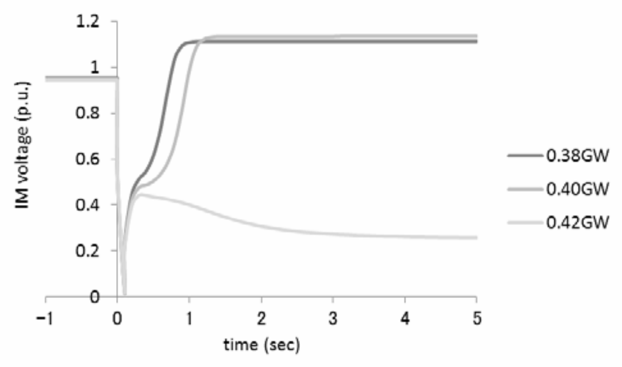

Fig. 4.20 Short term simulation (FRT-RE)

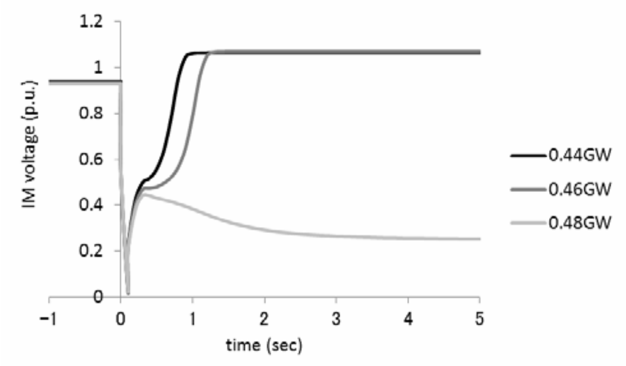

Fig. 4.21 Short term simulation (DVS-RE)

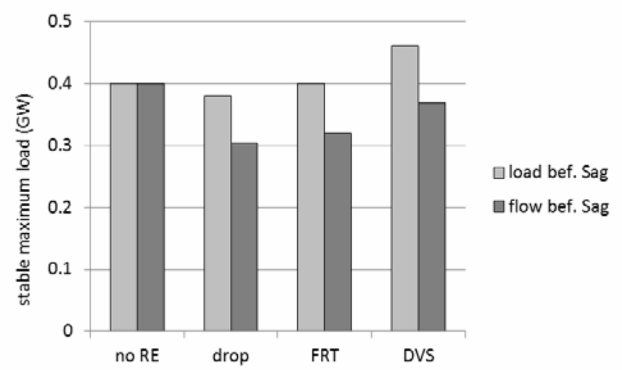

Fig. 4.22 Voltage stability limit by RE design

Results of assessing voltage stability limit by “load amount before sag” and “downward power flow before sag” are shown in Fig. 4.22. From “load amount” viewpoint, DVS type RE case seems superior to no RE case. However from “power flow” viewpoint, even DVS type RE case is inferior to no RE case. The results tells that cost cut effect on transmission equipments by RE cannot evaluate in full mark even in DVS type RE is adopted.

Examples of Trunk System

Above here, a pure load local system of primary substation fed by a 154kV two-circuit transmission line as the studied system. Because, the author thought that the example is suitable for understanding wide area issue such as voltage stability. Analyses and simulations are easily re-performed by readers. It is also understood that unexpected truths exist but are not well known. However, the last target is voltage stability in trunk system. By realistic modeling, it was found that voltage stability problems do exist in existing power system in Japan. Here, two examples among them are introduced.

[Small Trunk System] Structure of the studied system is shown in Fig. 4.23. The system interconnects to outer system through three points, and receives much

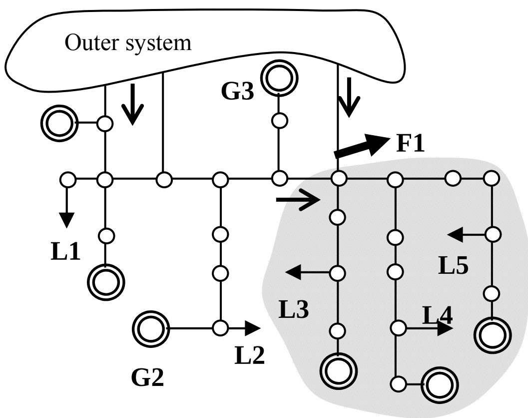

Fig. 4.23 Structure of the small system

power from outer system. Two-circuit tie line at right side is assumed to stop due to two-circuit 6LG-O fault. Fault clear time is set as 0.07 sec. Load are assumed as 50% IM and 50% CZ mixture. Load drop ratio is decided by sag depth of each load. Voltage stability of the area with gray background becomes ill, because a long and thin radial structure results by the fault.

Simulation results by system modeling are shown in Fig. 4.24, 4.25, and 4.26. In case of traditional aggregation without load drop (Fig. 4.24), voltages of all loads recover very fast, and no sign of voltage collapse are seen at all. In case of Y-connection without load drop (Fig. 4.25), load L3 and L5 go to voltage collapse. In case of Y-connection with load drop (Fig. 4.26), all loads recover fast, but voltage after sag rises considerably due to load drop. If voltage exceeds 120%, saturate in transformers begins, and as the results, harmonics, damage in capacitors, and mal-operation of relays are become anxious. The example does not show such harmful overvoltage, but it must be noticed that accuracy of power system model much affects simulation results.

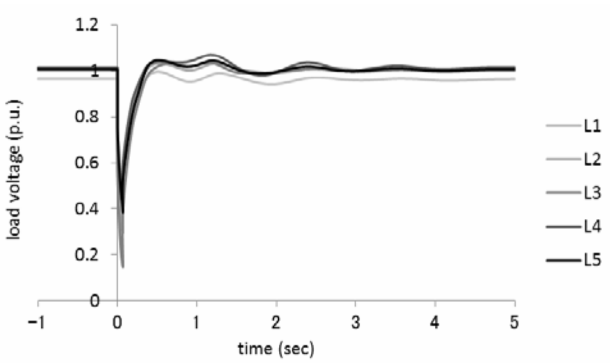

Fig. 4.24 Traditional aggregation w/o load drop

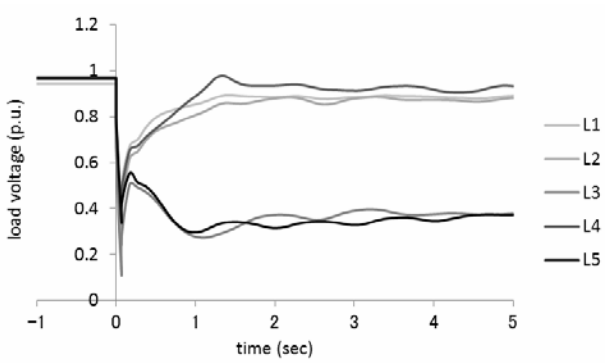

Fig. 4.25 Y-connection aggregation w/o load drop

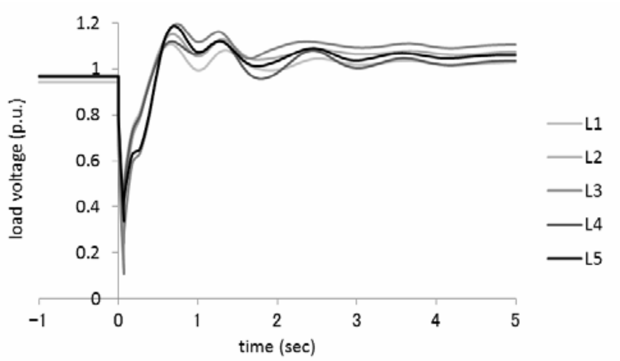

Fig. 4.26 Y-connection aggregation with load drop

Into the system RE penetrates at 20% of load. Some thermal generator stops because of demand supply balance. Partial load drop due to voltage sag is considered. Simulation results without RE is already shown in Fig. 4.26. For three design RE, simulations are performed and the results are shown in Fig. 4.27, 4.28 , and 4.29. In case of drop type RE (Fig. 4.27), not only three loads with poor voltage stability in the area with gray background but also two loads outside of the area go to voltage collapse. In case of FRT type RE (Fig. 4.28), all loads recover but slowly, and voltage after recovery becomes considerably higher. In case of DVS type RE (Fig. 4.29), load voltage recovers rapidly and over voltage after recovery is considerably mitigated.

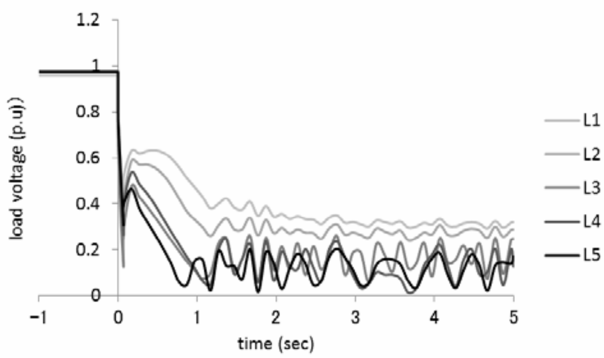

Fig. 4.27 Voltage stability with drop type RE

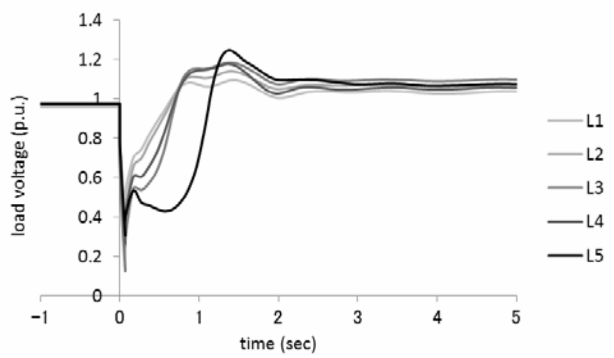

Fig. 4.28 Voltage stability with FRT type RE

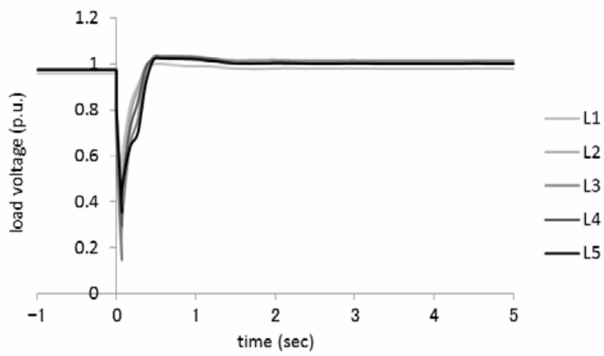

Fig. 4.29 Voltage stability with DVS type RE

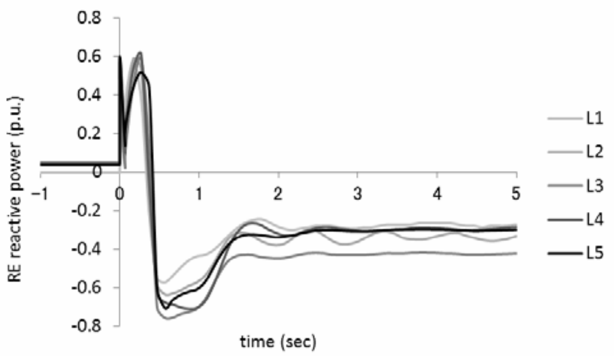

Fig. 4.30 Reactive power variation of DVS type RE

As shown in Fig. 4.30, DVS type REs supply reactive power during system voltage is low soon after fault clear and support voltage recovery (until 0.4 sec), and absorb reactive power after recovery and mitigate over voltage (after 0.4 sec). The reactive power absorbing operation causes DVS type RE slight over current. However, capacitors are switch off, reactors are switched in, and taps change so that voltage are mitigated, and as the result, over current of RE will be solved in a short time.

As stated above, DVS type RE is special effective countermeasure for preventing fast voltage collapse. That is said to be as a matter of course, because reactive power-voltage character of DVS type RE is quite like that of SVC, which is generally known as special countermeasure for voltage stability. That is, DVS type RE is a generator including SVC function. Since the RE can perform two main roles simultaneously as one machine, it will be economic. Many REs and most PVs employ IGBT (Insulated Gate Bipolar Transistor) for interconnecting to power system, and IGBTs have ability that enables DVS. In today, most PCSs do not use the ability. It seems regretful.

[Large Interconnection] Next, a gigantic large power system is taken as example. Its structure is shown in Fig. 4.31. The system interconnects to another small power system, which hardly affects voltage stability of the studied system. The system itself is said to be an interconnection. One circuit of two-circuit transmission line is assumed to stop due to 3LG fault at F1. Fault duration time is set as 0.07 sec. Loads are represented by 50% IM and 50% CZ. Partial load drop is considered, but cases without the consideration are included as contrast cases. Load drop ratio is set by sag depth at the load.

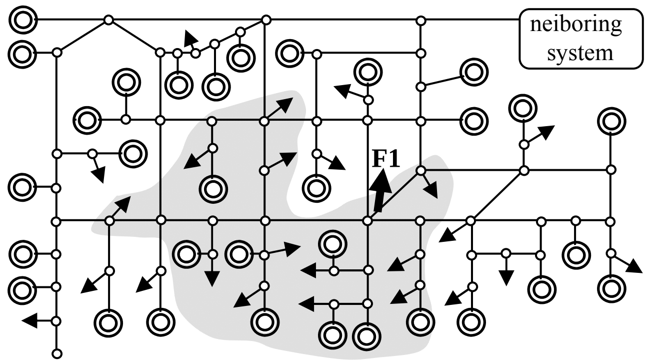

Fig. 4.31 Structure of the large system

The part with gray background has only small amount of generators, receives much power from the other parts surrounding it, and as the result, has poor voltage support capability. Voltage collapse may occur. F1 is a main route for importing power to the part. A not so serious fault such as 3LG-O may bring serious phenomena.

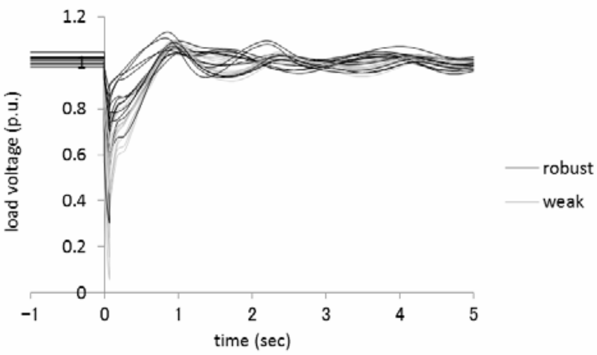

Fig. 4.32 Traditional aggregation w/o load drop

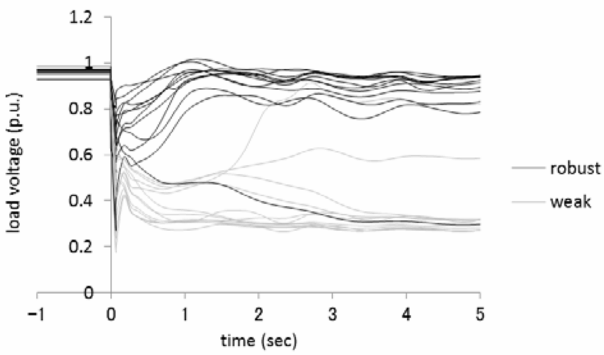

Fig. 4.33 Y-connection aggregation w/o load drop

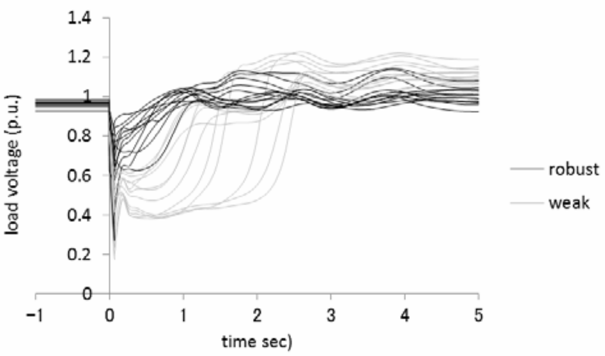

Fig. 4.34 Y-connection aggregation with load drop

Simulation results by system modeling are shown in Fig. 4.32, 4.33, and 4.44. Gray lined indicate voltage profiles of weak loads included gray back grounded part. The others are robust loads and drawn in black lines. In case of traditional aggregation without partial load drop (Fig. 4.32), all loads recover within 1 sec. In case of Y-connection aggregation without load drop (Fig. 4.33), most weak loads go to voltage collapse. In case of Y-connection with load drop (Fig. 4.34), All loads recover but at most 2.5 sec is needed for the recovery. Since ordinary compensation time of commercial voltage sag compensator is 1 sec, the long recovery time may be troublesome. Over voltage after recovery is not large.

There, three kinds of RE introduced above is penetrated by 20% of load amount. For demand supply balance, some thermal generators stop. Partial load drop due to voltage sag is considered. Simulation results in case of no RE are already shown in Fig. 4.34. Simulation results with RE are shown in Fig. 4.35, 4.36, and 4.37. In case of drop type RE (Fig. 4.35), not only all weak loads but also a few robust loads go to voltage collapse. In case of FRT type RE (Fig. 4.36), not only all weal loads but also one robust load go to voltage collapse. In case of DVS type RE (Fig. 4.37), all loads recover within 1 sec, and voltage stability becomes better than no RE case. No significant over voltages after recovery are seen in the three cases.

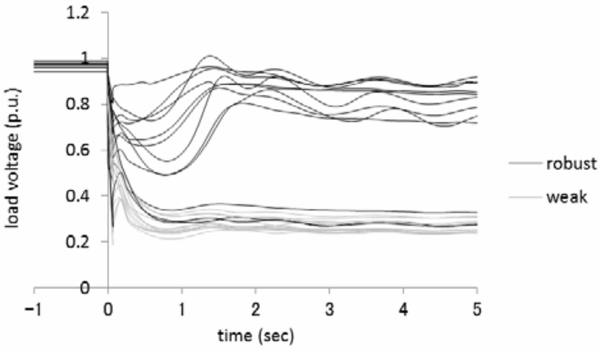

Fig. 4.35 Voltage stability with drop type RE

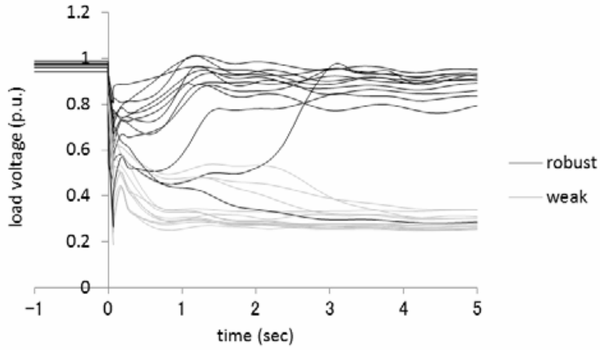

Fig. 4.36 Voltage stability with FRT type RE

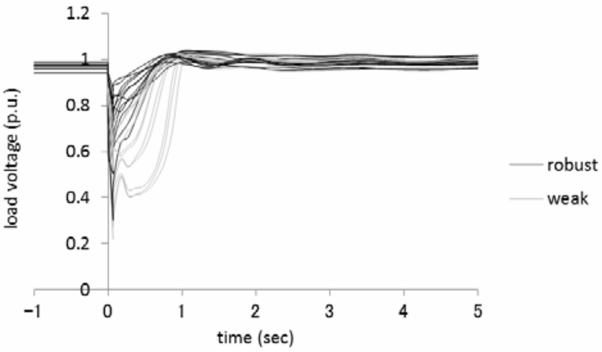

Fig. 4.37 Voltage stability with DVS type RE

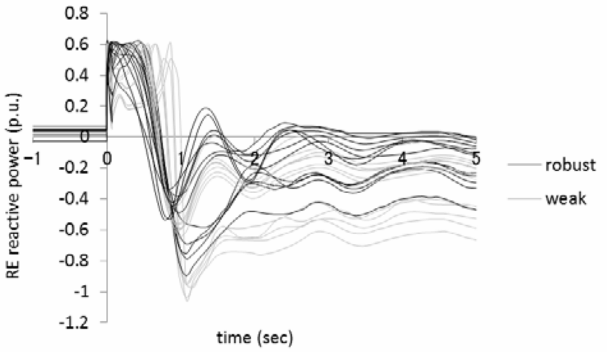

Fig. 4.38 Reactive power variation of DVS type RE

As shown in Fig. 4.38, DVS type REs supply reactive power during system voltage is low soon after fault clear and support voltage recovery (until 1 sec), and absorb reactive power after recovery and mitigate over voltage (after 1 sec). The reactive power absorbing operation causes DVS type RE slight over current. However, capacitors are switch off, reactors are switched in, and taps change so that voltage are mitigated, and as the result, over current of RE will be solved in a short time.

The example of large trunk system shows the same tendencies of the small trunk system already introduced. But from the beginning voltage stability is ill, therefore, difference by power system model and difference by RE design appears largely.

Possibility of Voltage Collapse

Voltage collapse without fault (voltage sag) is really happened in 1987. Another collapse may occur again unless sufficient reactive power reserve such as capacitor, rotary condenser, and so on. Since 20 years passed after the collapse, considerable amount of small aged thermal generator near loads were put away, and power system has become stand on severe condition about voltage stability. As to the fast voltage collapse, comment will be made at the end of chapter 5 with possibility of transient synchronous instability.

The Reason Why P-V Curve Is Inadequate for Transient Voltage Stability Analysis

Since used in analyses of west Kanto blackout in 1987 successfully, P-V curve has been considered as a reliable tool for voltage stability analyses. However, the P-V curve seems not be able to well explain “transient voltage stability” that deals stall phenomenon of induction motor load.

[Classic: Torque-Speed Curve] Power-angle curve (P-δ curve) is generally has been used in analyses of synchronous generator’s instability (asynchronism, step out) of synchronous generator. An example is shown in Fig. 4.39. Point A is a stable equilibrium meaning normal operation. Point B is an unstable equilibrium. If generator angle exceeds point B during disturbance, angle will exceed and exceed, and go to asynchronism.

In analyses of motor’s stall, torque-speed curve is used instead of power-angle curve in synchronous generator. Ref (3), (4) may be the first introduction of torque-speed curve in Japan.

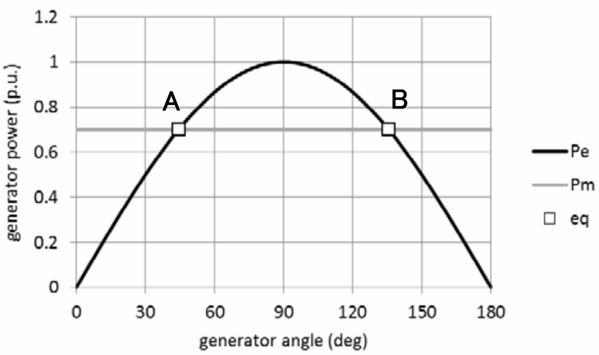

Fig. 4.39 Power-angle curve（P-δ curve）

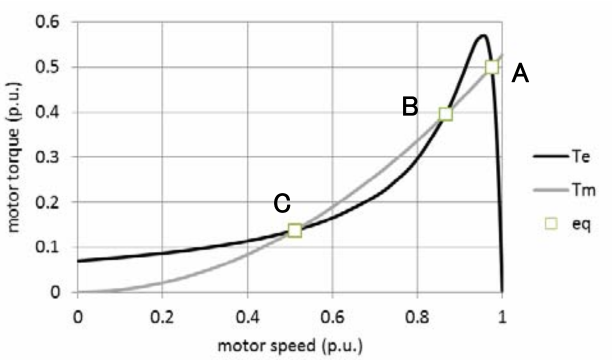

Fig. 4.40 Torque-speed curve（T-ω curve）

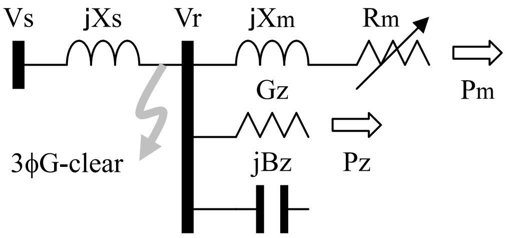

Fig. 4.41 Model structure used in the analysis

Table 4.1 Parameters used in the analysis

Vs	Xs	Vr	Xm	Pm	Rm	ω
1.06	0.725	1.0	0.2	0.5	1.979796	0.975
Gz	Bz	Pz	Wm	Mm	Lm	
0.5	0.363216	0.5	1.0	0.5sec	0.5	

An example of motor’s torque-speed curve is shown in Fig. 4.40. Model structure and parameters used in the analysis are shown in Fig. 4.41 and Table 4.1 respectively. For simple, resistance of system impedance and primary winding of motor and its main magnetic flux are neglected. The model is so called slip model. Motor’s rated capacity Wm is 1.0, load factor (Lm = power kW/rated kVA) is 0.5, and unit inertia constant is 0.5 sec at rated capacity base.

Under those parameters, three equilibriums at which electric torque Te is equal to mechanical torque Tm appear in torque-speed curve. Point A and B are stable. Point B is unstable. Slight speed-down from point B will bring Te < Tm, and motor cannot return to point A but will further decelerates toward point C meaning stall. In another condition, point B and C may disappear. In such cases, stall phenomenon never appears.

A 3ϕG (three-phase-to ground) - 0.1sec- clear fault via fault reactance Xf is assumed at load side of system reactance Xs. In the case, speed at point B is 0.8661. Since Xf = 0 brings around 10% speed-down from 0.975 at point A, condition just after fault clear locates a little right side of point B. Motor is stable. However in simulation, voltage stability becomes worse due to recovery of main flux. Stability of the motor will be critical or slightly unstable. If Xf = 0.1 or so, speed-down is smaller, and motor will recover toward point A.

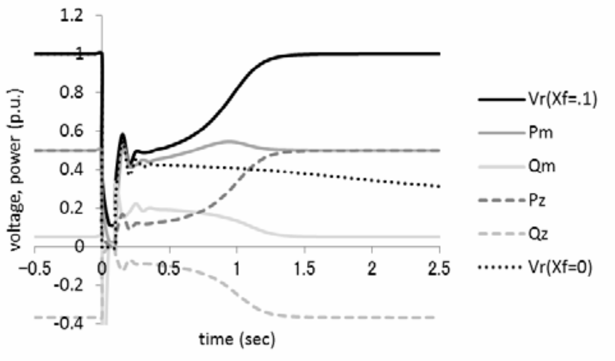

Fig. 4.42 Simulation result

To verify the theory above, a simulation is made. The result is shown in Fig. 4.42. In case of Xf =0, after fault clear, voltage continue to decrease very slowly, that is, the system is slightly unstable than critical. In case of Xf = 0, voltage recovers in around 1.0 sec. Simulation result well agree with analysis above.

Thus, torque-speed curve can explain motor's stall very well, like power-angle curve can explain generator's asynchronism very well. However in Japan, torque-speed curve is not generally used but P-V curve as follows is used for explaining motor's stall.

[Modern: P-V Curve] By plotting power and voltage on P-V plane by varying motor speed ω from almost 0 to almost 1, P-V curve can be drawn. The curve corresponds to electric torque in torque-speed curve.

Motor's secondary input is equal to electric torque. Mechanical power is calculated by subtracting secondary winding's Joule loss from the torque. Since primary winding resistance is neglected, motor input power is equal to electric torque.

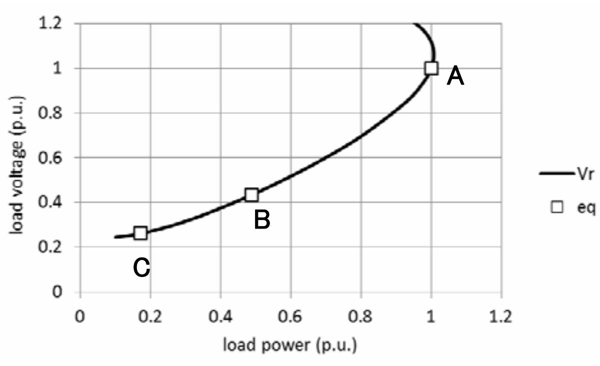

Fig. 4.43 P-V curve for load power

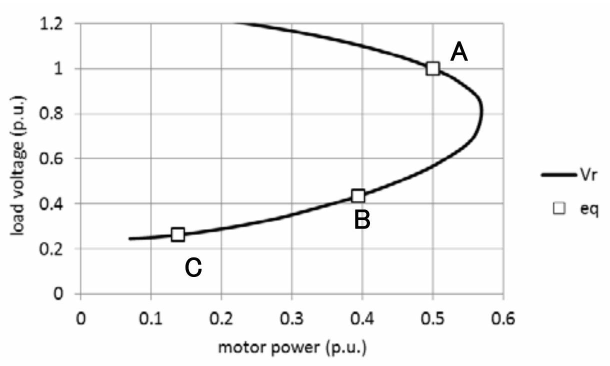

Fig. 4.44 P-V curve for motor power

Using the same parameter, P-V curves are drawn as Fig. 4.43 (for load power) and Fig. 4.44 (for motor power). The three equilibriums locate on those P-V curves. The two figures are considerably different each other. Point A meaning normal operation locates at lower half of P-V curve for load power. On the contrary, point A locates at upper half of P-V curve for motor power.

When voltage decreases, constant impedance load's power will decrease significantly. As the result, motor power will decrease very little. Therefore, it is reasonable that P-V curve for motor power shoes more optimistic result. Also in Simulation result, constant impedance load's power (P_z) significantly decreases just after fault clear. On the contrary, motor power (P_m) does not decrease much or slightly increases from initial condition. Of course, the increase brings speed recovery. Therefore, it can be said that P-V curve for motor power hits the nail-head better.

Now then, how can we distinguish stable/unstable using P-V curve? It is certain that point on upper half of P-V curve means stable. However, point on lower half of P-V curve does not always mean unstable, because voltage unstable never appear on constant impedance load. To distinguish stable/unstable, something indicating load's character considering motor, such as mechanical torque in torque-speed curve.

As a solution Ref. (5) proposed "constant slip curve" the can be drawn on P-V plane by fixing motor speed (slip) constant. In such condition motor becomes to mare constant impedance load, and a parabolic curve is drawn on P-V plane. "Constant slip curves" crossing the three equilibriums can be drawn as Fig. 4.45 for load power and as Fig. 4.46 for motor power.

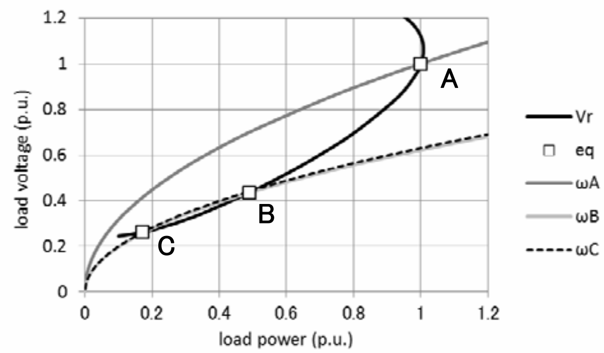

Fig. 4.45 Constant slip curves for load power

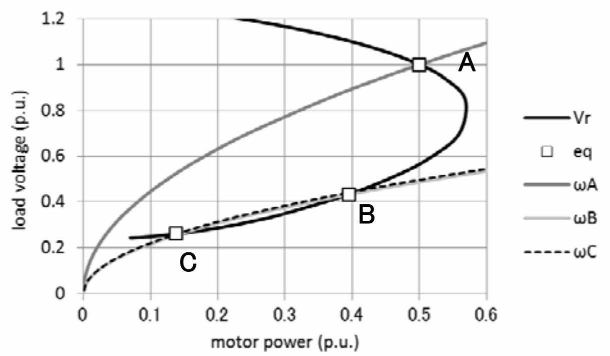

Fig. 4.46 Constant slip curves for motor power

In both figures, "constant slip curves" cross the two stable equilibriums A and C from left below to right high, and crosses the unstable equilibrium B from left high to right below. But the meaning is not clear now.

The "constant slip curve" is also introduced in Ref. (6) as "load character curve", which is criticized in Ref. (6). In stable cases, the point indicating just after fault clear moves toward higher voltage. On the contrary in unstable cases, the point moves toward lower voltage. Ref. (6) criticizes that the difference cannot be explained by P-V curve and "load character curve (constant slip curve)" only.

The author support Ref. (6) as follows. A small deceleration from point B on lower half of P-V curve will certainly make electric power smaller. However, the deceleration also makes mechanical torque smaller. Whether acceleration torque ($T_e - T_m$) becomes positive or negative is highly dependent to mechanical torque's speed sensitivity. Since "constant slip curve" never refer mechanical torque's speed sensitivity, criticism by Ref. (6) can be said as adequate.

As another solution, Ref. (6) proposes "stability boundary curve", which can be drawn on P-V plane by calculating motor speed ω that makes electric torque and mechanical torque equal for various fixed load voltage. Ref (6) calls right side of the curve as “stable”. However, the author will amend that the right side means “accelerate”.

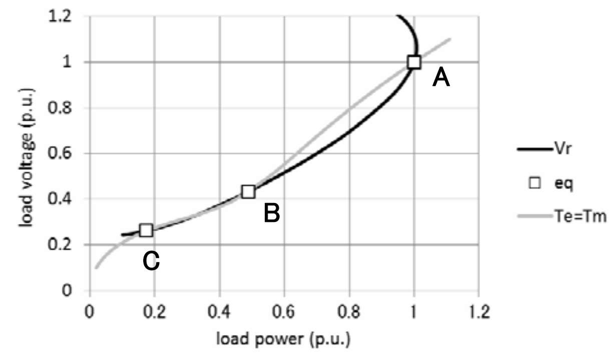

Fig. 4.47 Stability boundary curve for load power

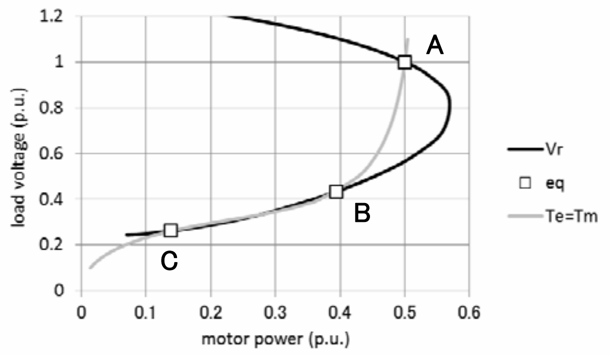

Fig. 4.48 Stability boundary curve for motor power

Using the same parameter of torque-speed curve, “stability boundary curves” are drawn as Fig. 4.47 for load power and as Fig. 4.48 for motor power. It is obvious that motor accelerates between point A and B. However, “stability boundary curve” lies almost on P-V curve itself at left side of point B, where accurate stable/unstable distinguish is hardly possible. Cause of the difficulty lies in assumption of “stability boundary curve” itself. Although mechanical torque T_m becomes equal to electric torque T_e at only three equilibrium: A, B, C, the curve assumes $T_m = T_e$ at any voltage (i.e. speed). It is illogical. Thus, “stability boundary curve” is also inadequate for explaining motor’s stall phenomenon.

[Answer: Torque-Speed Curve Is Transformed to P-V Curve] P-V curve has inherent defect that it is not suitable for motor’s transient voltage stability analysis. In spite of the defect, many engineers want to express motor’s instability on P-V curve. For them, the correct method is introduced here.

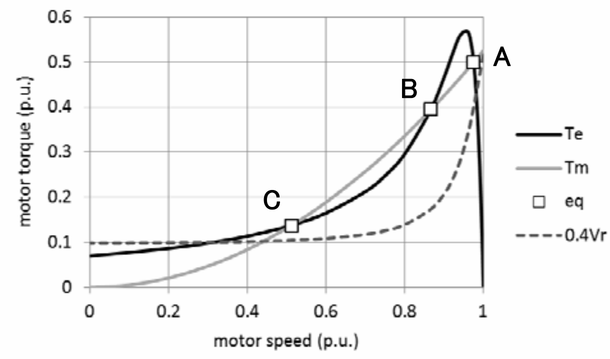

Fig. 4.49 Torque/voltage-speed curve

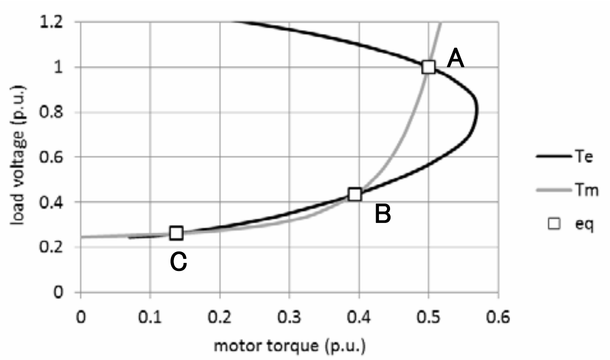

Fig. 4.50 Motor’s torque-voltage curve

Load voltage is drawn on torque-speed curve as Fig. 4.49. (Voltage is reduced by 0.4tymes due to graduation.) Speed is correspondent to voltage one by one, although strong non-linearity is seen. Therefore, voltage can be horizontal axis instead of speed. Then, exchanging vertical axis (torque) and horizontal axis (voltage), motor’s torque-voltage curve can be drawn as Fig, 4.50. A curve is obtained as mechanical torque curve, which is different from “stability boundary curve”. If electric torque T_e exceeds mechanical torque T_m, motor will accelerate and voltage will rise. Therefore, it will be easily understand that points A and C are stable equilibriums and point B is unstable one.

Since motor torque is equal to motor input power if stator resistance is ignored, adding consumption power of paralleled constant impedance load, load’s total power is easily calculated on the P-V plane as Fig.

4.51. Stable equilibriums A and C and unstable one B are distinguished.

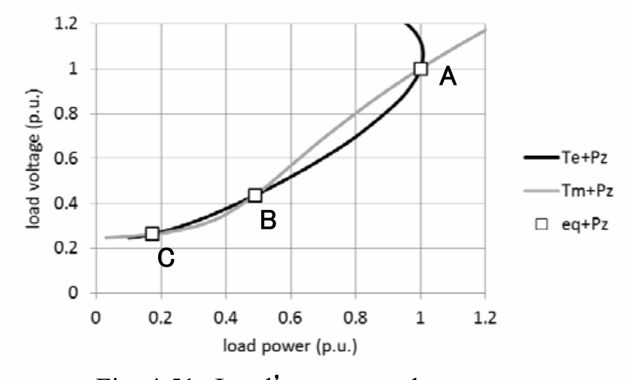

Fig. 4.51 Load's power-voltage curve

Thus, it is possible to induce P-V curve expressing motor's voltage instability from torque-speed curve by force, although the P-V curve not such an obvious meaning as torque-speed curve. However, usefulness of the P-V curve must be said as low, because original torque-speed curve can sufficiently explain motor's voltage instability. It is only taste to adopt P-V curve with additional labor instead of torque-speed curve.

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