7. Transient stability

In AC power system, each generator is to keep phase relationship according to the relevant power flow, i.e. for a certain reactance X, the both terminal voltages V1and V2, and phase angle difference θ, the active power flow P through the reactance is calculated as:

$$P = {V_1 \bullet V_2 \sin\theta}/{X} \tag{7.1}$$

In the previous chapter, such relationships are calculated for some steady state system conditions. By disturbances such as short-circuit, sudden load rejection, switching transmission line, etc. each generator may accelerate/ decelerate due to the probable unbalance between the driving and load torques. The angle θ before shown may swing and such phenomena are called as "Transient stability".
In this chapter the phenomena are explained mainly applying time domain analysis, contrasting with conventional process "Power frequency phasor domain analysis" or "Equi-area method", and also the counter measure to enhance the stability will be explained.

7.1 Classic analysing method -------- Equi-area method

Firstly let's check the conventional phasor domain based classic method "Equi-area method" by cross-checking with time domain analysis ---- ATP-EMTP.

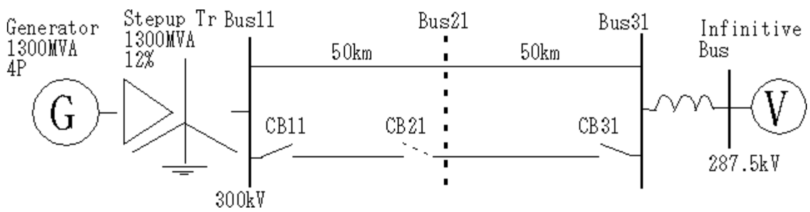


Fig. 7.1 One generator vs. infinitive bus system

Firstly introducing the so called one generator & infinitive bus system shown in Fig. 7.1, the basic phenomena is to be surveyed. For other parameters not shown in the figure, please refer the attached data file(s) of the chapter. Applying equation (7.1), what is to be V_1 as the sending point voltage? This seems to be an imagined inside of the machine voltage and may be changeable one. As shown later, the flux linkage just inside of the armature winding is relatively kept constant during the relevant phenomena, the voltage corresponding to the flux seems to be appropriate as this V_1. Therefore, as the reactance of the machine under the phenomena, the armature winding leakage one seems to be best applicable. For the transmission line reactance, parameters of transposed one are calculated for this time as simple calculation. For details, refer to chapter 3. The transformer's reactance and one in front of the infinitive bus are easily obtained.

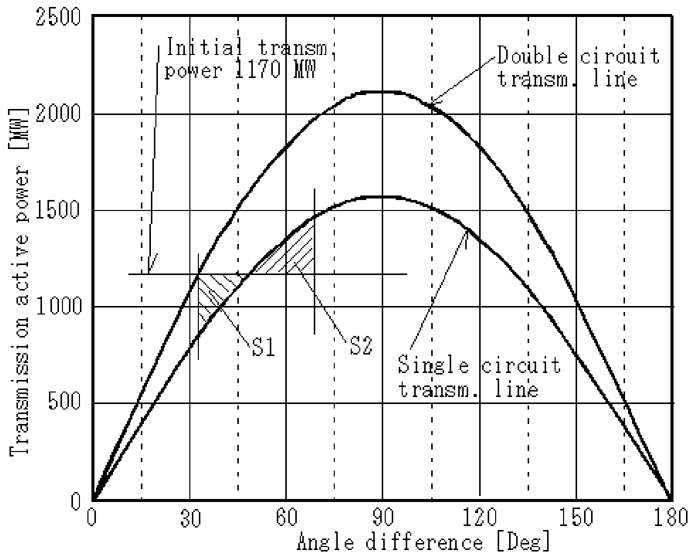


Fig. 7.2 Transmission active power characteristics for single circuited and double circuited line

In Fig. 7.2, transmission active power vs. angle difference, as for single-circuited and double-circuited lines, are shown. As the sending part voltage V_1, 300kV (generator terminal voltage based one) is applied though, quite correctly speaking, the inside voltage is more or less higher than the terminal voltage. As V_2 287.5kV is applied.
For double-circuited line transmitting 1170MW (90% of power factor of 1300MVA), the initial angle of 32.5 degree is calculated. For single-circuited, 48.5 degree is calculated. These values, of cause, agree with Fig. 7.2.
Assuming sudden switching over from double circuited to single one, in Fig. 7.2, as the vertical co-ordinate corresponds to the machine torque and therefore area, i.e. product of torque and angle shift, corresponds to energy, S_1 is excess energy from the turbine up to the steady state point by single-circuited line. Then the generator is accelerated and the angle advances up to the angle $S_1 = S_2$. This is the most simple case of equi-area method. The maximum angle over swing is approx. 69 degree.
Then, let's check these values by applying EMTP (time domain analysis).

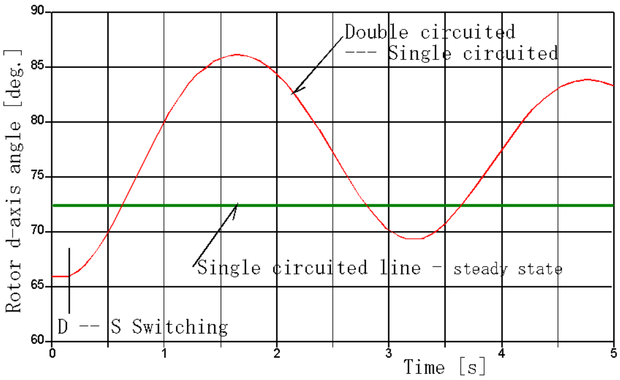


Fig. 7.3 Rotor d-axis position base on infinitive bus voltage angle via star-delta step-up Tr, for 4 pole machine

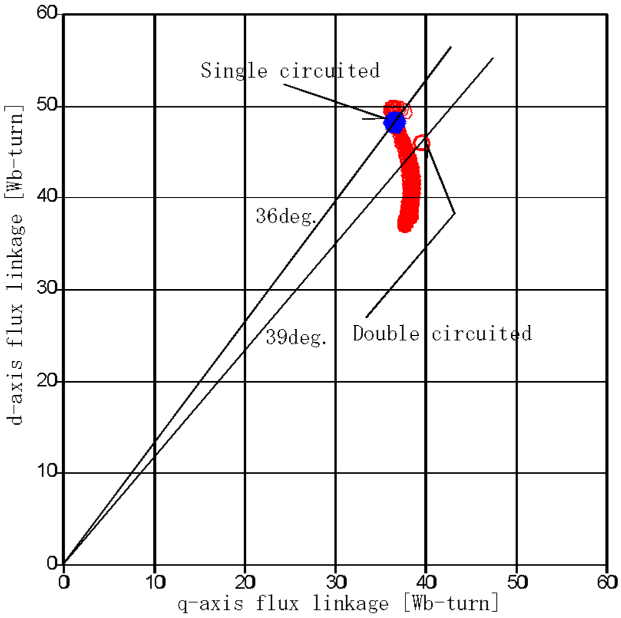


Fig. 7.4 Armature winding flux linkage position based on rotor position --- Electrical angle

The system and machine parameters are co-incide to ones in Chapter 6, and un-transposed line parameters are applied.
The machine's rotor angle position is shown in Fig. 7.3. Care should be taken (in EMTP) that the angle corresponds to the actual geometrical one for 4-pole machine based on the infinitive bus voltage angle. Also, the machine is connected to the system via delta-star connected step-up transformer. So, 66 degree for double-circuited line steady state case, corresponding normalised electrical degree is:
(66 X 2) (4P - 2P) + 30 (Delta - Star) = 162
Fig. 7.4 shows the flux vector linked with the armature winding, displayed on d-q axis plane.
The armature flux position angle is then:

162 – 39 = 123 degree

Therefore the voltage angle at the armature winding is, (as $d\phi/dt = -V$ for generator),

123 – 90 = 33 degree

The value well agrees with the former hand calculated one.
For single circuited, 49 degree is obtained, which also is a good agreement with the hand calculated one before shown.
For over-swinging, from Fig. 7.3 and 7.4 as for the time of maximum rotor angle in Fig. 7.3, the angle in Fig. 7.4 is approx. 45 degree, the maximum angle is, likewise:

86 X 2 + 30 – 45 – 90 = 67 degree

which is fairly good agreement with the equi-area method result.
Note:
In classic calculation method such as equi-area method, both mechanical and electrical source points are assumed to be based on a common point. Actually the mechanical energy transferring point is the rotor, but electrically transferring point is vague. In this section, values on the armature winding are shown but, in general case, also values on the armature terminal voltage are applied.

7.2 Time domain analysis ---- ATP-EMTP

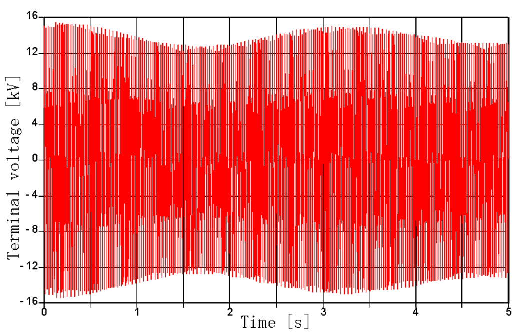


Fig. 7.5 Generator terminal voltage

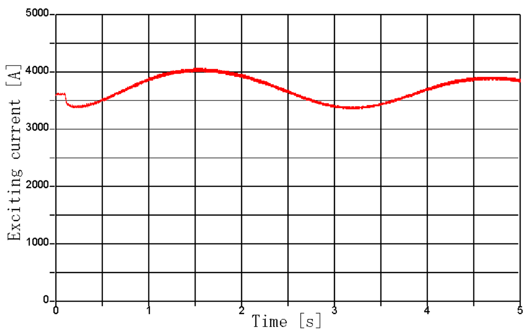


Fig. 7.6 Field exciting current

In Fig. 7.3, the maximum rotor swing is approx. 20 degree for 4 pole machine, i.e. electrically 40 degree. In Fig. 7.2, the value is 36 degree. The difference depends on the flux movement on the rotor shown in

Fig. 7.4. In classic method, such as equi-area method, source side voltage is an imagined one. In time domain analysis, every actual value is calculated. Also actual voltage amplitude is changeable, which can not be involved in classic method. A little more details are shown in Fig. 7.5 and 7.6, the former of which is generator terminal voltage and the latter field exciting current. Both change during the time interval. In Fig. 7.4 also the flux angle and amplitude changes are shown. These show the variables of the generator are changeable during the transient,

As the next example, increasing the transmission active power by 5%, the rotor angle swing is shown in Fig. 7.7 in comparison with the former case. The amplitude increases, furthermore, the recovery delays a lot. The condition seems to be critical. Actually, not shown, by more 5% of power increase, the generator losses the synchronism (out-of-phase).

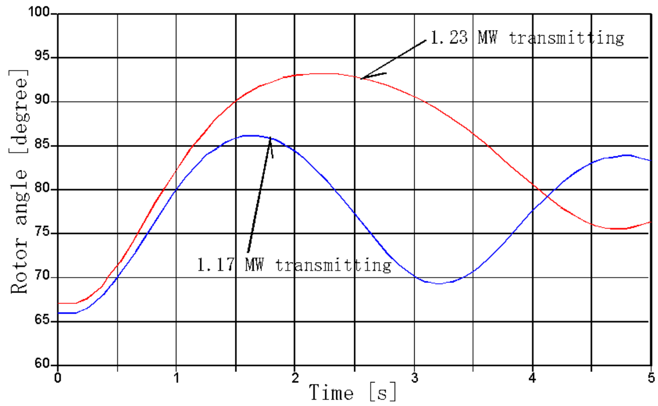


Fig. 7.7 Rotor angle by over-loading

In the next example, line faulting result in one circuit of the double-circuited line opening is taken up. Two cases are introduced.:

Case 1: excluding intermediate switching station in Fig. 7.8, faulting (F) is cleared by CB11 and CB31, i.e. whole length of the line is to be single-circuited.

Case 2: introducing intermediate switching station, the fault is cleared by CB11 and CB21, i.e. only half of the line is single-circuited.

The results are shown in Fig. 7.9 as the rotor angle swing. In case 1, 1.17GW of transmission power results in out-of-phase, so as the critical value, 1.13GW is introduced. In case 2, where only the half of the line is single circuited, due to less enhancement of the line impedance, significant improvement is apparent as for transient stability enhancement.

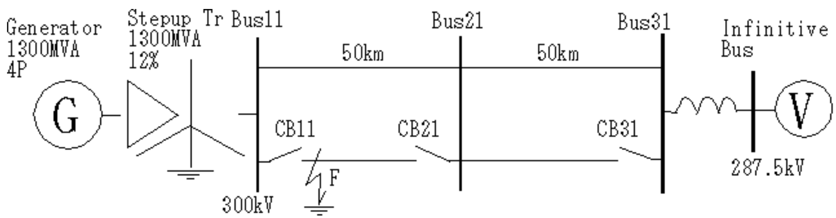


Fig. 7.8 Power system diagram, 3LG fault --- 1 circuit clearing

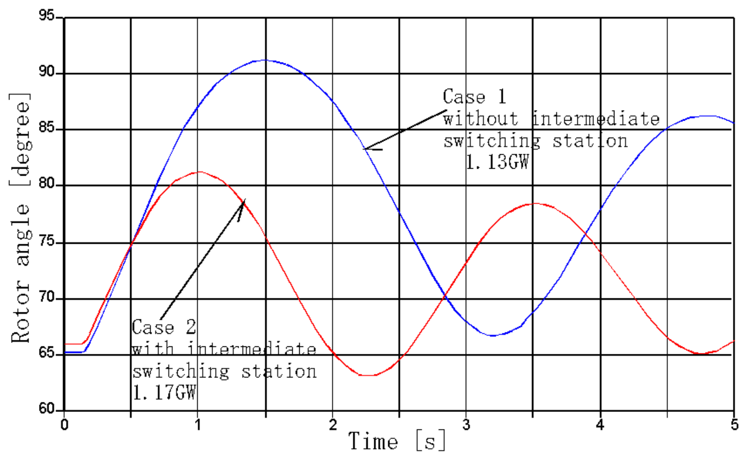


Fig. 7.9 Rotor angle swing by 3LG --- 1 circuit clearing

In the next case, second generator unit is connected to the intermediate bus, the rating of which is 600MVA with 2 pole, feeding 0.6GW. Faulting and clearing sequence is the same as the former.

The result (rotor angle swing) is shown in Fig. 7.11. For easy

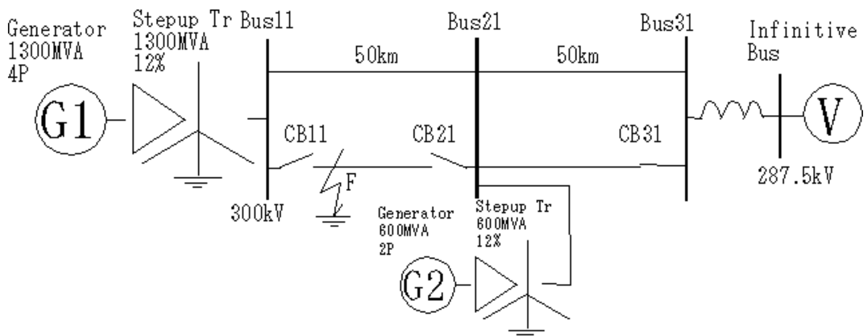


Fig. 7.10 Two generator vs. inf. bus case

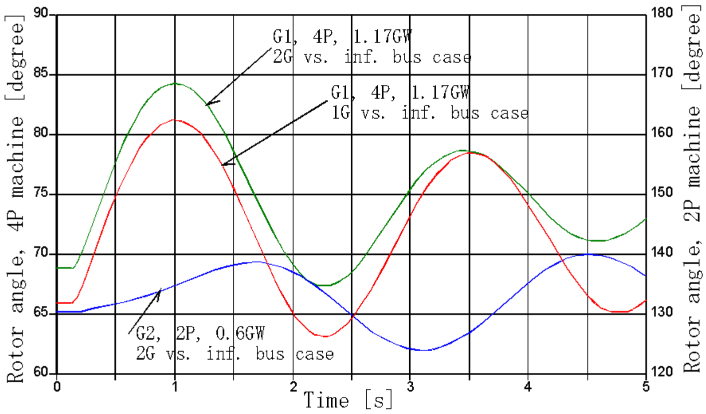


Fig. 7.11 Two generator and inf. bus case

comparison of the angle swing between 2P and 4P machines on a same basis, the right side co-ordinate scale (for 2P machine) is doubled as the left side. As the faulting spot is remote from the second generator, the angle swing is far less than the first one. For two-generator case, though the initial angle is higher than the one generator case, the stability state is almost the same. In two-generator case, the swing of the first generator seems to transfer to the second one, i.e. the second one's swing amplitude enhances. Much more complicated interaction phenomena may occur in multi-machine cases.

Field excitation control

Fig. 7.5 shows the terminal voltage is damped when the angle enhances. From the equation (7.1), the lower voltage corresponding lower transmitting power, thus the generator tends to accelerate. By increasing the excitation current resulting in higher terminal voltage, the transmitting power enhances and the machine acceleration is damped. Generator has AVR (automatic voltage regulator) and/or PSS (power system stabiliser), the main purpose of which is to keep the terminal voltage constant. But introducing special controlling of them, also enhancement of transient stability is expected. Especially PSS for such purpose is introduced to modern high capacity machine.

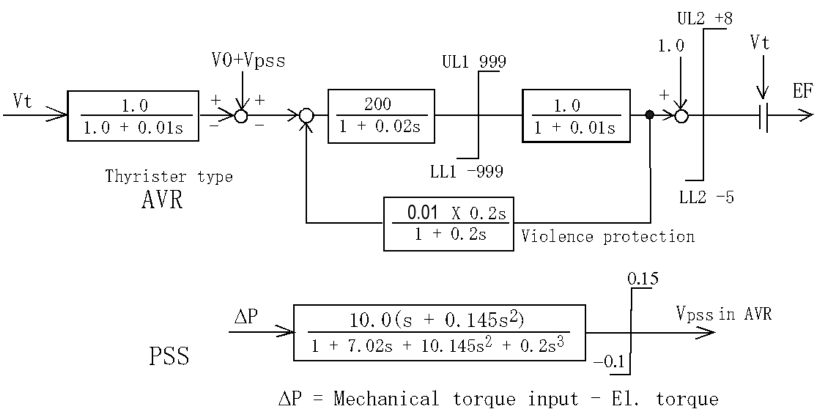


Fig. 7.12 AVR/PSS diagram applied to G1

Fig. 7.12 shows the block diagram of AVR/PSS applied to the generator, which is of very rapid response and thyrister type. As the output voltage is supplied by rectifying the generator output AC, the output is proportional to the generator terminal voltage as shown in the figure. In the following calculation cases only G1 (1.3 GVA machine) is furnished with AVR/PSS.

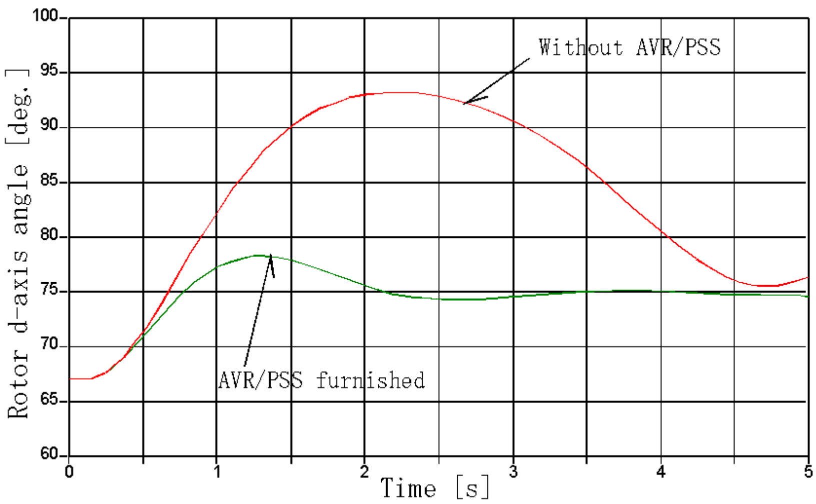


Fig. 7.13 Effect of AVR/PSS in one circuit of transmission line opening.

Fig. 7.13 shows for the case shown in Fig. 7.7 (over loading condition) with and without AVR/PSS as for rotor angle swing. The transient is well suppressed and in short time steady state is attained. Also the maximum swing amplitude is much damped. Introducing AVR/PSS, enhancement of transmission power is possible.

Fig. 7.14 shows AVR/PSS variables during the phenomena. During increase of the rotor angle, as the results of the input variables to AVR/PSS, the exiting voltage is much enhanced.

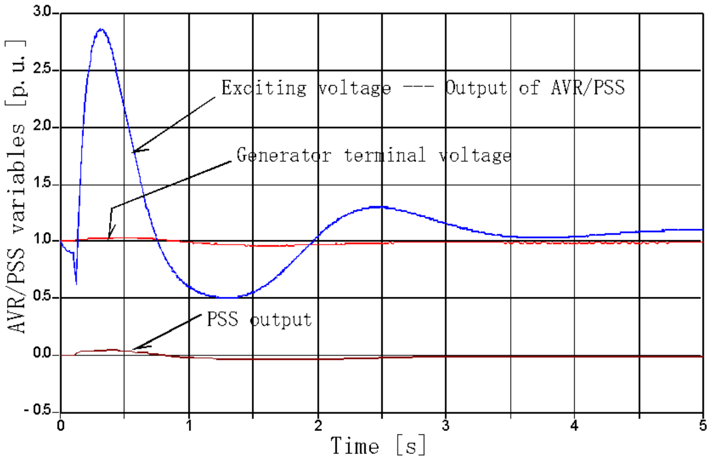


Fig. 7.14 Variables in AVR/PSS (for Fig. 7.13)

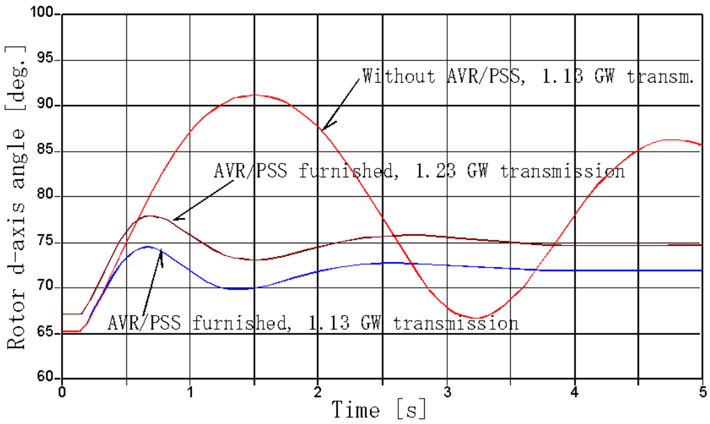


Fig. 7.15 3LG --- one circuit opening like Fig. 7.9 case 1

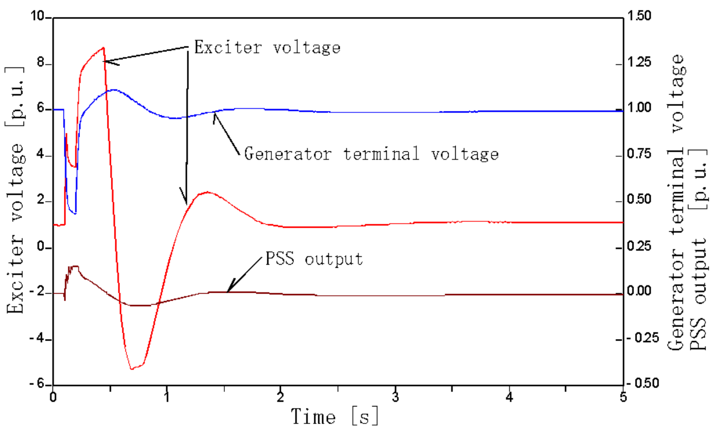


Fig. 7.16 AVR/PSS variables in Fig. 15

Thus significant effect of ARV/PSS for stability enhancement is proved.
Then, as typical transient stability calculation cases, many of the similar cases of which are done, transmission line faulting followed by clearing of the faulted section are surveyed. Calculations without AVR/PSS are shown in Fig. 7.9 and 7.11. Introducing AVR/PSS, the calculation results are shown in Fig. 7.15 and Fig. 7.16. In Fig. 7.15, the rotor angle swing during the transient is shown; where also for overloading case (1.23GW) is added. Even for the overloading, the swing is well suppressed and thus the stability limit can be enhanced with still some margin by introducing the field excite controlling system. Also the time interval of the disturbance is significantly shortened. Without such system, as shown before, by 1.17GW of transmission power, the system cannot be kept stable. Fig. 7.16 shows the AVR/PSS variables during the transient, where, PSS out put very quickly raises at the first stage and thus enhancing the exciting voltage, the rotor swing is strongly suppressed. In the phenomena, due to such great change of the voltage as short-circuiting, AVR/PSS variables show significant performances.

Note:

Great care should be taken as for initialising the AVR/PSS variables for accurate calculations. In the EMTP data, typing 77 in the end part of TACS in column 1 and 2, then initial values of TACS variables are written. For details, see the attached data files.

In Fig. 7.17, two generators Vs infinitive bus case is shown. The system layout is shown in Fig. 7.10 where also No. 2 generator is involved. As shown before, only No. 1 generator's field exciting is controlled by AVR/PSS. No. 2 generator's exciting voltage is kept constant during the transient.
The calculated result is shown in Fig. 7.17 as for the generators' swing angles. G1's, which field exciting is strongly controlled by AVR/PSS, swing is significantly damped as a natural result. Also G2's swing is to some extent suppressed. In Fig. 7-18, G2's torque during the phenomena is compared ------ with and without control of G1. The phenomenon is much complicated and the swing period of each machine may influence each other. These might be beyond the scope of this chapter.
For more sophisticated case study, 8 generator vs. infinitive bus case, where 3-phase short-circuit and clearing case is calculated, is shown in Fig. 7.19 and 7.20. 8 generators have no exciting controlling. For the data coding, see the attached data file. In the case, calculating longer time duration than 2 second, some instability appears, so more number of machines introducing, another calculation technique such

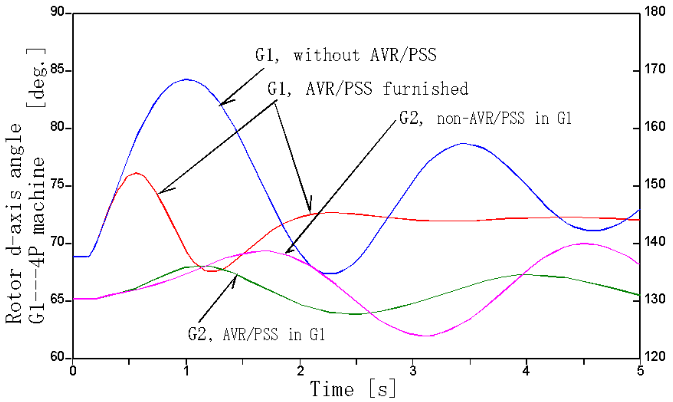


Fig. 7.17 Two Gen. Vs. infinitive bus case

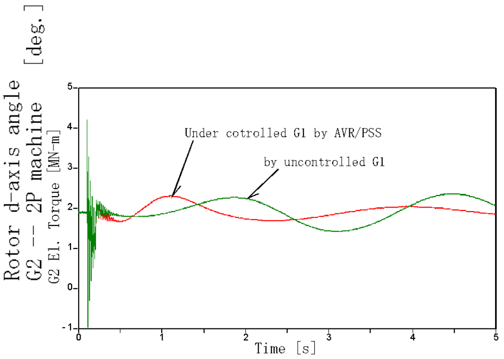


Fig. 7.18 G2 El. Torque

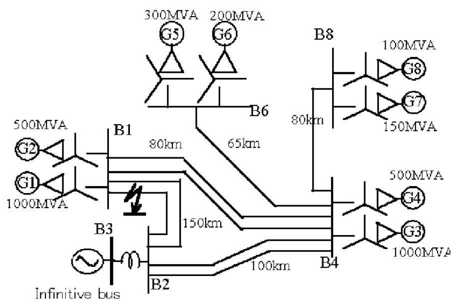


Fig. 7.19 8 generator vs. inf. bus system

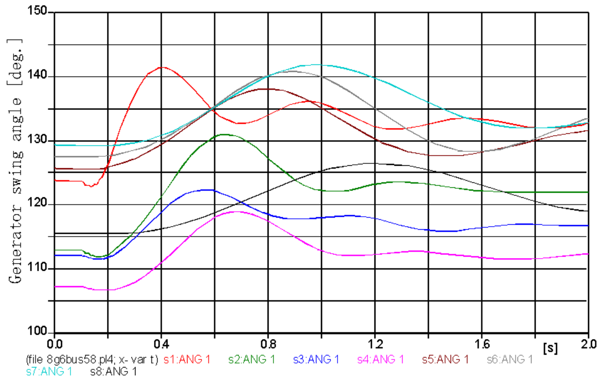
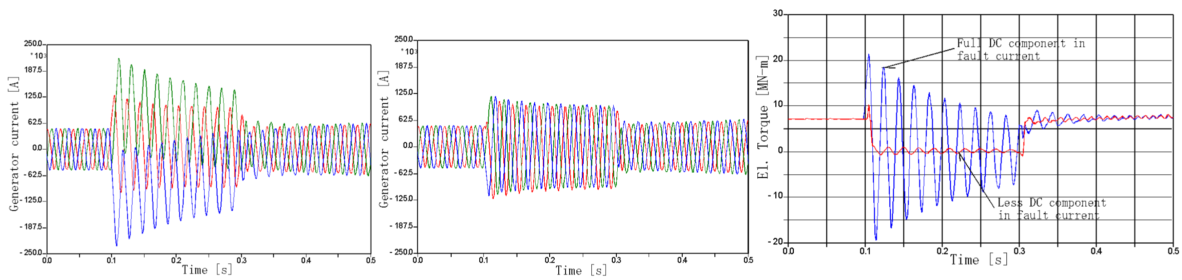


Fig. 7.20 Generator swing angle

as applying No. 19 synchronous machine model to be introduced partly, might be necessary. According to the Rule Book of ATP-EMTP, No. 19 synchronous machine model seems to be more stable for especially multi-machine case. Therefore machines distant from the disturbance, i.e. short-circuiting, might be suitable to be modelled as No. 19 machine.

Back swing phenomena

As shown in the previous chapter, during usual short-circuiting with DC component in the short-circuit current, more or less decelerating direction of torque acts to the generator. This may influence the transient stability in the relevant power system. As shown in the chapter, the cause of the torque is the trapped flux in the armature coil of the generator during short-circuiting. The phenomena is not involved in power frequency phasor domain analysis usually applied.
Picking up the case shown in Fig. 7.8 and 7.9, the line faulting initial detailed phenomena are surveyed regarding both under full of DC component and less in the fault current.



a) Fault current with full DC b) Fault current with less DC c) Torque under full/less DC

Fig. 7.21 Fault current with/without DC component

In Fig. 7.21 fault current and generator's air gap torque for both full of and less DC component are shown. DC component condition depends on the point on wave fault initiation timing. Significant difference between the two conditions is found in c). Nevertheless, difference in the swing angle is not so significant as shown in Fig. 7.22. Also for full DC condition, which is possible only in time domain analysis (EMTP), corresponds to less severe condition under full load condition such as the present case.

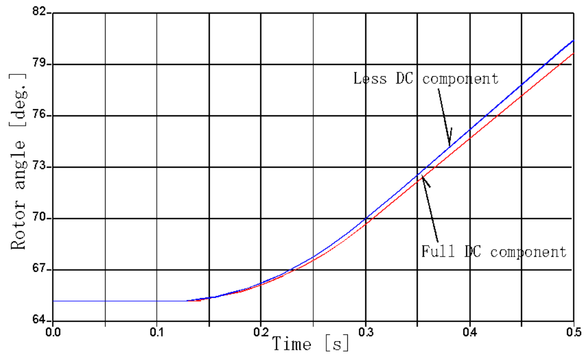


Fig. 7.22 Rotor swing angle (Full loading)

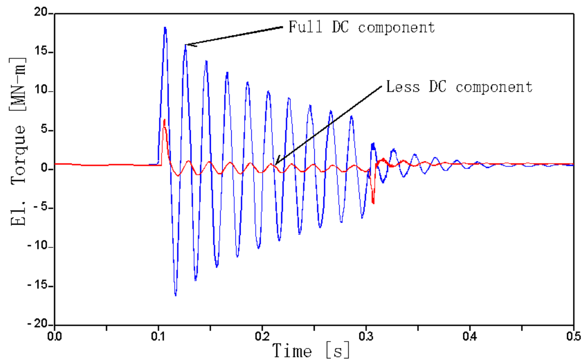


Fig. 7.23 S.C. torque under light loading

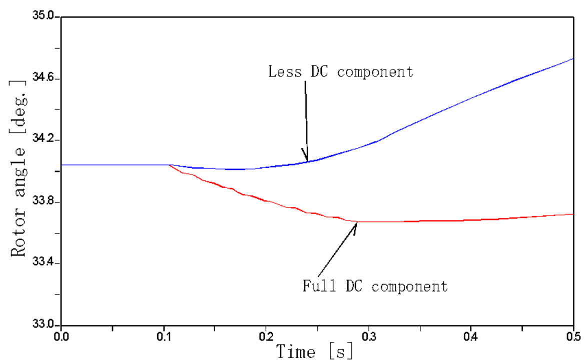


Fig. 7.24 Rotor swing angle (Light loading)

Under very light loading condition (less power output), much more significant difference in torque as shown in Fig. 7.23 is observed. Then, as shown in Fig. 7.24, even negative direction of swing occurs. This is the cause of the name "Back swing". In very light loading condition, negative direction of out of step might occur. As talked before such phenomena are only studied by time domain analysis such as EMTP.

More severe condition is exists in pumping station where the machine works as a motor. The mechanical torque is in inverse direction, to which the electrical back swing torque is superimposed. So, under heavy load of pumping-up condition, DC component in the fault current may introduce extremely severe condition.

Attached data files

- Data7-00.dat: 1G(No. 58 SM) vs. inf. bus, full loading initialised by CAO LOAD FLOW.
- Data7-01.dat: Ditto, but one circuit of double circuited transmission line dropping.
- Data7-02.dat: Ditto, but 105% overloading.
- Data7-03.dat: Ditto but 3-phase earthing fault and clearing by dropping one circuit (full length), by critical loading condition (96%).
- Data7-04.dat: Ditto, but half length of transmission line, by full loading condition.
- Data7-05.dat: 2G vs. inf. bus system, 3-phase earthing fault and clearing by dropping one circuit (half length) of the line.
- Data7-11.dat: Same as –02 case but high-speed AVR/PSS is introduced to the generator.
- Data7-12.dat: Same as –01 case but high-speed AVR/PSS is introduced to the generator.
- Data7-13.dat: Same as –03 case, but AVR/PSS introduced.
- Data7-14.dat: Same as –04 case, but AVR/PSS is introduced to one generator.
- Data7-15.dat: 8 generators vs. infinitive bus case, all are modelled by "No. 58 synchronous machine".
- Data7-16.dat: Same as –05 case, but one generator is modelled by Universal Machine model (Type 59 format).
- Data7-17.dat: Ditto, but general Universal Machine's Synchronous Machine model applied (Standard U.M. format).
- Data7-21.dat: Like –03 case, but maximum of DC component in the fault current condition introduced.
- Data7-22.dat: Ditto, but minimum DC component in the fault current condition introduced
- Data7-31.dat: Like –21 condition but under very light loading condition.
- Data7-32.dat: Like –22 condition but under very light loading condition.
- Data7L01.dat: 50km, double circuited transmission line parameter calculation, Pi representation.

Appendix 7.1 Modelling by No. 19 Universal Machine

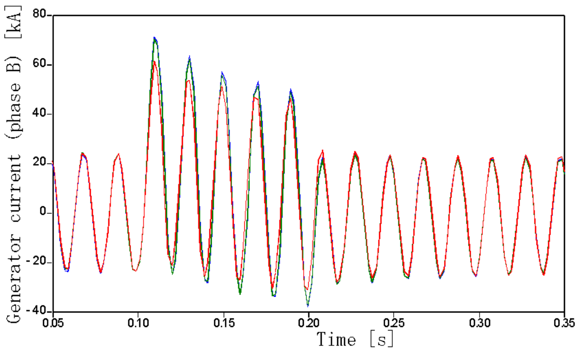


Fig. 7A.1 G2 current by 3 type of modelling

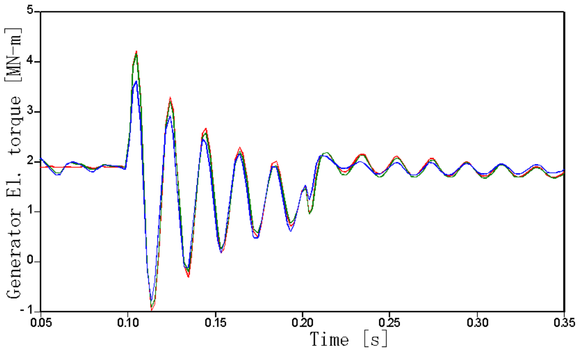


Fig. 7A.2 G2 El. torque by 3 type of modelling

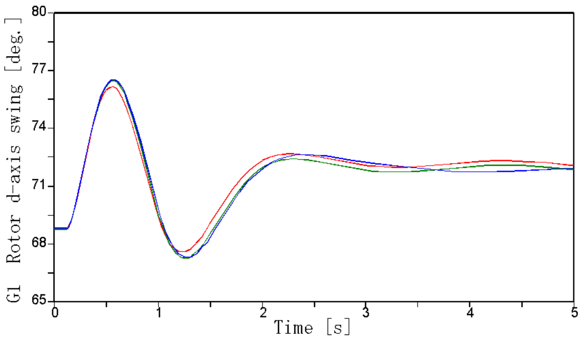


Fig. 7A.3 G1 rotor swing by 3 type of modelling In G2

It is known, for type No. 58/59 synchronous machine, the number of machine is limited. Actually by Data7-15 case where 8 machines are introduced, occasionally instability or even divergence is experienced. While, according to the rule book, by No. 19 universal machine modelling multi machine case is easier with no limitation in the number. Also by No. 19 machine synchronous machine is applicable, though the modelling is not so sophisticated as type 58/59 synchronous machines.

In the universal machine menu, two kind of synchronous machine modelling is applicable. :

* Synchronous machine in Type-59 format

* Synchronous machine in Standard U.M. format

Both cases were applied in modelling G2 of Data7-14 case (Fig. 10 and 12, where AVR/PSS is applied to G1). The following points are to be noted. :

Type-59 format

- Only No. 59 SM is applicable, but not 58.
- Parameter Fitting is ≤ 2.0, i.e. only open circuited time constants are to be applied.
- English unit for mechanical constants mandatory.
- The second card of Class 3 data card is to be excluded, since common saturation characteristics for d- and q-axis is applied.
- Rn, Xn (for neutral earthing) and Xcan (Canay's reactance) are to be excluded since not applicable in the program.
- Typing output option is different from No. 58/59 SM.
- Connecting to TACS is districted.

Standard U.M. format

- For U.M. parameter calculation, usage of INDSYNW.EXE, which is down-loadable from your convenient ATP web-site, is highly recommended.
- Some tuning according to your calculation is to be done, i.e. node name, initialisation, etc.

For both modelling initialisation by FIX SOUCES / CAW LOAD FLOW is not suitably applicable. To the author's experience, giving the generator terminal voltages and phase angles to all generators has been suitably applied. For No. 58/59 machines and U.M. in type-59 format, values are directly typed. In U.M. by standard format, as automatic initialisation of U.M. the values are also applicable. For details, see Data7-14, -16 and 17, also Rule Book. Obtaining these initial values (terminal voltages and phase angles), another power flow calculation is necessary, where, No. 14 alternating current voltage sources instead of generators and FIX SOURCES menu are best applicable.

In Fig. 7A.1 --- 3, calculation results by three type of S.M. modelling for G2 are shown where in the graphs three kind of results are drawn superimposed. Difference between the modelling methods is not significant, so any kind seems to be applicable depending on your choice.