Chapter-8

ASYNCHRONOUS OPERATION OF HIGH VOLTAGE SYNCHRONOUS GENERATORS UNDER SUDDEN LOSS OF EXCITATION

8.1 Introduction

Field failure gives rise to partial or complete loss of excitation. Under this condition, the synchronously generated power falls off to zero after a short period of electromagnetic transience [50,51]. As the mechanical power input does not fall to zero, an accelerating power becomes operative which pushes the generator to super-synchronous zone thus giving rise to a negative slip. The machine develops asynchronous power as an induction generator. Eventually a new steady state condition is reached at a particular value of negative slip at which the mechanical power produced by the turbine equates with the asynchronously developed power [112,132]. The mechanical power produced is determined by the reference power setting and the static droop of the turbine-governor [104].

Operation under loss of excitation has many undesirable effects [49,50,51] viz.

a) The generator continues to supply active power but it draws large amount of reactive power from the system for its own excitation. So it runs at a leading power factor.
b) The resulting current may be more than rated in many cases giving rise to overheating and thermal damage.
c) The reactive power burden on the other generators connected to the system, particularly those in the neighbourhood of the faulty machine, becomes very high. They run at a poor lagging power factor.
d) This mismatch of reactive power and the flow of large amount of reactive power through the transmission lines give rise to a heavy voltage dip in neighbourhood of the faulty machine.
e) Loss of excitation is associated with exchange of pulsating power with the system due to saliency effect.
f) It also gives rise to pulsation in voltage and slip.

For all these reasons, the general practice is to shut down the generator on occurrence of loss of excitation. An offset type mho relay is used along with time delay for this purpose which distinguishes between a recoverable swing and a loss of excitation(LOE) condition [52,53].

The following sections deal with asynchronous phenomena arising out of sudden loss of excitation of an alternator[55]. Programs have been developed for computation of torque, active and reactive power, armature current and slip for a fixed speeder gear-setting, using Newton-Raphson method. The program also finds out the pulsating component of torque & power and the pulsations in slip. The alternators have been represented in Park's reference frame on the basis of idealized configuration of one machine on infinite bus through a series impedance. The effect of discharge resistance has been accounted for. Comparison has been made between turbogenerator and hydrogenerator and it has been established through case-studies that sustained asynchronous operation is possible for considerable time for a steam turbogenerator where as it is not possible for a hydrogenerator.

8.2 Comparison of LOE-phenomena in turbogenerator and hydrogenerator

The impact of LOE on salient pole hydrogenerator is much more severe than in cylindrical pole turbogenerator. As the short circuit ratio of hydroalternators is high and consequently their synchronous impedance is low, the reactive power drawn by them is high. The armature current generally exceeds the rated value on occurrence of LOE even if the active power production is reduced by resetting the speeder gear. The exchange of pulsating power with the system and pulsation in voltage and slip are also unacceptably high. Therefore sustained operation of salient pole generators under conditions of LOE is not permitted[132]. They are taken out of the system within a few minutes by the action of sensing relay and the circuit-breaker [54,55,56].

The short circuit ratio in a modern turbogenerator is kept at a low value to get an economic design. As such the synchronous impedance is high which keeps the reactive power drawn at a relatively low value and the armature current is, in general, below rated. The pulsations are also relatively small due to low saliency (only slot-saliency effect is present). If the system is capable of meeting its reactive power demand without appreciable voltage dip, then the cylindrical pole alternators may be run for considerable time under LOE [61,62]. Attempts may be taken to resynchronize the machine within this time removing the fault.

8.3 Qualitative analysis and mathematical modelling

The electromagnetically developed power in a synchronous generator connected to infinite bus is given as [104]:

$$P = (EV / X_d)\sin\delta + (V^2 / 2)(1 / X_q - 1 / X_d)\sin(2\delta) \qquad 8.1$$

The first part on the RHS of eqn. (8.1) is the expression for synchronous power and the second part for the reluctance power. When a synchronous generator loses excitation, its synchronous power falls to zero almost immediately. The generator continues to develop its reluctance power so long as it retains synchronism. The reluctance power is very small for a cylindrical pole machine and may be neglected but it cannot be neglected in the case of a salient pole machine. However for a loaded generator, the reluctance power will not be able to retain synchronism [132].

Therefore, the generator will run at a leading p.f. It may have to supply more than rated current even if the active power is kept at 30-40% of its rated value due to reactive power burden. It causes overheating of the stator winding. The rotor body of a cylindrical pole machine is generally of solid iron and the pole-shoes for a salient pole machine are also of solid iron. The continuously reversing flux under asynchronous condition cannot penetrate deep into the rotor body of solid iron. Therefore the heating is limited to the skin which causes adverse effect [128].

The other generators connected to the system will have to supply the difference in reactive power. As such, they will run at a considerably poor lagging power factor. Due to the flow of reactive power from neighbouring machines and from the system to the machine suffering LOE, there will be considerable voltage drop in the vicinity of the faulty machine. Also, the asynchronous power will have a double frequency pulsating power due to saliency and also a power frequency pulsating power if the loss of excitation is partial. For salient pole machine the power pulsation is quite pronounced, even if the residual excitation after occurrence of fault is removed. The exchange of this pulsating power with the system causes disturbance to the consumers and cannot be allowed to be continued. The pulsation of torque and power is obviously associated with cyclic variation of the slip[132].

In terms of operational impedance of an alternator, the average asynchronous power is given as [112]:

$$T_{as}=\frac{V^2}{2}\left[\frac{1}{jsX_d(j\omega_o)}+\frac{1}{jsX_q(j\omega_o)}\right] \qquad 8.2$$

and the asynchronous active power is given as:

$$P_{as}=(1-s)T_{as} \qquad 8.3$$

The reactive power of the system is given as:

$$Q_{as}=\frac{V^2}{2}\,\mathrm{Im}\left[\frac{1}{jsX_d(j\omega_o)}+\frac{1}{jsX_q(j\omega_o)}\right] \qquad 8.4$$

It is not an easy task to calculate the slip and other variables for a given value of T_{as} of an alternator under asynchronous mode of operation from this expression. A more workable expression is given below:

$$P_{as}=s(1-s)\frac{V^2}{2}\left[\left(\frac{1}{X_d^{'}}-\frac{1}{X_d}\right)\frac{T_d^{'}}{(1+sT_d^{'})^2}+\left(\frac{1}{X_d^{''}}-\frac{1}{X_d^{'}}\right)\frac{T_d^{''}}{1+(sT_d^{''})^2}+\left(\frac{1}{X_q^{''}}-\frac{1}{X_q}\right)\frac{T_q^{''}}{1+(sT_q^{''})^2}\right] \qquad 8.5$$

Under conditions of equilibrium, the following equation is satisfied:

$$P_{as}=P_{ref}+s/R_U \qquad 8.6$$

Where R_U is the static droop. The expression reduces to:

$$f(s)=P_{as}-P_{ref}-s/R_U=0 \qquad 8.7$$

This equation can be solved by applying Newton-Raphson method for finding out value of slip for specified value of reference power-setting. The value of the reactive power under LOE is given by the following expression (time constants are in radians)[148]:

$$Q_{as}=-\frac{V^2}{2}\left[\left(\frac{1}{X_d^{'}}-\frac{1}{X_d}\right)\frac{(sT_d^{'})^2}{(1+sT_d^{'})^2}+\left(\frac{1}{X_d^{''}}-\frac{1}{X_d^{'}}\right)\frac{(sT_d^{''})^2}{1+(sT_d^{''})^2}+\left(\frac{1}{X_q^{''}}-\frac{1}{X_q}\right)\frac{(sT_q^{''})^2}{1+(sT_q^{''})^2}\right] \qquad 8.8$$

8.4 The effect of discharge resistance

As soon as a machine is subject to an LOE fault, the field winding should be disconnected from the supply and short-circuited through a discharge resistance. The reason is obvious. Unless the field is disconnected, it will generate a synchronous pulsating power at power frequency which is highly disturbing. Secondly, the induced e.m.f in the field winding due to slip frequency may be objectionably high. Though the discharge resistance is essentially a non-linear resistance, its value may be taken as constant at steady state asynchronous condition. The value of discharge resistance is quite large, may be 8-10 times the field resistance[132].

As the discharge resistance is in series with the field circuit, it reduces the value of the open circuit transient time constant, as given below:

$$T_{do-\mathrm{mod}}^{'} = r_f T_{do}^{'} / (r_f + r_d) \qquad 8.9$$

Obviously, the value of $T_d^{'}$, the d-axis short circuit time constant is also reduced.

8.5 The effect of series reactance to infinite bus

The series reactance to infinite bus has got a beneficial value. It reduces the magnetizing current drawn from the grid and hence the reactive powerflow into the machine. But at the same time it reduces the terminal voltage of the machine and hence increases the slip for a given reference power [132]. It gives rise to an increment in reactive power which partly offsets the saving in reactive power due to lower magnetizing current. The series reactance reduces the effective short-circuit time constants of the machine as shown below:

$$T_{d-\mathrm{mod}}^{'} = T_d^{'} X_d^{'} / (X_d^{'} + X_e) \qquad 8.10a$$

$$T_{d-\mathrm{mod}}^{''} = T_d^{''} X_d^{''} / (X_d^{''} + X_e) \qquad 8.10b$$

$$T_{q-\mathrm{mod}}^{''} = T_q^{''} X_q^{''} / (X_q^{''} + X_e) \qquad 8.10c$$

The generator terminal voltage is given as:

$$V_g = V_{\inf} - I_a \angle \phi (r_a + j.X_e) \qquad 8.11$$

The voltage is normally depressed under LOE, to such an extent that undervoltage relays may trip in many cases.

8.6 The pulsating torque and power

The amplitude of pulsating power is obtained from the following expressions:

$$T_{asp} = (V^2 / 2)\{Y_d - Y_b + j.(Y_b - Y_a)\} \qquad 8.12$$

where

$1/\{j.X_d(js\omega_o)\}=Y_a+j.Y_b$ 8.13a

$1/\{j.X_q(js\omega_o)\}=Y_c+j.Y_d$ 8.13b

The pulsating power is given as:

$P_{asp}=T_{asp}(1-s)$ 8.14

If the loss of excitation is partial, and if the machine runs at asynchronous mode, a power frequency pulsation is superposed. The expression for the same is given below:

$P_{sp}=(EV/X_d)(1-s)^3\sin(\delta_o-st)$ 8.15

Hence the resulting pulsating power is given as:

$P_p=P_{asp}+P_{sp}$ 8.16

The magnitude of the pulsating power depends on terminal voltage, slip, excitation and the machine parameters. The slip cycle depends on mechanical parameters of the turbine & its governor and the electrical damping. Successful resynchronization depends on the nature of the slip cycle [132].

8.7 The mechanical transients following LOE and slip cycle:

a) Ignoring the time lags introduced by the pilot valves & the servomotors and the turbine itself, the equation of motion of an alternator on sudden loss of excitation is given below:

$2H(d\omega_\Delta/dt)=T_{mo}-T_{as}(s)$ 8.17

where, T_{mo} = mechanical torque input; $T_{as}(s)$ = Average asynchronous torque at slip s;

H = Inertia constant; D = Mech. damping coefficient; ω_Δ = s = slip

Further simplification can be made, without much loss of accuracy, that the asynchronous torque is proportional to the slip i.e. $T_{as}(s)=K_d s$ 8.18

Where, K_d = Electrical damping

The mechanical power input is related to the reference torque setting by the following equation:

$$T_{mo} = T_{ref} - s / R_U \qquad 8.19$$

Combining equations 8.17 to 8.20, the following expression is obtained:

$$2H(ds/dt) + (D + K_d + 1/R_U)s = T_{ref} \qquad 8.20$$

Or, $2H(ds/dt) + D_e s = T_{ref}$ 8.21

where D_e = equivalent damping.

The time domain solution of the equation is given as:

$$s(t) = (T_{ref} / D_e)(1 - e^{-t/T_{me}}) \qquad 8.22$$

where, $T_{me} = 2H / D_e$ = equivalent mechanical time constant.

Equation 8.22 shows an exponential rise of slip which settles down at an average value:

$$s_{av} = T_{ref} / D_e \qquad 8.22a$$

b) If the system lags are taken into account, the describing eqns. will change. If the turbine-governor, the pilot valve system and the turbine are represented by simple time lags, an expression of the following form is obtained:

$$\frac{T_{ref}}{p} = \left(2Hp + D + \frac{1 + CpT_t}{R_U(1 + pT_g)(1 + pT_t)} \right) s + K_d s \qquad 8.23$$

Where, C = Fraction of power generated at the H.P. stage

T_g = Time constant of the turbine -governor and the pilot valve

T_T = Time constant of entrained steam in the reheater, I.P. & L.P. stages.

Therefore, the slip is given as:

$$s = \frac{T_{ref} R_U (1 + pT_g)(1 + pT_t)}{p[1 + CT_t p + R_U (2Hp + K_d + D)(1 + pT_g)(1 + pT_t)} \qquad 8.24$$

The poles of the characteristic eqn. can be found out by applying Newton-Raphson method. Then resolving the eqn. by Heavyside's fraction, an expression of the following form is obtained:

$$s(t) = 1 - k_1 e^{-t/T_1} - k_2 e^{-t/T_2} - k_3 e^{-t/T_3} \qquad 8.25$$

where k_1, k_2, k_3 are constants and T_1, T_2, T_3 are equivalent time constants of the feedback system.

Expressions for slip given by eqn. 8.22 or 8.24 do not reveal the slip cycle as the pulsating component of the torque has been neglected. Including the pulsating components of the torque, and simplifying eqns. 8.12 and 8.13, the following expression has been derived:

$$2H(ds/dt) = P_{asyn-\max} \sin(2st + \phi_1) + P_{syn-\max} \sin(st + \phi_2) \qquad 8.26$$

$(D_e s)$ gets cancelled against steady average asynchronous torque. This equation shows the existence of two pulsating components of slip, one of power frequency caused by residual excitation, if any, and another of double the power frequency caused by saliency. The amplitude of the power frequency pulsating component of slip is given as:

$$s_{syn} = P_{syn-\max/} / (2H) \qquad 8.26a$$

and the amplitude of the double power frequency pulsating component of slip is given as:

$$s_{asyn} = P_{asyn-\max/} / (2H) \qquad 8.26b$$

If the turbine-governor and the turbine are accurately modeled, the nature of the expressions will not change. Only the amplitudes will be slightly modified. Case studies on slip cycle have been made on this simplified model.

After the advent of soft-computing technique, pattern classification of synchronous generator stability and loss of excitation has become a topic of research interest [59,60].

8.8 Case-studies on loss of excitation

Case studies on operation of synchronous generators on occurrence of sudden loss of excitation have been made for the following:

i) a 210 MW, 15.75 KV turbogenerator set directly connected to infinite bus through its transformer leakage reactance and

ii) a 84 MW, 11 KV hydrogenerator set connected to infinite bus through an equivalent series reactance representing the effect of generator transformer and the transmission line.

All quantities are in p.u. & time constants are in sec. Parameters and the time-constants have been modified to take into account the series reactance to infinite bus and the discharge resistance in the field circuit under LOE.

A. Parameters and time-constants of Turbogenerator Set

Rating: 210 MW, 15.75 KV

d-axis synchronous reactance, $X_d = 2.225$

d-axis transient reactance, $X_d' = 0.305$

d-axis sub-transient reactance, $X_d'' = 0.214$

q-axis synchronous reactance, $X_q = 2.11$

q-axis sub-transient reactance, $X_q'' = 0.311$

d-axis open circuit transient time constant, $T_{do}' = 7$

d-axis short circuit transient time constant, $T_d' = 0.9596$

d-axis open circuit subtransient time constant, $T_{do}'' = 0.17245$

d-axis short circuit subtransient time constant, $T_d'' = 0.121$

q-axis open circuit subtransient time constant, $T_{qo}'' = 0.6$

q-axis short circuit subtransient time constant, $T_q'' = 0.08844$

Leakage reactance of the transformer referred to rated MVA of the generator, $X_e = 0.1366$

The field resistance, $R_f = 0.001018\ \Omega$

Discharge resistance in the field circuit, $R_d = 0.008142\ \Omega$; Ratio $R_d / R_f = 8$

B. Asynchronous variables- turbogenerator

Asynchronous variablesfor the turbogenerator set mentioned above have been computed for three different conditions under case-I, case-II and case-III.

Case-1: Asynchronous variables for the turbogenerator, in this case, have been calculated for varying slip, fixed input voltage $(V = 1.0)$ and fixed $(K_d = R_d / R_f = 8)$ ratio of discharge resistance to field resistance. The results are given in table 8.1

TABLE 8.1

Asynchronous variables for varying slip, fixed discharge resistance, fixed input voltage

$s =$	$P_{as} =$	$Q_{as} =$	$I_{as} =$	$P_{asp} =$
0.0005	0.0441	0.4352	0.4374	0.0149
0.0010	0.0882	0.4380	0.4468	0.0232
0.0015	0.1321	0.4427	0.4620	0.0325
0.0020	0.1757	0.4491	0.4822	0.0422
0.0025	0.2188	0.4574	0.5071	0.0521
0.0030	0.2615	0.4673	0.5355	0.0618
0.0035	0.3034	0.4789	0.5670	0.0716
0.0040	0.3447	0.4922	0.6009	0.0812
0.0045	0.3851	0.5071	0.6367	0.0907
0.0050	0.4246	0.5234	0.6740	0.1001
0.0055	0.4632	0.5411	0.7123	0.1092
0.0060	0.5006	0.5602	0.7513	0.1183
0.0065	0.5370	0.5805	0.7908	0.1271
0.0070	0.5722	0.6020	0.8305	0.1357
0.0075	0.6061	0.6245	0.8702	0.1441
0.0080	0.6388	0.6479	0.9099	0.1522

Case-I1: Asynchronous variables in this case, have been calculated for varying discharge resistance, given reference power (0.4) and static droop (0.04). Newton-Raphson method has been used for finding out the slip corresponding to different ($K_d = R_d / R_f$) ratio. The results are given in table 8.2

TABLE 8.2

Asynchronous variables for varying discharge resistance, given reference power and given static droop

$K_d = R_d / R_f$	$s =$	$P_{as} =$	$Q_{as} =$	$I_{as} =$	$P_{asp} =$
0	0.00120	0.42010	0.61615	0.74574	0.37812
1	0.00192	0.40212	0.56448	0.69307	0.29465
2	0.00346	0.36359	0.50439	0.62178	0.13779

3	0.00529	0.31764	0.49032	0.58421	0.03343
4	0.00627	0.29328	0.50161	0.58106	0.11163
5	0.00653	0.28684	0.50647	0.58205	0.13223
6	0.00657	0.28567	0.50743	0.58232	0.13593
7	0.00658	0.28550	0.50757	0.58236	0.13648
8	0.00658	0.28548	0.50759	0.58236	0.13655

Case-II1: Asynchronous variables, in this case, have been calculated for fixed discharge resistance $(K_d = R_d / R_f)$ =8, given reference power (0.4) and static droop (0.04) and varying voltage. Here again, Newton-Raphson method has been used for finding out the slip corresponding to different voltages. The results are given in table 8.3

TABLE 8.3

Asynchronous variables for fixed discharge resistance, given referencepower, and varying voltage.

s =	V	P_{as} =	Q_{as} =	I_{as} =	P_{asp} =
0.0050	0.8600	0.3140	0.3871	0.6321	0.0740
0.0048	0.8800	0.3182	0.4008	0.6327	0.0750
0.0047	0.9000	0.3221	0.4148	0.6335	0.0759
0.0045	0.9200	0.3259	0.4292	0.6344	0.0768
0.0044	0.9400	0.3302	0.4442	0.6355	0.0778
0.0042	0.9600	0.3337	0.4593	0.6375	0.0786
0.0041	0.9800	0.3369	0.4748	0.6390	0.0793
0.0039	**1.0000**	**0.3400**	**0.4906**	**0.6406**	**0.0801**
0.0038	1.0200	0.3430	0.5068	0.6425	0.0808
0.0037	1.04o00	0.3458	0.5235	0.6445	0.0815

Frequency of slip cycle = 2.447 hertz.

Neglecting turbine-governor parameters:

\Maximum slip= 0.0045;   Minimum slip= 0.0033

Including turbine-governor parameters:

Maximum slip= 0.0041;   Minimum slip= 0.0037

C. *Parameters and time-constants of Hydrogenerator Set:*

Rating: 84 MW, 11 KV

Armature leakage reactance, X_a = 0.1

d-axis transient reactance, $X_d^{'}$ = 0.32

d-axis sub-transient reactance, $X_d^{''}$ = 0.258

q-axis synchronous reactance, X_q = 0.67

q-axis sub-transient reactance, $X_q^{''}$ = 0.306

d-axis transient open circuit transient time constant, $T_{do}^{'}$ = 6.628 sec.

d-axis transient short circuit transient time constant, $T_d^{'}$ = 2.02 sec.

d-axis sub-transient open circuit transient time constant, $T_{do}^{''}$ = 0.05457 sec.

d-axis transient short circuit transient time constant, $T_d^{''}$ = 0.044 sec.

q-axis open circuit subtransient time constant, $T_{qo}^{''}$ = 0.03722 sec.

q-axis short circuit subtransient time constant, $T_q^{'}$ = 0.017 sec.

Leakage reactance of the transformer referred to rated MVA of the generator, X_{tr} = 0.14

Leakage reactance of transmission line connecting to infinite bus, X_{tl} = 0.1537

Reactance to infinite bus, X_e = 0.2937 ; Infinite bus voltage, V = 1

The field resistance, R_f = 7.252943E-04 Ω

Discharge resistance in the field circuit, R_d = 5.802354E-03 Ω ; Ratio R_d / R_f = 8

D. *Asynchronous variables- hydrogenerator*

Case-IV: Asynchronous variables for varying slip, fixed input voltage (1.0) and fixed discharge resistance are given in table 8.4 for the above-mentioned hydrogenerator set.

TABLE 8.4

Asynchronous variables for varying slip, fixed discharge resistance, fixed input voltage

s =	P_{as} =	Q_{as} =	I_{as} =	P_{asp} =
0.0020	0.0971	0.9100	0.9152	0.1553
0.0040	0.1742	0.9586	0.9743	0.1751
0.0060	0.2236	1.0192	1.0435	0.1970
0.0080	0.2496	1.0779	1.1064	0.2162
0.0100	0.2601	1.1282	1.1578	0.2315
0.0120	0.2620	1.1693	1.1982	0.2433
0.0140	0.2596	1.2021	1.2298	0.2525
0.0170	0.2532	1.2395	1.2651	0.2625
0.0210	0.2447	1.2747	1.2980	0.2716
0.0250	0.2385	1.3000	1.3217	0.2779
0.0290	0.2349	1.3196	1.3404	0.2824
0.0330	0.2332	1.3359	1.3561	0.2857

Case-V: Asynchronous variables for fixed discharge resistance, given reference power, and varying voltage are given in table 8.5, for reference power = 0.5225 ; static droop = 0.04 ; $K_d = R_d / R_f$ =8 Newton-Raphson method has been used for finding out the slip corresponding to different voltages.

TABLE- 8.5

Asynchronous variables for fixed discharge resistance, given reference power, and varying voltage

s =	V	P_{as} =	Q_{as} =	I_{as} =	P_{asp} =
0.0099	0.8600	0.2780	-0.9723	1.1801	0.2428
0.0095	0.8800	0.2880	-1.0077	1.1952	0.2503
0.0091	0.9000	0.2977	-1.0432	1.2097	0.2577
0.0087	0.9200	0.3070	-1.0790	1.2237	0.2650
0.0084	0.9400	0.3159	-1.1151	1.2373	0.2721
0.0080	0.9600	0.3243	-1.1516	1.2505	0.2793
0.0077	0.9800	0.3324	-1.1885	1.2635	0.2863

0.0074	**1.0000**	**0.3400**	**-1.2260**	**1.2764**	**0.2934**
0.0071	1.0200	0.3472	-1.2640	1.2892	0.3004
0.0069	1.0400	0.3540	-1.3027	1.3020	0.3075

Frequency of slip cycle = 4.74 hertz.

Neglecting turbine-governor parameters:

Maximum slip= 0.008436 ; Minimum slip= 0.006649

Turbine- governor parameters are not available for the hydro-set.

Even for catering a small power, the armature current is exceeding the rated value. So, asynchronous variables for varying discharge resistance have not been computed.

8.9 Conclusion

It is observed from the tables generated by the programme that for the same asynchronous power at rated voltage, for a turbogenerator compared to a hydrogenerator

a) The pulsating power component is much lower
b) The absolute value of the slip is much lower
c) The reactive power absorbed from the system is much lower
d) The armature current is much less and is below rated.
e) The frequency of slip cycle is also lower.

On the basis of these observations, sustained operation as induction generator is permitted for 15-30 minutes for a turbogenerator. If the field fault can be removed within this time, the generator can be resynchronized. Otherwise a shutdown is to be opted. It has been recommended by Bharat Heavy Electricals Ltd. to reduce the active power to 60% within 30 seconds and further reduce it to 40% (which comes out to be 0.34 p.u. for the machines rated for a power factor of 0.85 lagging) within 90 seconds for their makes [139].

In the earlier days, the voltage profile under LOE-condition was very poor. But now-a-days the reactive power generation by long HV/EHV transmission lines is substantively high which partially offsets the reactive power burden imposed by the faulty generator(s) and allows sustained operation of the grid system with one machine under LOE without voltage collapse. Installation of mid-point STATCOM also enhances LOE-protection [60]. Moreover, FACTS devices have been installed in many systems which may come for rescue under this fault.

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