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Performance Evaluation of Synchronous Generator under Sudden Loss of Excitation

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Abstract: **Synchronous generators under sudden loss of excitation behave as an induction generator, supplying active power to the system and absorbing reactive power from the system. In general the armature current exceeds its rated value. Hence, the reference power is reduced in steps to keep the armature currents within limits. The voltage profile around the faulty machine becomes unacceptably poor and in addition there is exchange of pulsating power with the system. Hence, the general practice is to switch off the machine by the action of an offset type MHO-relay. Recently, the capacitive VAR-generation of a H.T. system has gone up due to addition of EHV/SHV lines, such that there is no or little problem in supplying the faulty machine with its required VAR. Also, the magnetizing current drawn by modern turbo generators has reduced much due to the use of smaller air-gaps for economic design of the rotor. The combined effect has been assessed, and it has been found that it is permissible to run the machine for a relatively long duration under LOE without staking on its health. It may be allowed to run the machine for 30-60 minutes under LOE, within which time the fault may be detected and removed and the machine resynchronized. However, this is not possible for hydro-generators drawing large magnetizing currents.**

Keywords: **Synchronous generator, Governor Action, Newton-Raphson method, Excitation system, Loss of excitation, Mho-relay.**

Symbols, abbreviation and subscripts:

E, V	Induced voltage, Infinite bus voltage
$V_g, I_a\angle\phi$	Generator terminal voltage, armature current
X_d, X_q	D-axis/ Q-axis synchronous reactance
X_{md}, x_f	D-axis magnetizing reactance, field leakage reactance
x_a, ω	Armature leakage reactance, angular frequency in r/s
X_d'	D-axis transient reactance
X_d'', X_q''	D-axis/Q-axis sub-transient reactance
r_e, X_e	External resistance, leakage reactance to infinite bus
T_d', T_{do}'	D-axis S.C./ O.C. transient time constant.
T_d'', T_{do}''	D-axis S.C./ O.C. sub transient time constant
T_q'', T_{qo}''	Q-axis S.C./ O.C. sub transient time constant
r_f, r_d	Field/ field discharge resistance
P_{ref}, R_u	Reference power-setting, Static droop
P, P_s, P_r	Total, synchronous, reluctance power
T_{as}, I_{as}	Asynchronous torque/ current
P_{as}, Q_{as}	Asynchronous active/reactive power
δ, s	Power angle, slip
D,Q	Direct/ quadrature
S.C./O.C.	Short circuit/ open circuit
ϕ	Angle of lag of current behind voltage

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1. INTRODUCTION TO LOE PHENOMENA

A synchronous generator is forced to asynchronous operation under sudden loss of excitation. Operation under LOE has many undesirable effects e.g. thermal injury of the faulted machine, poor voltage profile in its neighbourhood, pulsations in voltage and power etc. [1,2,3]. These effects are more pronounced for a salient pole hydrogenerator compared to a cylindrical pole turbogenerator [1,4]. The equivalent circuit parameters of the 210 MW turbogenerator set of BHEL have been computed [5,6]. Then it has been equivalenced with the generator transformer. On the basis of one machine on infinite bus, the parameters and the time constants of the equivalenced machine have been modified [7,8] . Then the machine variables under asynchronous condition have been computed. A comparison has been made between the field directly short-circuited and the same closed through a properly chosen value of discharge resistance. It has been found that the use of discharge resistance is beneficial, but the relay operates even in its absence.

2. BAD EFFECTS OF L.O.E. ON THE MACHINE AND THE SYSTEM

The undesirable and damaging effects of operating a generator under loss of excitation are listed below:

a) The alternator runs at a leading power factor. It draws large amount of reactive power from the system for its excitation. The generator bus voltage cannot be held fixed- the bus gets converted to load bus with negative value of active power.

b) The resulting stator current may be more than rated- its value depends on the network conditions and the bus voltage. The over-current gives rise to overheating and thermal injury.

c) The reactive power burden on the neighbouring generators becomes very high. They run at a poor lagging power factor, provided there is no capacitive support or FACTS-devices for the rescue.

d) Large amount of reactive power flows through the transmission links causing voltage dips in the neighbourhood of the faulty machine. It makes the voltage profile unacceptable.

e) Loss of excitation is associated with exchange of pulsating power with the system due to saliency effect. It also creates pulsation in voltage and slip.

f) The tip of the impedance phasor of the machine flies off from 1^{st}. quadrant to 4^{th}. quadrant. It can be sensed by admittance relays and protective actions taken.

These effects are more pronounced for the salient pole hydro-alternators compared to turbo-alternators.

For all these reasons, the general practice is to shut down the generator on occurrence of loss of excitation. The bulk power system reliability is adversely affected on L.O.E. of a generator, provided there is no reactive power support. Load flow studies on the L.O.E.-faulted system of W.B. power grid revealed that the voltage collapse and resulting instability could be avoided only against large scale capacitive support. But now the scenario has somewhat changed due to addition of highly capacitive long EHV lines in our grid system. Asynchronous operation for a short time may be continued without any capacitive support. Hence sufficient time delay can be given to the admittance relay without any risk.

3. CAPABILITY OF TURBO-GENERATOR SETS TO OPERATE UNDER LOE

The turbo-generators manufactured by BHEL are capable of sustained operation under LOE for limited time. On occurrence of an L.O.E.-fault, the company has instructed to do the following:

- To disconnect the field circuit from the source immediately and short-circuit it, preferably through a discharge resistance of appropriate value.
- To reduce the asynchronous power to 60% of rated power within 30 sec.
- To reduce it further to 40% within 90 sec.
- To continue for 15-20 minutes under asynchronous condition and try to resynchronize.

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- To switch off the faulty machine, in case of failure to resynchronize within this time.

Following these instructions, the analysis has been made at first with field short-circuited directly and then short-circuited through a discharge resistance. The reference power-setting has been reduced to 0.6 p.u. within 30 second and then reduced further to 0.4 p.u. within 90 second.

4. THE MATHEMATICAL MODEL

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

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

Under L.O.E., the synchronous power falls to zero almost immediately. The relatively small reluctance power fails to retain synchronism. The rotor gradually speeds up and eventually settles at a steady negative slip. The average slip is determined by the reference power setting, the static droop and the machine parameters. A cyclic variation of slip is superposed on it due to saliency. This is associated with exchange of pulsating power and current with the system at double the line frequency (also at power frequency if the loss of excitation is partial). In terms of operational impedance of an alternator, the average asynchronous torque is given as:

$$T_{as} = \frac{V^2}{2}\mathrm{Re}\left[\frac{1}{jX_d(js\omega_o)} + \frac{1}{jX_q(js\omega_o)}\right] \qquad (2)$$

and the asynchronous active power is given as: $P_{as} = (1-s)T_{as}$ (3)

The reactive power of the system is given as: $Q_{as} = \frac{V^2}{2}\mathrm{Im}\left[\frac{1}{jX_d(js\omega_o)} + \frac{1}{jX_q(js\omega_o)}\right]$ (4)

It is not an easy task to calculate the asynchronous variables from this expression. Breaking up into fractions, we get a more workable expression as given below:

$$P_{as} = s(1-s)\frac{V^2}{2}\left[\left(\frac{1}{X_d^{'}} - \frac{1}{X_d}\right)\frac{T_d^{'}}{1+(sT_d^{'})^2} + \left(\frac{1}{X_d^{''}} - \frac{1}{X_d^{'}}\right)\frac{T_d^{''}}{1+(sT_d^{''})^2} + \left(\frac{1}{X_q^{''}} - \frac{1}{X_q}\right)\frac{T_q^{''}}{1+(sT_q^{''})^2}\right] \qquad (5)$$

The corresponding value of the reactive power is given by the following expression (time constants are in radians):

$$Q_{as} = -\frac{V^2}{2}\left[\left(\frac{1}{X_d^{'}} - \frac{1}{X_d}\right)\frac{(sT_d^{'})^2}{1+(sT_d^{'})^2} + \left(\frac{1}{X_d^{''}} - \frac{1}{X_d^{'}}\right).\frac{(sT_d^{''})^2}{1+(sT_d^{''})^2} + \left(\frac{1}{X_q^{''}} - \frac{1}{X_q}\right)\frac{(sT_q^{''})^2}{1+(sT_q^{''})^2}\right] \qquad (6)$$

5. THE EFFECT OF TURBINE-GOVERNOR

The turbine-governor is set with a reference power by the speeder gear and a static droop which may vary from 3 to 4%. Under synchronous condition, $P_{as} = P_{ref}$, where P_{ref} is the active power setting of the turbine-governor. But under asynchronous condition, we have:

$$P_{as} = P_{ref} + s / R_u \qquad (7)$$

Now, the expression reduces to the following form:

$$f(s) = P_{as} - P_{ref} - s / R_u = 0 \qquad (8)$$

This equation can be solved by applying numerical methods like that of Newton-Raphson to find out the slip for specified value of the active power (appendix-1).

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6. INFINITE BUS ASSUMPTION - EFFECT OF SERIES REACTANCE AND DISCHARGE RESISTANCE

As the rating of the machine is not comparable to the grid power, we treat it as one machine on infinite bus connected through series impedance. The series impedance is the sum of the impedance of the transformer and that of the short transmission line (if any) connecting the machine to the grid system. The line capacitance is neglected for a short line. The schematic diagram of the idealized machine is given in fig. 1.

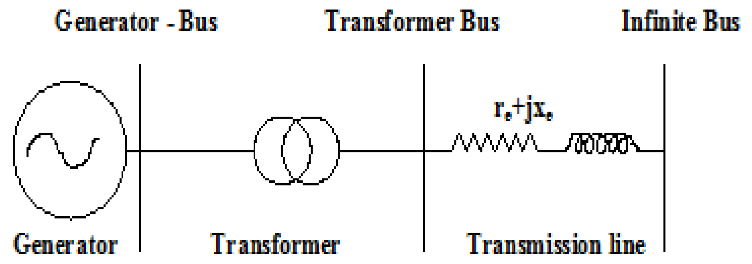

Fig. 1. A generator connected to infinite bus through a transformer and a transmission line

The effect of series impedance to infinite is beneficial as it reduces the magnetizing VAR drawn from the system. But it also reduces the terminal voltage of the machine and hence increases the slip for a given reference power. 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 modifies the reactances of the machine and the short-circuit time constants. The discharge resistance also modifies the d-axis open circuit and short-circuits transient time constants. The resultant expressions are given below:

$$X_{de} = X_d + X_e;\ X_{qe} = X_q + X_e;\ X'_{de} = X'_d + X_e;\ X''_{de} = X''_d + X_e;\ X''_{qe} = X''_q + X_e \tag{9}$$

$$\begin{aligned} &T'_{do} = T'_d.X_d / X'_d\ ;T''_{do} = T''_d.X'_d / X''_d\ ; T''_{qo} = T''_q.X'_q / X''_q\ ; \\ &T'_{dom} = T'_{do}.r_f / (r_f + r_d)\ ; T'_d = T'_{dom}.X'_{de} / X_{de}\ ; \\ &T''_d = T''_{do}.X''_{de} / X'_{de}\ ; T''_q = T''_{qo}.X''_{qe} / X_{qe} \end{aligned} \tag{10}$$

The generator terminal voltage is given as:

$$V_g = V - I_a\angle\phi(r_e + jX_e) \tag{11}$$

The voltage is normally depressed under LOE, to such an extent that under voltage relays may trip at many buses.

7. CASE-STUDIES ON ASYNCHRONOUS OPERATION

Now we shall undertake a no. of case studies on asynchronous variables under sudden loss of excitation. The alternator under LOE is assumed to be on infinite bus through its transformer.

This programme computes asynchronous. torque and power for varying input voltage and fixed ref. power of BANDEL TPS 5th unit, using N-R method. All quantities are in p.u. & time constants in sec. All quantities refer to the equivalent machine including the generator transformer. The first case-study is being made for LOE with 60% power and the second case study is being made for LOE with 40% rated power. The computer print outs converted to word-format are given below:

The parameters and time constants:

Leakage reactance, x_a = 0.152

D-axis syn. Reactance, X_d = 2.3616

D-axis transient reactance, $X_d^{'} = 0.4416$

D-axis subtransient reactance, $X_d^{''} = 0.3506$

Q-axis syn. Reactance, $X_q = 2.2466$

Q-axis subtransient reactance, $X_q^{''} = 0.4476$

D-axis open circuit transient time constant, $T_{do}^{'} = 0.7778$

D-axis s.c. transient time constant, $T_d^{'} = 0.1454$

D-axis s.c. subtransient time constant, $T_d^{''} = 0.1369$

Q-axis short circuit subtransient time constant, $T_q^{''} = 0.1195407$

Synchronous speed = 314.2 r/s

Reactance to infinite bus, $X_e = 0.1366$

Discharge resistance, $R_d = 4 \times r_f$

Static droop in p.u., $R_u = 0.04$

Case-I: The reference torque (or power) has been set at 60% of rated power = 0.6 x 0.85 = 0.51 p.u. by speeder gear within 30 sec from the occurrence of fault and may be continued up to 90 sec.

Table-1: Reference torque = 0.51 p.u. P_{as} (60% of rated power) (from 30 to 90 sec.)

Slip s	Terminal Voltage V	Asyn. reactive Power Q_{AS}	Asyn apparent power S_{AS}	Asyn current S_{AS}	Pulsating power P_{pul}
0.00344	1.00	0.62276	0.80494	0.80494	0.31929
0.00364	0.98	0.61588	0.79963	0.81595	0.32069
0.00386	0.96	0.61041	0.79543	0.82857	0.32225
0.00411	0.94	0.60569	0.79181	0.84235	0.32339
0.00440	0.92	0.60376	0.79033	0.85905	0.32539
0.00472	0.9	0.60335	0.79002	0.87780	0.32721
0.00512	0.88	0.60653	0.79245	0.90051	0.32987
0.00559	0.86	0.61259	0.79710	0.92686	0.33258
0.00618	0.84	0.62359	0.80558	0.95903	0.33593
0.00696	0.82	0.64163	0.81963	0.99955	0.33999
0.00803	0.8	0.66830	0.84067	1.050840	0.34397

Case-II The reference torque (or power) has been set at 40% of rated power = 0.4 x 0.85 = 0.34 p.u. by speeder gear within 90 sec from the occurrence of fault and may be continued up to breaker operation..

Table- 2 : Reference power = 0.34 p.u. (40% of rated power) (after 90 sec.)

Slip s	Terminal Voltage V	Asyn. reactive Power Q_{AS}	Asyn apparent power S_{AS}	Asyn current S_{AS}	Pulsating power P_{pul}
0.00211	1.00	0.51306	0.61549	0.61549	0.20883
0.00221	0.98	0.49962	0.60434	0.61667	0.20932
0.00232	0.96	0.48675	0.59374	0.61848	0.20975
0.00242	0.94	0.47394	0.58329	0.62052	0.20954
0.00255	0.92	0.46250	0.57403	0.62394	0.21015
0.00270	0.90	0.45185	0.56548	0.62831	0.21084

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0.00285	0.88	0.44198	0.55762	0.63366	0.21155
0.00301	0.86	0.43235	0.55003	0.63957	0.21174
0.00320	0.84	0.42438	0.54378	0.64736	0.21266
0.00341	0.82	0.41719	0.53189	0.65633	0.21342
0.0036	0.80	0.40822	0.53126	0.66408	0.21201

It may be noted from table-1 that the rating has not been exceeded for 60% of rated power except for V = 0.8 p.u. Such an under-voltage is not likely to occur. From table-2 it may be noted that the asynchronous variables are well within limits. Therefore, the instruction of BHEL may be followed to limit the power cut-off for at least half-an-hour safely.

8. CONCLUSION

The computation of asynchronous torque and power for a given load and a given terminal voltage is a formidable task. It can be made by breaking up the formula for asynchronous power and applying computer iterative techniques to them. We have used the Newton-Raphson method which fast converges to the solution.

It has been noted that a turbo generator under LOE-fault is quite safe at 60% of rated power for limited time and at 40% power of rated power for unlimited time. Therefore, the instruction of BHEL to continue power supply under asynchronous mode of operation for 20-30 minutes is quite justified. If the fault cannot be removed within this time then the machine is to be switched off, as the pulsating power exchange and low voltage profile around the faulty machine is not acceptable from the power quality point of view.

However, it is not admissible for hydro generators as the asynchronous variables are much larger for them, particularly the pulsating power. So they must be switched off within 2-3 minutes.

By running turbo generators under LOE for some time, we can reduce the extent of load-shedding. This is possible only if the system is rich in capacitive VARs, such that the voltage profile is not extremely poor..

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APPENDIX - A

Algorithm:

Algorithm for numerical solution of eqn. 5 using Newton-Raphson method is given below:

Step-1: $Read\ P_{ref}, V, X_d, X_d^{'}, X_d^{''}, X_q, X_q^{''}, T_d^{'}, T_d^{''}, T_q^{''}, f, r_f, r_d, X_e, R_u$

Step-2: $X_{de} \leftarrow X_d + X_e;\ X_{qe} \leftarrow X_q + X_e;\ X_{de}^{'} \leftarrow X_d^{'} + X_e;\ X_{de}^{''} \leftarrow X_d^{''} + X_e;\ X_{qe}^{''} \leftarrow X_q^{''} + X_e$

Step-3: $T_{do}^{'} \leftarrow T_d^{'}.X_d / X_d^{'};\ T_{do}^{''} \leftarrow T_d^{''}.X_d^{'} / X_d^{''};\ T_{qo}^{''} \leftarrow T_q^{''}.X_q^{'} / X_q^{''};\ T_{dom}^{'} \leftarrow T_{do}^{'}.r_f / (r_f + r_d)$

Step-4: $T_d^{'} \leftarrow T_{dom}^{'}.X_{de}^{'} / X_{de};\ T_d^{''} \leftarrow T_{do}^{''}.X_{de}^{''} / X_{de}^{'};\ T_q^{''} \leftarrow T_{qo}^{''}.X_{qe}^{''} / X_{qe}$

Step-5: $k_1 \leftarrow V^2 T_d^{'}(1/X_{de}^{'} - 1/X_{de})/2;\ k_2 \leftarrow V^2 T_d^{''}(1/X_{de}^{''} - 1/X_{de}^{'})/2;\ k_3 \leftarrow V^2 T_q^{''}(1/X_{qe}^{''} - 1/X_{qe})/2$

Step-6: $Initialize\ slip, convergence\ const., \max.\ no.\ of\ iteration: s, \varepsilon, n_{\max}$

Step-7: $f \leftarrow -P_{ref} + s/R_u + s(1-s)\left[\frac{k_1}{1+(sT_d^{'})^2} + \frac{k_2}{1+(sT_d^{''})^2} + \frac{k_3}{1+(sT_q^{''})^2}\right]$

Step-8: $f^{'} \leftarrow 1/R_u + \left[\frac{k_1\{1-2s-(sT_d^{'})^2\}}{\{1+(sT_d^{'})^2\}^2} + \frac{k_2\{1-2s-(sT_d^{''})^2\}}{\{1+(sT_d^{''})^2\}^2} + \frac{k_3\{1-2s-(sT_q^{''})^2\}}{\{1+(sT_q^{''})^2\}^2}\right]$

Step-9 $s_{new} \leftarrow s - f/f^{'}$

Step-10 $If\ |s_{new} - s| < \varepsilon\ then\ goto\ step 14$

Step-11 $count \leftarrow count + 1$

Step-12 $If\ count > n_{\max}\ then\ goto\ step 19$

Step-13 $s \leftarrow s_{new} : goto\ step 7$

Step-14 $s \leftarrow s_{new}$

Step-15 $P_{as} = s(1-s)\left[\frac{k_1}{1+(sT_d^{'})^2} + \frac{k_2}{1+(sT_d^{''})^2} + \frac{k_3}{1+(sT_q^{''})^2}\right]$

Step-16 $Q_{as} = s\left[\frac{k_1 sT_d^{'}}{1+(sT_d^{'})^2} + \frac{k_2 sT_d^{''}}{1+(sT_d^{''})^2} + \frac{k_3 sT_q^{''}}{1+(sT_q^{''})^2}\right]$

Step-17 $S_{as} \leftarrow (P_{as}^2 + Q_{as}^2)^{1/2};\ I_{as} = S_{as}/V$

Step-18 $print\ s, P_{as}, Q_{as}, S_{as}, I_{as} :\ goto\ step 20$

Step-19 $No\ convergence\ in\ 'n_{\max}'\ no\ of\ iterations. Try\ again\ changing\ initial\ value.$

Step-20 $stop : end$