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Coordination of Loss of Excitation with Capability Curve and Steady State Stability Limit for a Large Alternator

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Abstract

With the introduction of availability based tariff in the open access power transfer regime, utilities may derive benefit by proper coordination of Loss of Excitation (LOE) Relay with Generator Capability Curve (GCC) and Steady State Stability Limit (SSSL). The co-ordinated operation of protection and excitation may extend the time of availability of the generator during some of the system disturbances, without jeopardizing the generator and system health. In this work an algorithm has been developed which specifically ensures the coordination of LOE relays with generator full load capability and machine steady state stability limits during normal & abnormal conditions by adopting specific calculation methods. Modeling has been done in PSCAD/EMTDC software to check the required coordination of the relay on a large alternator.

Keywords: Minimum Excitation Limiter (MEL), Over Excitation Limiter (OEL), Under Excitation Limiter (UEL), Steady State Stability Limit (SSSL), Loss of Excitation (LOE)

Introduction

A protection scheme in a power system is designed to protect the power system and its apparatus to ensure maximum continuity of electrical supply with minimum damage to life and equipments. Stable operation of power system requires continuous matching between energy supply to prime mover and the electrical load on the system and an adequate reactive power support mechanism to maintain voltage within limit at different buses. Performance of excitation system is very important during a disturbance as it acts to maintain system stability. The excitation limit determines the steady state stability characteristic of the generator. If the excitation is not sufficient to provide the vast demand of the generator, then the stability limit is exceeded. Our objective is to keep the generator online for an optimizing time without infringing on the system stability limits and at the same time without compromising the health of the generator.

Generator Capability

Synchronous generators have the capability of generating (overexcited generator) or absorbing (under excited generator) power. The capability curve [1] establishes the steady state (continuous) generator operating limits of generator. The generator capability curve is normally published at generator rated voltage.The generator capability is a composite of three different curves: the stator winding limit, the rotor heating limit and the stator end iron limit. GCC depends upon Generator excitation voltages, coolant pressure, turns in the armature & field windings.

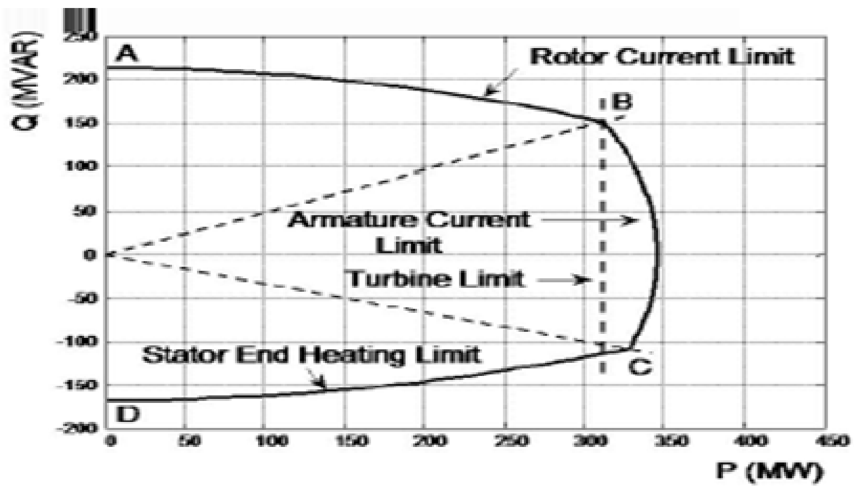

Figure 1: Generator Capability Curve

There are varieties of controls like Automatic Voltage Regulator (AVR), which may operate manually or automatics. All the automatic control modes may have supplementary controls Minimum Excitation Limiter (MEL), over excitation limiter (OEL) etc.

This supplementary control may ensure that the generator is always operated within capability limit. The main duty of the limiters is to keep the synchronous machine operating within the safe and stable operation limits, avoiding the action of protection devices that may trip the unit. Also the purpose of the work is to maximize the time operation of the generator during Loss of excitation (LOE) within its capability limit without infringes on the system stability.

Brief Background

Earlier work has been done in [1] to describe traditional protection function related to the Capability curve, such as stator thermal, rotor thermal, motoring, over voltage, under voltage and loss of field protection. The paper by Mozina [2] provided practical guidance about proper coordination of generator protection and generator AVR control to enhance security and system stability. The paper by Benmouyal [3] proved the impact of the excitation system with an AVR or a power system stabilizer (PSS) on the generator stability limits. The paper by ZHANPENG [4] analyzed the generator loss of excitation fault and described an investigation on existing loss of excitation protection schemes. The paper by Berube [5] presented a brief review of the experience and perspective of a large Canadian utility with Under Excitation Limiters (UELS). The paper by Hurley [6] presented Under Excitation Limiter (UEL) models which can be applied to the excitation system models of synchronous machines. The paper by Seba [7] provided UEL control effect on dynamic behavior of synchronous generators in a Power System. Another work by an IEEE group [8] presented Computer Models for representation of newer digital-based excitation systems in transient stability programs.

A Theoretical Understanding

Generator Capability Curve

Synchronous generators have the capability of generating (overexcited generator) or absorbing (under excited generator) power. The capability curve [1] establishes the steady state (continuous) generator operating limits of generator. The generator capability curve (GCC) is normally obtained at generator rated voltage. The generator capability is a composite of three different curves (Fig.1): the armature current limit, the rotor current limit and the stator end region heating limit. GCC depends upon Generator excitation voltages, coolant pressure, turns in the armature & field windings, altogether described in Fig.1 & Fig.2.

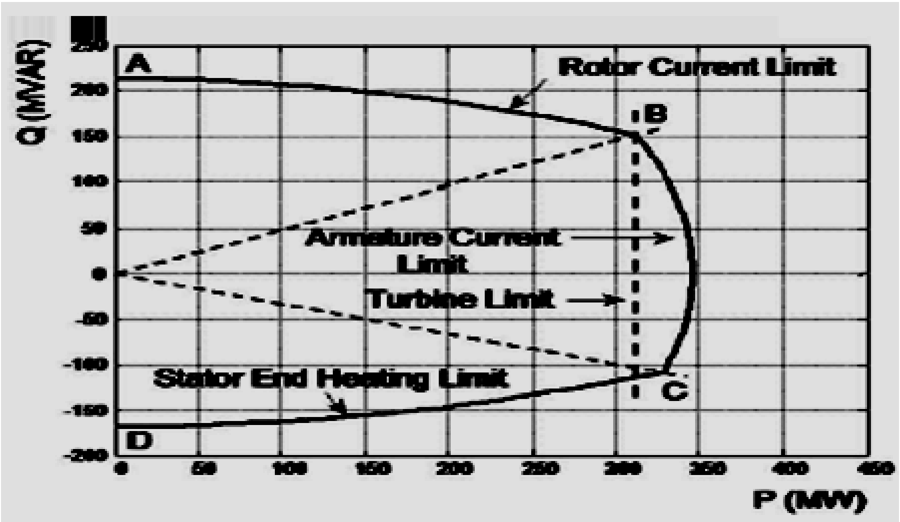

Figure 1: Generator Capability Curve

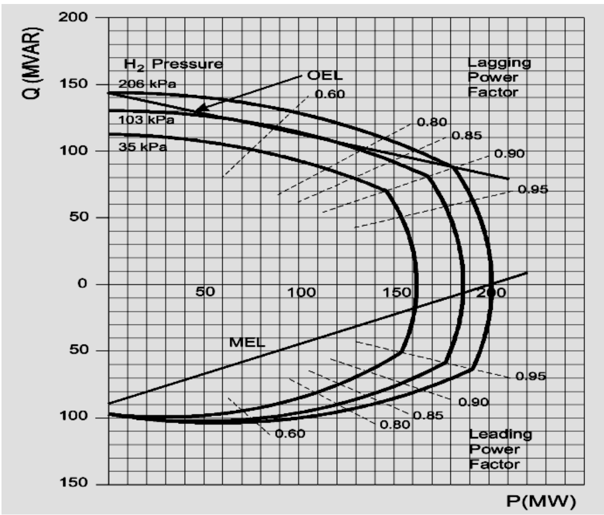

Figure 2: Effect of hydrogen pressure on GCC

Steady State Stability Limit

The steady-state stability limit (SSSL) of a generator determines the region in the P-Q plane where the generator operation will be stable in a normal mode of operation. Normal mode of operation is defined here as a mode where only small and minor disturbances are occurring on the network, as opposed to major disturbances such as faults, significant addition of load, or loss of generation.

The steady-state stability limit is used by protection engineers [3] in some coordination studies and for the adjustment of the under-excitation limiter (UEL) function in the AVR. An Elementary Generator system is shown in Fig.3 for which the locus of the SSSL curve has been shown (Fig.4).

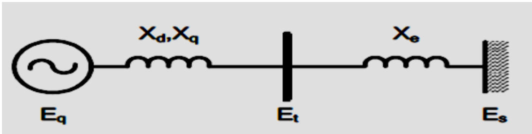

Figure 3: Elementary Generator system

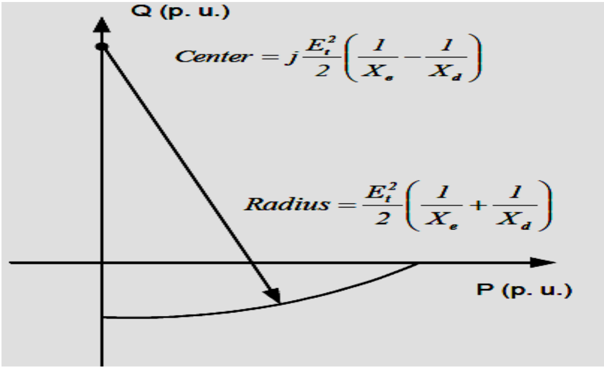

Figure 4: Steady State Stability Limit in P-Q Plane

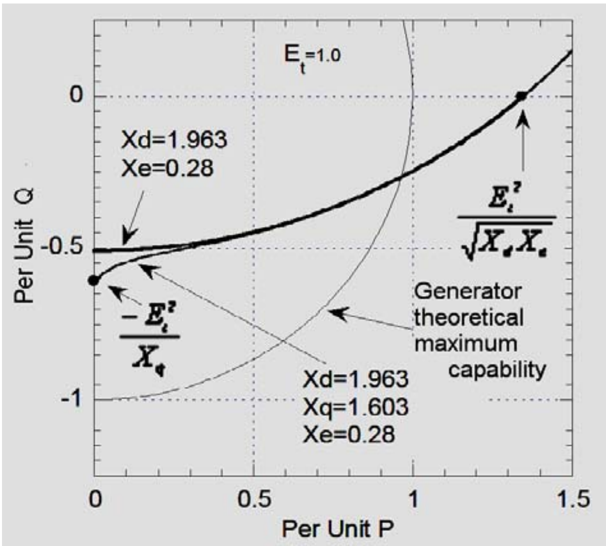

Figure 5: Nature of SSSL for Round Rotor and Salient pole Type Generator

Fig.5 shows the SSSL of both a salient pole and round rotor generators [3] with the indicated characteristics. Difference between the two curves lies only in the area close to the Q-axis where the point of intersection is at point 1/Xq for the salient pole generator rather than 1/Xd for the round-rotor generator. Therefore the difference between the two SSSL curves should be considered as negligible for all practical purposes.

Effect of Excitation & System Reactance over SSSL

When an unstable condition exists in the power system, one equivalent generator [4] rotates at a speed that is different from the other equivalent generator of the system. We refer to such an event as a loss of synchronism or an out of-step condition of the power system. The system remains stable until the power angle δ= 90°. Beyond the curve maximum (δ > 90°) a load increase causes a decrease in the transfer power and the system loses synchronism. The value of Pe for δ = 90° represents the SSSL for this ideal lossless system. The generator electric power output versus load angle and with system reactance as shown in Fig.6 & Fig.7.

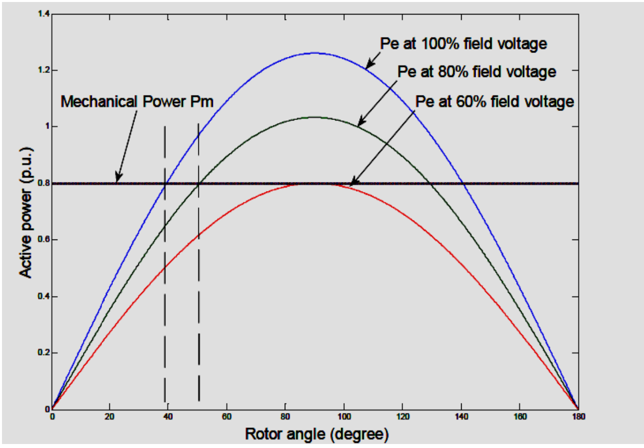

Figure 6: Dependence of SSSL on Excitation voltage

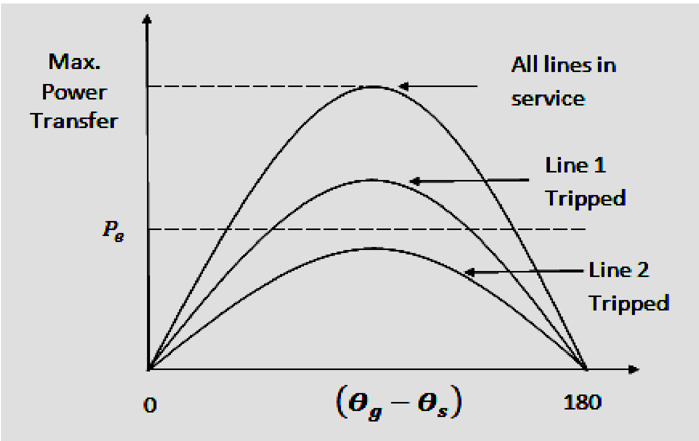

Figure 7: Dependence of SSSL on system reactance

Typically, when the power system is strong [2] (Xs is low) the SSSL locus is outside the generator capability curve as shown in Fig.8.However, on weak systems, the manual SSSL can be more restrictive than the generator capability in the under excited region as in Fig.9.

The increase in the extent of shaded portion of the Relay operating zone highlights the vulnerability of the system with a weak Xs as shown in the fig.

As stated previously, three factors may limit the capability of a synchronous generator to operate in the under excited region.

In this region, core-end heating, power-system stability or allowable operating voltage limit to the generator capability to absorb reactive power.

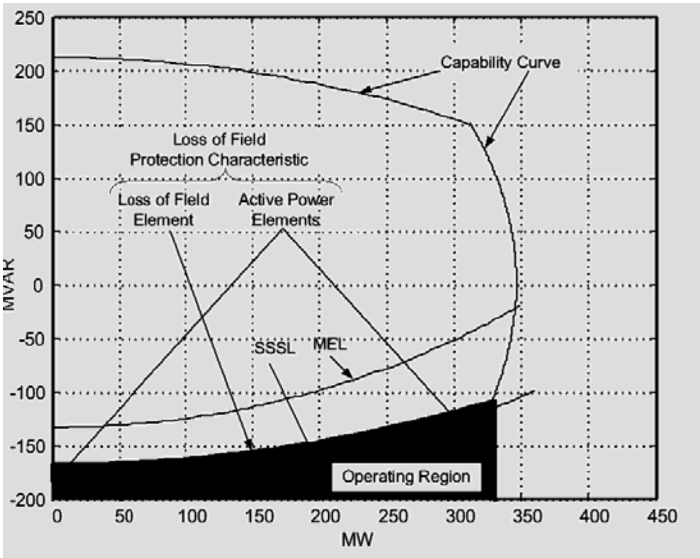

Figure 8: Loss of field element characteristics in the P-Q plane set to coordinate with the Generator capability curve when the SSSL characteristics is outside the capability curve

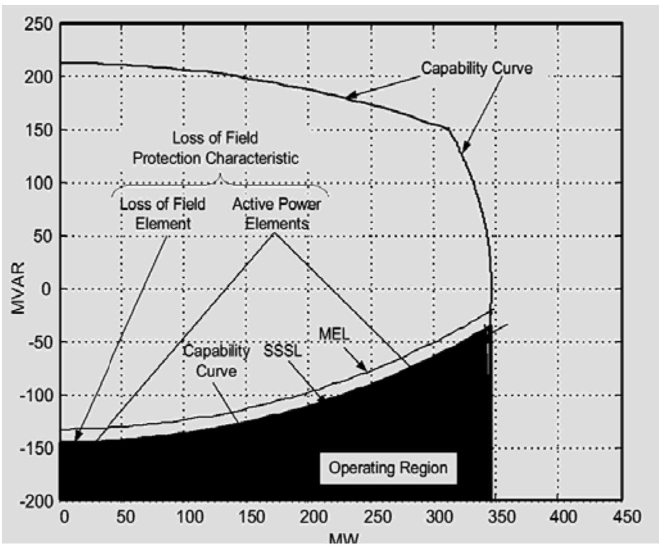

Figure 9: Loss of field element characteristics in the P-Q plane set to coordinate with the SSSL when the SSSL characteristics is inside the capability curve

Loss of Excitation Protection

Protection from Loss of excitation condition of the generator is provided to prevent machine damage due to large stator currents and to prevent large reactive drain from the system resulting in voltage collapse and tripping of transmission lines.

Normally, there are two approaches to detect the loss of excitation based on impedance measurement. One is using [2] two negative-offset mho elements as shown in Fig.10 and the other is using a positive-offset mho and a directional element as shown in Fig.11.

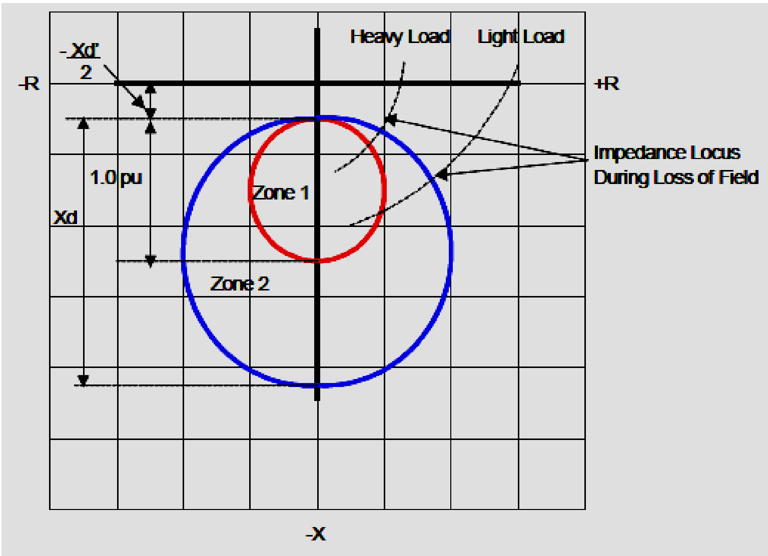

Figure 10: LOE Relay Locus in R-X Plane Scheme-1

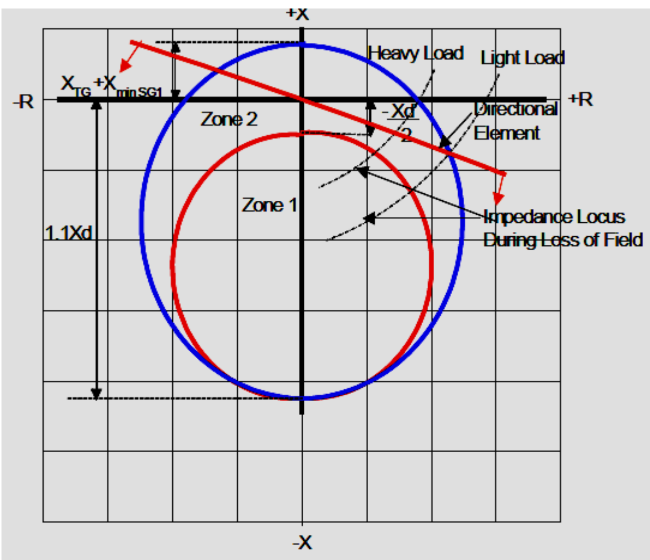

Figure 11: LOE Relay Locus in R_X Plane Scheme2

LOE Coordination in R-X Plane

The LOE coordination in R-X plane needs to transfer all three characteristics of GCC, UEL [2]. It also needs to draw SSSL in R-X plane. The UEL limit will remain quite away from both the relay operating zones. The impedance locus has to cross the UEL limit first which may take care of the system voltage. GCC and SSSL will have their position next to UEL before the relay operating zone (Fig.12). It is an established procedure to detect LOE in R-X plane.

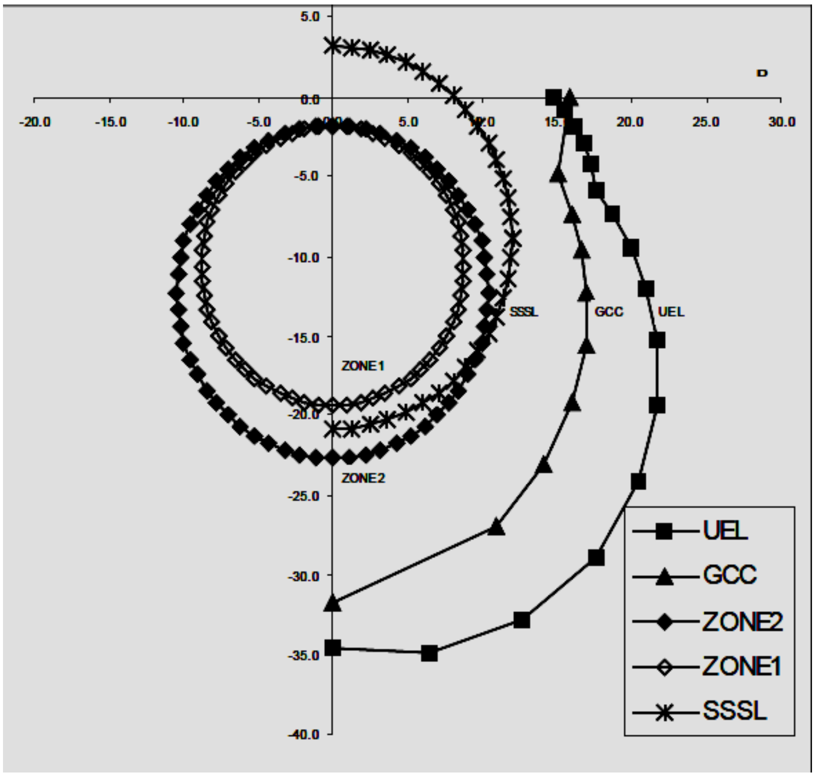

Figure 12: Relay Coordination in R-X Plane

Objective of the Study

Protection relays are to be set to adjust the generator full load capability and within the system steady state stability limit. Therefore setting of protective relay should adjust itself with the changes in the parameters of terminal voltages and active and reactive power flows which determine the steady-state stability limit.

The objective of study is to make proper coordination of loss of field protection setting with steady state stability limit and generator capability curve under the varying condition of system reactance and voltage. The purpose is that the unit should be tripped before the steady state stability limit is reached without crossing the boundary of the GCC at that existing system conditions.

The LOE scheme should be provided with adequate time delay for providing security against operation during stable power swing.So the LOE relay setting should be properly coordinated with Generator capability curve (GCC) and Steady State Stability Limit (SSSL) for a loss of excitation unit in a large alternator.

Proposed Scheme for Coordination of Loss of Excitation with SSSL and GCC in P-Q Plane

Our aim is to make the LOE relay characteristic adaptable with the changing Steady State Stability Limit (SSSL) or Generator capability curve (GCC) in P-Q plane according to system operating condition. Keeping this in mind we converge on the following deliberations.

The study of the SSSL trajectory of the system in the P-Q plane with the change of system reactance (Xe) and voltage at generator terminal voltage (Vt) during LOE. The LOE relay characteristic is then to be set properly by coordinating with the changing SSSL and GCC in the P-Q plane to detect loss of excitation Condition and ultimately how long the generator to be kept in system, without losing stability.

When the SSSL characteristic is outside the capability curve (for strong system) the loss-of-field element characteristic is set to coincide with the capability curve to protect the generator from stator-end core heating, as in Fig.8. This setting permits full use of the generator capability to absorb reactive power, beyond the MEL setting. When the SSSL characteristic is inside the generator capability curve (as may occur in a weak power system), the SSSL characteristic becomes the factor that limits the amount of reactive power that the generator can absorb and then the loss of field element characteristic is set to coincide with SSSL, as in Fig.9.

This change in system voltage, current and eventually active and reactive power (P and Q respectively) is to be sensed and computed on-line.

The work evolves into the development of an algorithm which tracks the dynamic of the P-Q trajectory.

Numerical calculation of steady state limiting points and the corresponding generator Capability Points in the P-Q plane(with changing Hydrogen Pressure) are found out and judged through the algorithm the criterion for system instability or system inability during loss of excitation and tripping action initiated.

No separate LOE Relay in R-X plane is necessary.

Flow Chart of Proposed Methods

Therefore the intelligence developed a coordination of SSSL, GCC UEL and LOE locus in the P-Q plane. In our work coordination of only SSSL and GCC have been done with the LOE relay in Fig.13.

Mathematical Equations & Models used in flowchart are described in Appendix-B

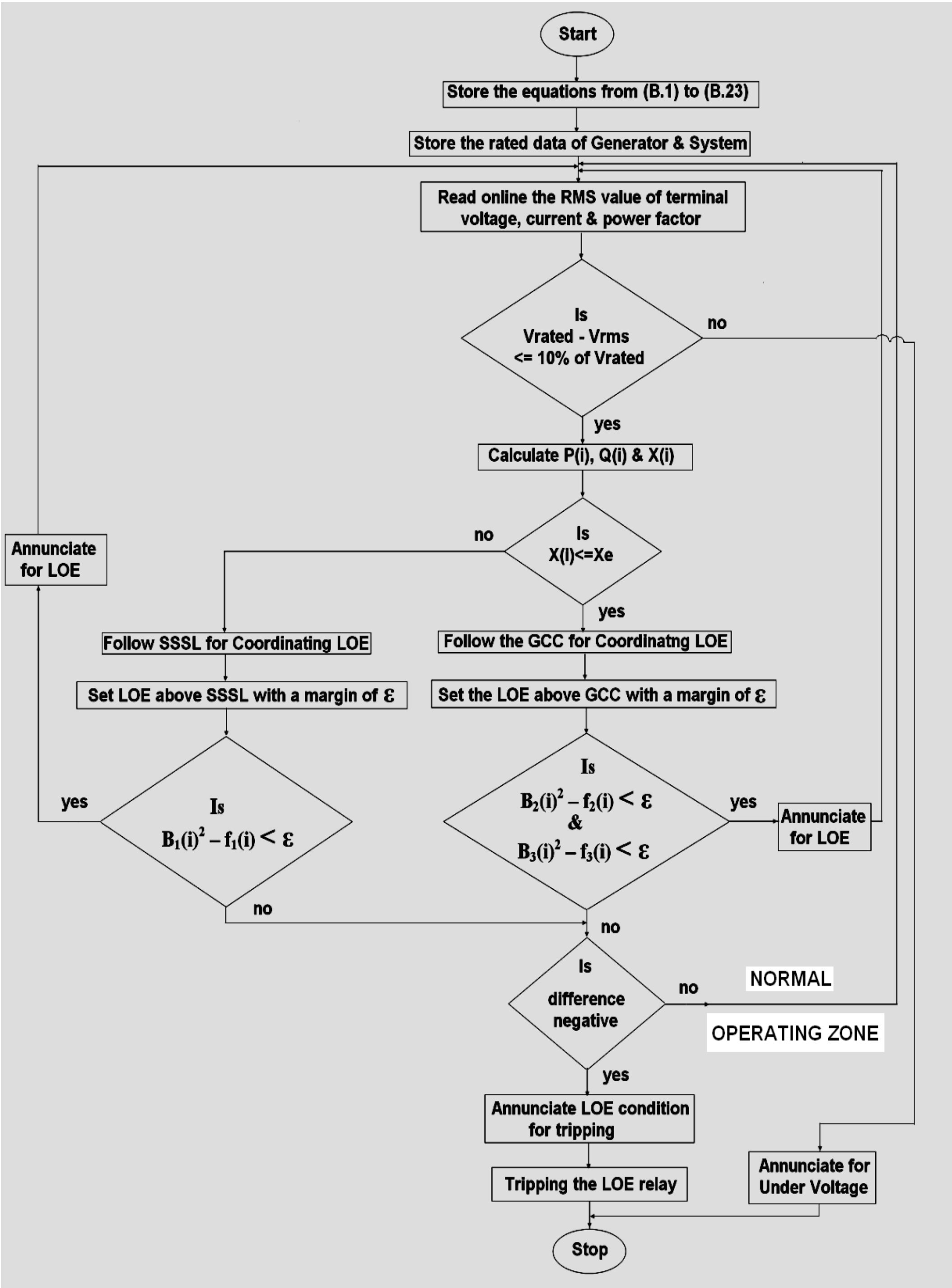

Figure 13: Representation of LOE Scheme

System Modeling for LOE using PSCAD

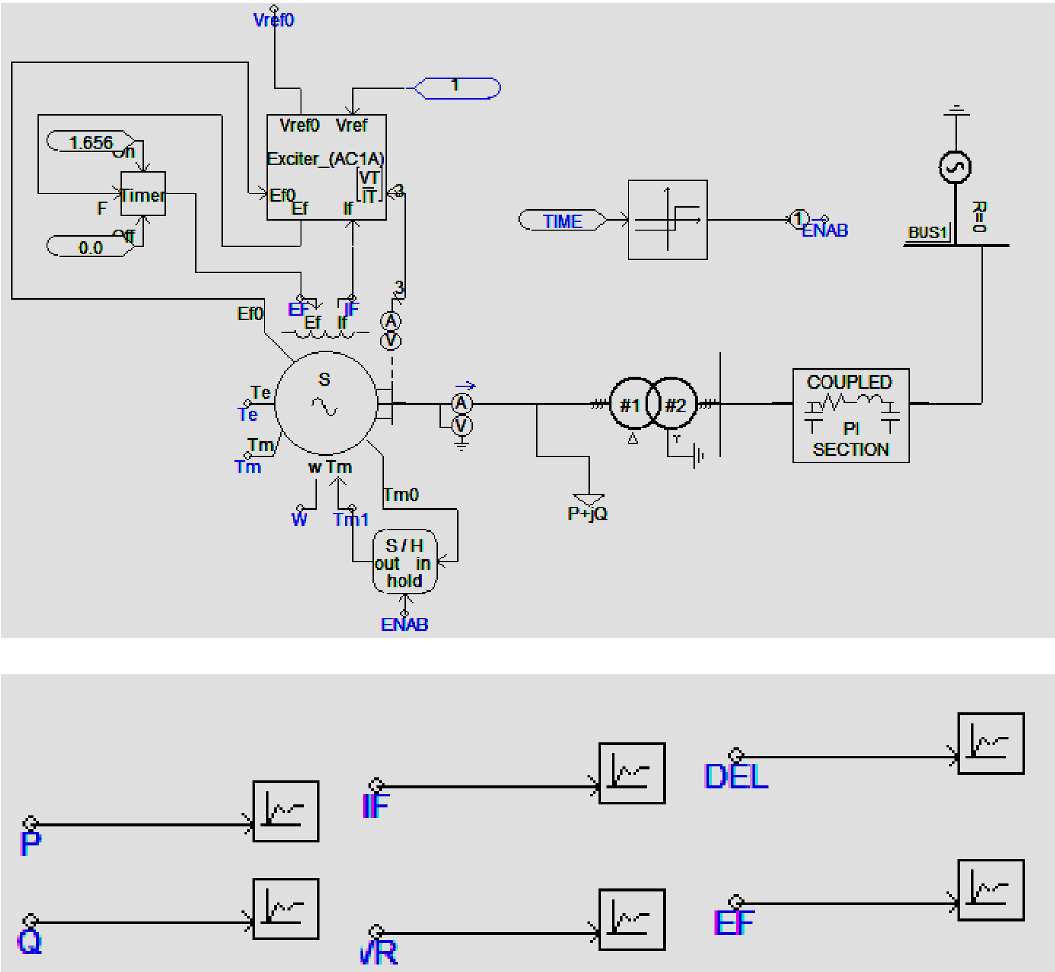

Figure 14: Single Line Diagram of Generator and Power System Model Using PSCAD for Study of Loss of Excitation

Results of PSCAD Simultion

Appendix-A provides data on the generating units and associated power system. With reference to single line diagram (Fig.14) of a generator and power system the following results are found for various system parameters with respect to time. The x-axis represents the time in second and in y-axis field voltage in p.u (EF), field current (IF) in p.u, the terminal voltage in (V) in kV, active power (P) in MW and reactive power (Q) in MVAR are taken. The results as simulated are shown in the following graphs.

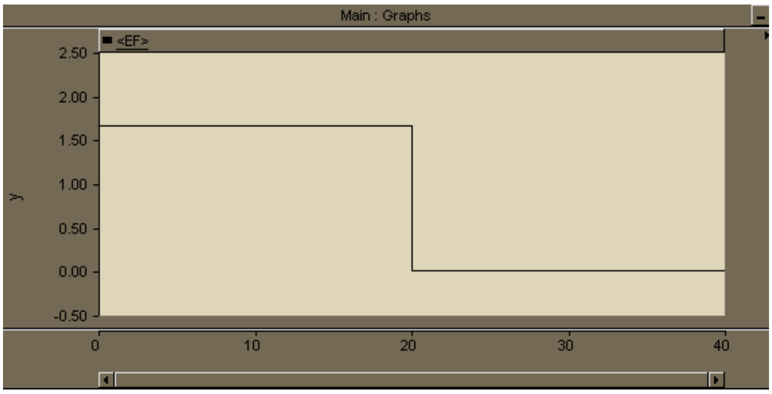

Figure 15.1: Field voltage (EF) vs. Time

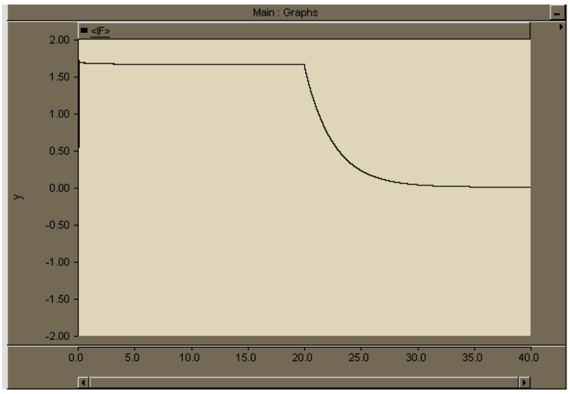

Figure 15.2: Field current (IF) vs. Time

The field voltage from excitatory is made zero after 20th second of steady state operation with the help of a timer circuit. The fig15.1 shows the field voltage becomes zero instantly at 20th second. The fig15.2 shows that the field current decreases exponentially according to field time constant.

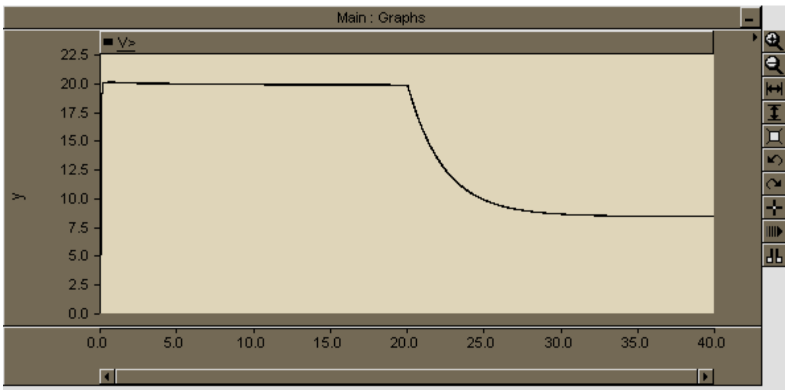

Figure 15.3: Terminal voltage (V) vs. Time

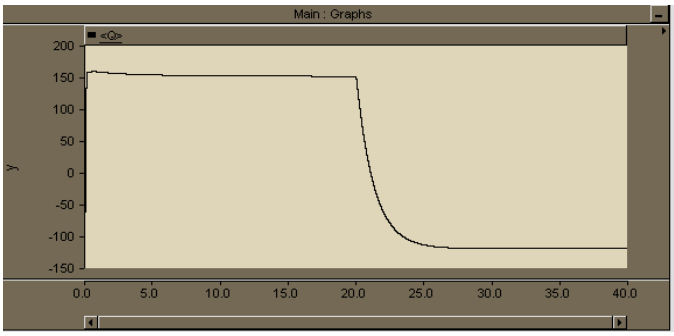

Figure 15.4: Reactive power (Q) vs. Time

When loss of excitation occurs, the terminal voltage starts to decrease. The terminal voltage is related to reactive power delivered which in turn depends on excitation (Fig.15.4). As excitation is lost the reactive decreases to zero and become negative and hence it draws huge reactive power from system or nearby generator (i.e. the direction of reactive power reverses.) to maintain its excitation. If the system is not able to supply sufficient reactive, the voltage reduced to a very small value causing voltage collapse. Large amount of reactive power causes High stator current to flow which in turn heats up the stator winding and stator end iron heating. In this case voltage reduced from 19.75 kV to 8.75 kV as shown in Fig.15.3.

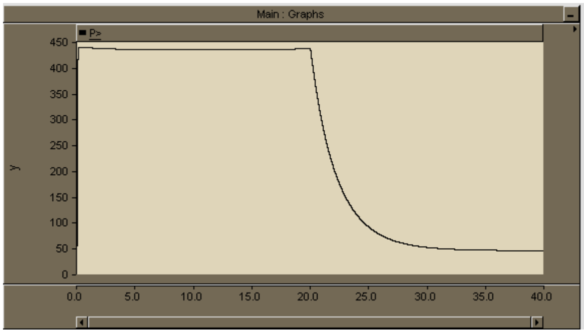

Figure 15.5: Active Power (P) vs. Time

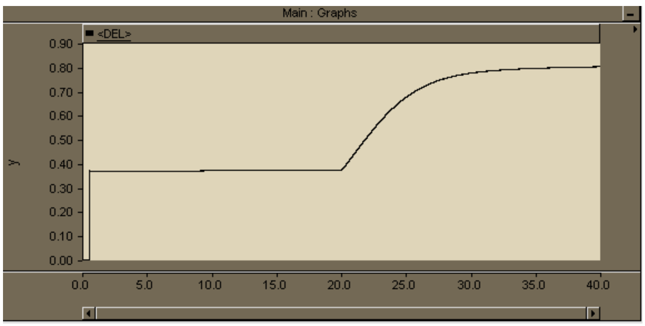

Figure 15.6: Load Angle (Del) vs. Time

The active power output decreases to a very small value as the excitations reduced and there is no other generator to support the excitation instantly except the system bus. The electrical output decreases from 434MW to 50 MW during loss of excitation period as shown in Fig.15.5 and the load angle increases from 0.38 radian to 0.8 radian at rated load as shown in Fig.15.6. If load is decreases to small value both active power output increases to 458Mw and load angle increases to 0.7rad.

Further Analysis & Verification of Results Through Matlab Simulation

The LOE relay loci are mapped from R-X plane to P-Q plane for steady state coordination. The locus in P-Q plane is obtained for zone1 & zone 2 relay locus in R-X plane which is verified by use of MATLAB. This locus will shifted up ward as we consider the system operating condition of varying voltage. So the PQ operating point may fall in to the relay operating zone thus the user may consider the LOE relay locus well inside the SSSL and GCC according to the operating conditions.

The position of the locus of zone one will be below the position of zone two. Each points of the relay locus in R-X plane are mapped in to P-Q plane. The lowest point of the locus in R-X plane mapped to highest point in P-Q plane. The relay locus in R-X plane is drawn in generator base because the coordination is to done in P-Q plane where generator steady state operating regions is plotted as shown in Fig.16.

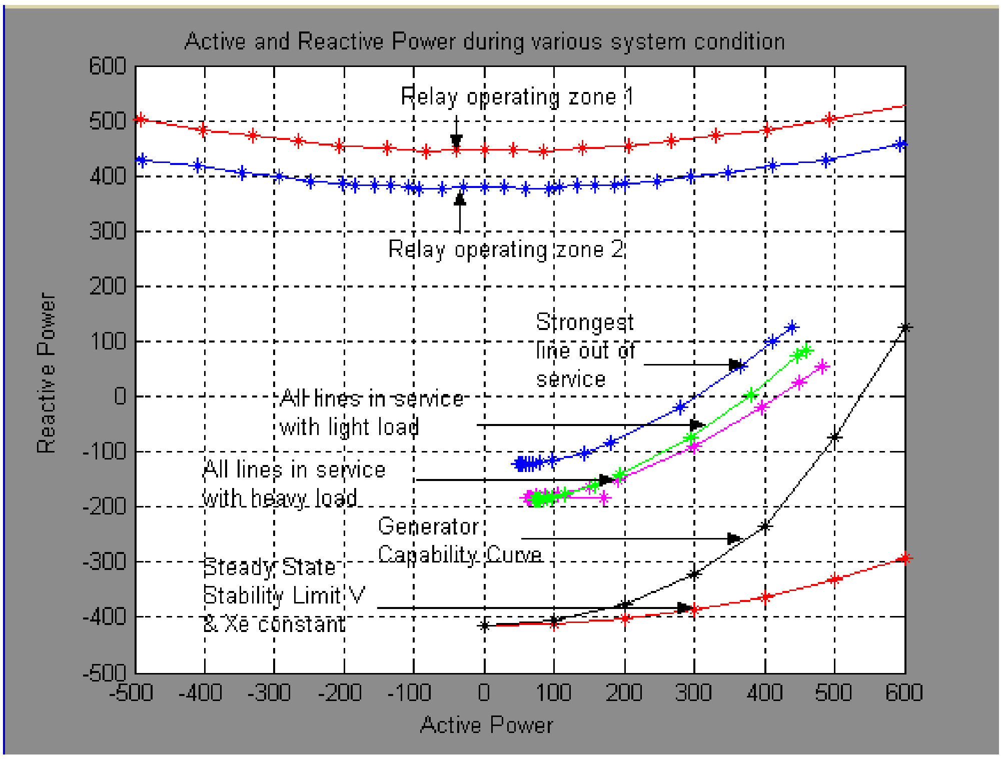

Figure 16: P-Q operating Point at Different system Condition

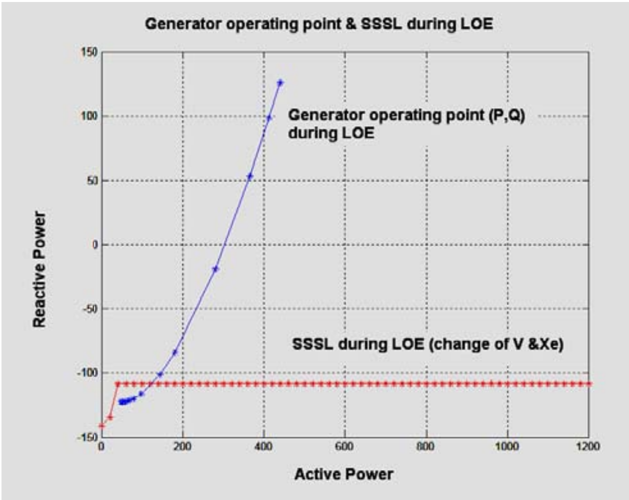

Figure 17: SSSL trajectory during changing system voltage at LOE &Generator operating point

Fig.17 shows the P-Q operating point falls below the SSSL under dynamic condition of system voltage and reactance when the unit losses excitation because of field supply reduced to zero instantaneously.

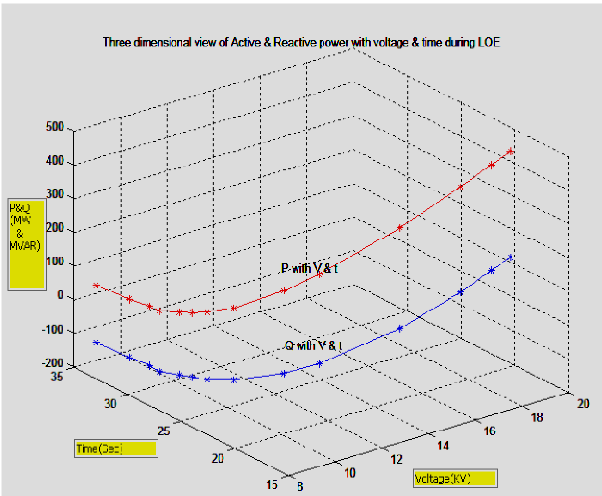

Figure 18:: Dynamic three Dimensional Views of Active and Reactive Power with Voltage and Time during Loss of Excitation.

Fig.18 shows Dynamic three dimensional views of p-q locus with Voltage & Time during Loss of Excitation through MATLAB simulation. The red curve & blue curve show dynamic three dimensional views of Active & Reactive Power locus respectively with Voltage & Time during Loss of Excitation.

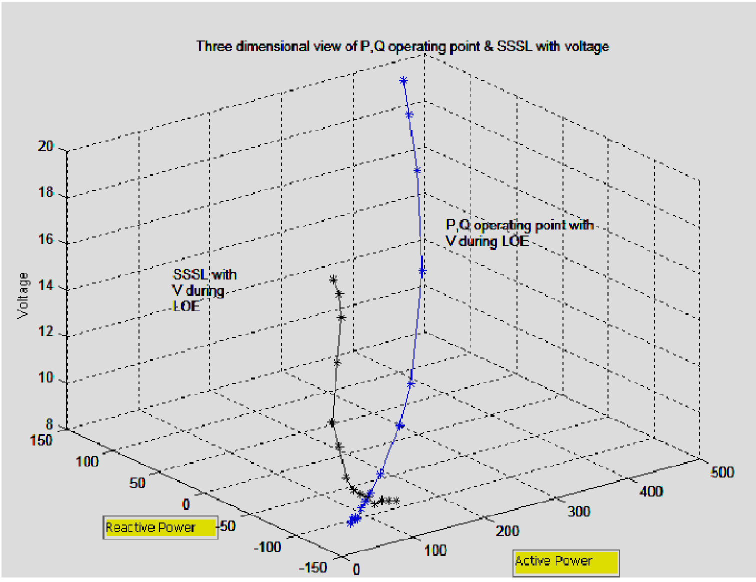

Figure 19: Three Dimensional Views of P-Q Operating Point and SSSL with varying Voltage.

Fig.19 shows three dimensional views of P-Q operating Point & SSSL with varying voltage through MATLAB simulation. The blue curve & red curve show P-Q operating point & SSSL locus respectively with voltage during LOE.

Conclusions

Major generator tripping events are not as rare as many people believe. Should they occur, such events can be very disruptive and costly to the utility power production. Delays in determining the cause of the disruption and in assessing equipment damage can add hours to reenergizing and returning to normal operations.

There are many advantages of this Co-ordination [1] Process:-(i) Reduction of loss of revenue due to reduction in power transfer. (ii)Improve reliability of generator VAR support to system. (iii) Reduction of transmission line overload. (iv) Reduction of unnecessary tripping of breaker and other equipments operation. (v) Reduction of likelihood of islanded system condition. (vi) Increased confidence in results of planning studies.

The LOE condition entails a check for both the generator capability as well as the system network to which the generator is connected. The fullest utilization of the generator capability within the SSSL of the power system is targeted before going for tripping.

Our work depicted the method to establish an optimum utilization of the generator capability without infringing on the stability limit. With the development of this intelligent system, on line monitoring of the SSSL points and GCC may be made possible with the integration of adaptive feature in the LOE relay.

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Appendix A

Source of System

System data
Positive sequence impedance:
Zmin = 0.00105 + j0.016463 pu (138KV, 100 MVA)
Zmax = 0.000511 + j0.010033 pu (138KV, 100 MVA)
System voltage = 138 KV, (L, L)
System frequency = 60 HZ

Generator Data
Rated MVA = 492 MVA
Rated voltage = 20 KV
Xd = 1.18878 pu
Xq = 0.146 pu
Xd'= 0.20577 pu
Tdo'= 5.2 s
Transformer Data
Rated MVA = 425 MVA

Rated voltage = 19/145 KV

AC1A Exciter
Rated feedback Gain (KF) = 0.03 pu
Rated feedback Time constant (TF) = 1.0 s
Infinite Bus Data
Base voltage = 138KV
Base MVA = 100 MVA
Frequency = 60 HZ
Timer
Duration on = 20 s

Appendix B

Mathematical Models used in flowchart

The equation representing SSSL circle as shown in Fig.4

$P^2 + (Q - q\ (i))^2 = B1\ (i)^2$ ….eqn. (B.1)

Where q (i) is the coordinate of the center A1 (i) on the Q-axis at ith instant, where the centre

A1 (i) = (0, q (i))…eqn. (B.2)

$q\ (i) = \frac{V_t(i)^2}{2}\left[\frac{1}{X(i)} - \frac{1}{X_d}\right]$…… eqn.(B.3)

And the corresponding radius is

$B1\ (i) = \frac{V_t(i)^2}{2}\left[\frac{1}{X(i)} + \frac{1}{X_d}\right]$… eqn.(B.4)

$f1\ (i) = P^2 + (Q - q\ (i))^2$ … eqn. (B.5)

Where f1 (i) represents a point on the SSSL when P=P (i) and Q=Q (i) and system reactance = X (i).Vt (i) is the terminal voltage at the ith instant.

To test the points P(i) &Q(i) on the B(i) curve representing the SSSL curve at the ith instant the following equation is used.

$B1\ (i)^{2-} f1\ (i) < \epsilon$… eqn. (B.6)

A separate LOE locus is not maintained. It is the difference ϵ (Eta) with the SSSL at respective instants that determines the LOE status. If the difference is negative, it indicates the point f1 (i) is outside the stability limit, then instant tripping initiated.

This criterion checks whether the measured P-Q has crossed the SSSL point at that instant.

Where ϵ is small margin which 3% of rated MVA of generator.

To determine a point on GCC the following equation are used

Armature current limit

The centre and radius of the curve BC as shown in Fig.1

A2 (P, Q) = (0, 0) and

B2= MVA rating which is constant …… eqn. (B.7)

$P^2 + Q^2 = B2^2$ … eqn. (B.8)

f2 (i) = $P^2 + Q^2$ … eqn. (B.9)

f2 (i) represents the value of armature current limit at ith instant when P=P (i) and Q=Q (i)

To test the points P(i) &Q(i) on the B(i) curve representing the GCC curve at the ith instant the following equation is used.

$B2^2$-f2 (i) <ϵ … eqn. (B.10)

Likewise as in the previous, a separate LOE locus is not maintained. The equation (B.10) checks whether the measured P-Q falls on armature current limit.

Stator end iron heating limit

The centre of the curve CD as in fig.1

A3 (i) (P, Q) = (0, K1* $\frac{V_t(i)^2}{X_d}$*492)…. eqn. (B.11)

Where K1=0.3 & Vt (i) is the terminal voltage at the ith instant. And the radius of the curve CD as in fig.1

B3 (i) =K2*$\frac{V_t(i)}{X_d}$…. eqn. (B.12)

Where K2 =1.3

Here the constants K1and K2 are assumed for temperature rise in field and armature winding.

The equation representing stator end iron heating curve is

$P^2 + (Q - q3\ (i))^2 = B_3\ (i)^2$… eqn. (B.13)

Where the coordinate on Q axis is

q3 (i) = K1*$\frac{V_t(i)^2}{X_d}$ *492… eqn. (B.14)

If f3 (i) = $P^2 + (Q - q3\ (i))^2$ … eqn. (B.15)

Then f3 (i) represents stator end iron heating limit point at ith instant when P=P (i) and Q=Q (i).To test the points P(i) &Q(i) on the B(i) curve representing the GCC curve at the ith instant the following equation is used.

B_3 (i) ^{2}-f3 (i) <ϵ … eqn. (B.16)

Likewise as in the previous, a separate LOE locus is not maintained. The equation (B.16) checks whether the P-Q operating point crosses the stator end iron heating curve.

Rotor heating current limit

The centre of the curve AB as in Fig.1

A4 (i) (P, Q) = (0, -$\frac{V_t(i)^2}{X_d}$*492) … eqn. (B.17)

And the radius of the curve AB as in Fig.1

B4 (i) = $\frac{EqV_t(i)}{X_d}$*492… eqn. (B.18)

The equation representing Rotor heating current limit circle is

P^2 + (Q – q4 (i)) ^{2} = B_4 (i) ^{2}… eqn. (B.19)

Where the coordinates on Q axis is

q4 (i) = $\frac{V_t(i)^2}{X_d}$ *492 … eqn. (B.20)

f4 (i) = P^2 + (Q – q4 (i)) ^{2} … eqn. (B.21)

Then f4 (i) represents the operating point at ith instant of time when P=P (i) and Q=Q (i). Vt (i) is the terminal voltage at the ith instant.

To test the points P(i) &Q(i) on the B(i) curve representing the GCC curve at the ith instant the following equation is used.

B_4 (i) $^{2-}$f4 (i) <ϵ…. eqn. (B.22)

Likewise as in the previous, a separate LOE locus is not maintained. The equation (B.22) checks whether the P-Q operating point lies inside the rotor current heating limit.

The equation used to calculate the system reactance on line is

$X(i) = \frac{V_t(i)^2 * Q(i)}{P(i)^2 + Q(i)^2}$…… eqn.(B.23)

For all decision blocks a delay subroutine is to be called to tide over transitory system inconsistencies.

$\frac{V_t(i)^2}{2}\left[\frac{1}{X(i)} - \frac{1}{X_d}\right]$