Modelling of Three Phase Short Circuit and Measuring Parameters of a Turbo Generator for Improved Performance

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***Abstract* - For use in power system stability simulations, utilities and system operators may desire to derive accurate model parameters of generators. Adjustments may have been made by field or operating personnel that have altered the response of the equipment. In these situations, there is a need to obtain more accurate models for simulation. Of a great extent in time, the research works directed at studying transients in synchronous generators have not yet provided fully sufficient comparative studies in respect to sudden short circuits of the machine. The present paper puts forward an idea of comprehensive process models for dynamic modelling of short circuit faults of unloaded synchronous generator, using the generalized *d-q*-0 mathematical model as starting point in derivation. Also, the computational efficiency is being increased by introducing a set of auxiliary variables common to different state equations. The models derivation is carried out without altering the structural equations of the generalized *d-q*-0 mathematical model of synchronous generators. The research has also proposed ways of obtaining synchronous machine parameters through direct test or measuring techniques. A plot of open circuit and short circuit characteristics shows why and how saturation should be considered to obtain the internal voltage, hence the reactance of the generator when sudden short circuit occurs.**

***Key Words*: Synchronous generator, dynamic modelling, open circuit, Short circuit, auxillary variables.**

INTRODUCTION

Modelling of short circuit characteristics of synchronous generator is an ongoing research for many researchers. The essence of it is to have indept knowledge of the dynamic performance either when in offline mode or on line mode. Different ratings of synchronous machines have been used and these vary from a few watts to hundreds of megawatts. Synchronous machine operating as a generator is of particular interest because it produces power to the mains. Its rotating speed is proportional to the frequency of the alternating – supply and is independent of the load. When it delivers power, the electromagnetic torque developed in the generator opposes the torque of the prime mover. A synchronous machine is an ac rotating machine whose speed under steady state condition bears a constant relationship to the frequency of current in the armature winding. A synchronous machine is one of the important types of electric machines. Large ac networks operating at constant frequency of 50Hz or 60Hz rely almost exclusively on synchronous generator, also called alternators for the supply of electrical energy and may have synchronous compensators at key points for control of reactive power.

1.1 Over view of a Synchronous Generator

The three phase machines are the largest and also perhaps the most common electric machines that run at synchronous speed. The higher efficiency of synchronous machine over others is an advantage at a higher power rating. Another advantage that makes a synchronous machine different from other machines is that varying its field excitation can vary its power factor of operation. This property makes it useful for the industry which is always operating at low lagging power factor. Part of the load is handled by synchronous machine whose field is adjusted such that it is operating at leading power factor to improve the overall power factor to nearly unity.

There are two types of synchronous generator; **the stationary field and the rotating dc magnetic field.**

The only difference between these two types of generator is their armature.

The stationary field synchronous generator has salient poles mounted on the stator. The poles are magnetized either by permanent magnets or by a dc current. The armature normally containing a three phase winding is mounted on the shaft, the stator windings are each spaced 120^0 apart from each other round the stator.

Voltages of equal magnitude are induced so producing a set of balanced three phase supply voltages, which can be used as either an isolated supply or can be connected in parallel with other generators to make up grid system in which all generators produce the same frequency and are in phase synchronism with one another.

The rotating magnetic field (also known as revolving field) synchronous generator has the field windings wound on the Rotor and the armature wound on the Stator. A dc current creating a magnetic field that must be rotated at synchronous speed energizes the rotating field winding. The field winding can be energized through a set of slip rings and brushes (external excitation) or from a diode bridge mounted on the rotor shaft (self excited). Large ac generators usually have exciters consisting of an ac source with solid state rectifiers. The rectifier-bridge is fed from a shaft-mounted alternator which is itself excited by the pilot exciter. In externally fed fields, the source can be a shaft-driven DC generator, a separately excited DC generator or a solid state rectifier. [1]. The synchronous generators are built with either salient pole or cylindrical iron rotors, depending on the speed and size of the machine. To any machine designer and power engineer, the prediction of the machine's performance characteristics is of highest priority [2]. In order to understand the characteristics of a machine, there are a number of different techniques available. These techniques are able to determine parameters defining the steady state , transient and subtransient response of a machine.

Analysis of synchronous machines has been implemented using different approaches such as open circuit step response test [3], time domain test using finite-elements [4] and time domain identification of generator transfer functions [5]. Modeling of the dynamics of three-phase round-rotor or salient-pole machine is important in using any of these methods. Synchronous generator short circuit studies are an essential tool for the power system designer. The task is to calculate the fault conditions and to provide protective equipment designed to isolate the faulted generator from the remainder of the system in the appropriate time. The interrupting capacity of breakers should be chosen to accommodate the largest of short circuit currents and hence care must be taken not to base the protection decision simply on the results of a balanced three-phase short circuit. The circuit breakers are capable of carrying for a short time the specified short circuit current. However, the possibility of catastrophic failure exists if the short circuit currents are not properly calculated and the breakers are subjected to fault duties that exceed their rating. The stator phase and rotor field currents at short circuit stressing take dangerous values, thermally overloading the installation. The critical value of electromagnetic torque, during short circuit transient, has to be known by the generator designer to appraise the mechanical strength of the structure. The vast majority of commercial software designed for short circuit transient analysis are based on the empirical calculations encompassed by the accepted standards. Dynamic simulation of short circuit faults is always an option, not expressly for validation of the results received from standardized calculations but also for an accurate and effective representation of the transient behaviour. The present paper describes various novel, comprehensive, and general process models for modelling of synchronous generators short circuit transients. The models derivation was carried out without altering the structural equations of the generalized *d*-*q*-0 mathematical model of synchronous generator. The proposed simulation technique offers the advantage of an increased computational efficiency by introducing auxiliary variables, common to different state equations. The time-consuming matrix inversion at each step of numerical integration, performed when currents are selected as state variables and with a view to computing the currents derivatives, is eliminated by advancing the models in a convenient split matrix form that allows symbolic processing. For practical purposes, besides the time-domain analysis, the peak values of short circuit characteristic quantities are depicted as dependencies upon the initial value (at short circuit occurrence) of the rotor lag angle. Such kind of representation considerably facilitates the examination of the differences among the results corresponding to different short circuit types, hence permitting to study the synchronous generator behaviour closely. **[6]**

2.0 THE BASICS OF THREE PHASE FAULT

A balanced 3-phase fault implies that all three phases of the power system are simultaneously short-circuited to each other through a direct or "bolted" connection.

* Often, a 3-phase fault produces the largest short-circuit current magnitude; thus, this worst-case result is then used as the basis to select the short-circuit capabilities of switchgear from manufacturers' tables.

* Short-circuit calculations are easier for a balanced 3-phase fault because symmetry of the fault connection permits one to consider only one of the three phases.

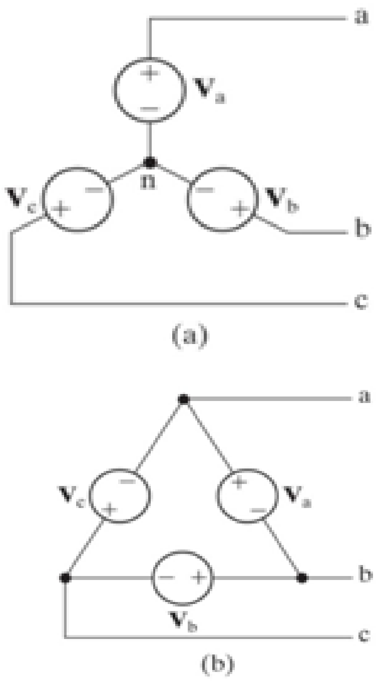

Figure 1 Balanced three phase circuit

The other types of unbalanced short-circuit faults are important in selecting the time-current characteristics and settings of phase-overcurrent and ground-fault protective devices to provide selective coordination. This coordination assures service continuity and minimizes damage to switchgear and load equipment.

2.1 Symmetrical RMS Current versus Short-circuit Duty

In general, a 3-phase synchronous generator, previously unloaded, that has been subjected to a balanced, 3-phase fault across its accessible terminals is used.

The root mean-square (rms) value of the asymmetrical short-circuit current waveform obtained, is the basis for the selection of the short-circuit capabilities of circuit breakers and fuses. Calculation of the precise rms value of an asymmetrical current at any time after the inception of a short-circuit may be very involved. Accurate decrement factors to account for the DC component at any time are required, as well as factors for the rate of change of the apparent reactance of the generators. This precise method may be used, if desired; however, simplified methods have evolved whereby the DC component is accounted for by simple multiplying factors. These multiplying factors convert the rms value of the symmetrical AC component (symmetrical rms current) into rms current of the asymmetrical waveform, including the DC component (asymmetrical rms current or short-circuit current duty).

2.1 Types of Networks used to Calculate Symmetrical rms Current

In order to utilize AC circuit theory in calculating symmetrical rms current, three types of networks are used to represent the power system over three time intervals of the fault-on time period.

* First-cycle (momentary) network.

* Contact-parting (interrupting) network.

* Approximately 30 cycle network.

These networks only differ from one another by the assignments of constant reactances for the machines.

2.2 First-cycle(momentary) Network.

This network is used to calculate the first-cycle (momentary) symmetrical rms current. Here, the rotating machine sources of short-circuit current are represented, for the most part, by their subtransient reactance, according to the entries in the first column of Tables 4-1 and 4-2 of the 1993 edition of the IEEE Red Book (or Tables 24 and 25 of the 1986 edition).

2.3 Contact-parting (interrupting) network.

This network is used to calculate the contact-parting (interrupting) symmetrical rms current for circuit breaker minimum contact-parting times of 1.5 to 4 cycles after the inception of the short-circuit fault. Here, the rotating machine sources of short-circuit current are represented by different constant reactances than the first-cycle (momentary) network, according to the entries in the second column of Tables 4-1 and 4-2 of the 1993 edition of the IEEE Red Book (or Tables 24 and 25 of the 1986 edition).

2.4 Approximately 30 cycle network.

This network is often a minimum-source representation to investigate whether minimum short-circuit currents are sufficient to operate current-actuated relays. Minimum-source networks might apply at night or when production lines are down for any reason. Some of the source circuit breakers may be open and all motor circuits may be off. In-plant generators are represented with transient reactance or a larger reactance that is related to the magnitude of decaying generator short-circuit current at the desired calculation time.

3.0 THE *D-Q*-0 MODEL OF SYNCHRONOUS GENERATOR

The generalized mathematical model of a turbo synchronous generator encompasses two distinctive sets of structural equations. These are the differential equations, that is, voltage and motion equations, and the algebraic correlations between flux linkages and currents (the flux equations).
The voltage equations of synchronous generators are given by means of the following ordinary differential equations. [7-11]

Stator Voltage equation

$$v_d = Ri_d + \frac{d}{d\tau}\lambda_d - \omega\lambda_q \qquad (1)$$

$$v_q = Ri_q + \frac{d\lambda_q}{d\tau} + \omega\lambda_d \qquad (2)$$

For the Rotor windings:

$$\left.\begin{aligned} v_{fd} &= R_{fd}i_{fd} + \frac{d\lambda_{fd}}{dt} \\ 0 &= R_D i_D + \frac{d\lambda_D}{dt} \\ 0 &= R_Q i_Q + \frac{d\lambda_Q}{dt} \end{aligned}\right\} \qquad (3)$$

Where:

v denotes voltage

i denotes current

λ denotes flux linkage

d-q denotes direct axis components

f_d, D, Q denote variables and parameters associated with field winding and the d-q axis damper windings respectively.

R denotes resistance

ω denotes rotor speed

σ denote stator and rotor leakage inductances

3.1 The development of Three Phase Short Circuit

Note the following relations for the development of the three phase short circuit models

$$L_d = L_\sigma + L_{md}$$

$$L_q = L_\sigma + L_{mq}$$

$L_{fd} = L_{fd\sigma} + L_{md}$
$L_D = L_{D\sigma} + L_{md}$
$L_Q = L_{Q\sigma} + L_{mq}$

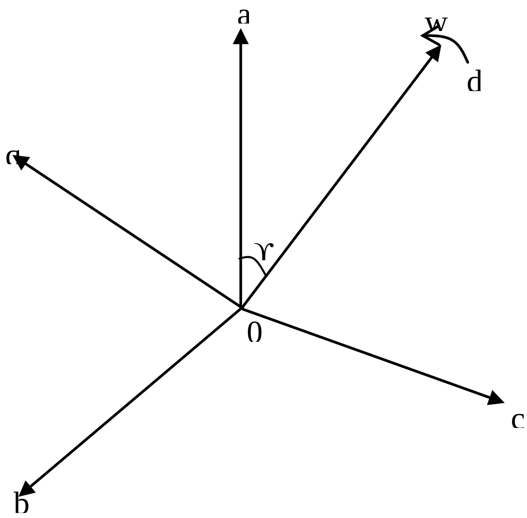

Figure 2 Systems of stator phase axes and the d-q references frame.

a = phase A axis   d = Direct axis
b = phase B axis   q = Quadratic axis
c = phase C axis

Figure 2 shows that rotor quantities are referred to stator, it also show that the lag angle of the rotor γ is measured between the stator phase A axis and the direct (d-axis) and its decrease in time, correspond to a positive rotor angular velocity

$$\frac{d\gamma}{dt} = -\omega \qquad (4)$$

The direct and converse Park-Goren transform are given by

$$X_d = \frac{2}{3}\left[X_A \cos\gamma + X_B \cos\left(\gamma + \frac{2\pi}{3} + X_c \cos\left(\gamma + \frac{4\pi}{3}\right)\right)\right]$$
$$X_q = \frac{2}{3}\left[X_A \sin\gamma + X_B \sin\left(\gamma + \frac{2\pi}{3} + X_c \sin\left(\gamma + \frac{4\pi}{3}\right)\right)\right]$$
……(5)

$X_A = X_d \cos\gamma + X_q \sin\gamma + X_o$

$X_B = X_d \cos\left(\gamma + \frac{2\pi}{3}\right) + X_q \sin\left(\gamma + \frac{2\pi}{3}\right) + X_o$

$X_c = X_d \cos\left(\gamma + \frac{4\pi}{3}\right) + X_q \sin\left(\gamma + \frac{4\pi}{3}\right) + X_o.$ (6)

respectively.

The substitution X which can be current, voltage or flux linkage are to be performed in equations (3.5) and (3.6). The mapping (3.5) performs the transformation of the stator winding variables to a coordinate system in which the rotor is stationary. The equivalent winding are identified in the direct and quadratic axis. The direct axis (d-axis) winding is the equivalent one of the phase winding but aligned directly with the field. The quadrature axis (q-axis) is situated so that its axis is perpendicular to the axis of rotor field winding.
In order to improve legibility in presentation and to increase computational efficiency during numerical integration, the following set of auxiliary variables are introduced:

$L_{d1} = L_d \cos\gamma$, $L_{d2} = L_d \sin\gamma$,
$L_{q1} = L_q \cos\gamma$, $L_{q2} = L_q \sin\gamma$,
$L_{md1} = L_{md} \cos\gamma$, $L_{md2} = L_{md} \sin\gamma$,   (7)
$L_{mq1} = L_{mq} \cos\gamma$, $L_{mq2} = L_{mq} \sin\gamma$.

Flux equation

$$\lambda_d = L_d i_d + L_{md} i_{md} = L_d i_d + L_{md}.(i_{fd} + i_d) \qquad (8)$$
$$\lambda_q = L_q i_q + L_{mq} i_{mq} = L_q i_q + L_{mq}.(i_{fq} + i_q) \qquad (9)$$

Rotor voltage Equations to eliminate flux variables

$$L_{md}\frac{di_d}{d\tau} + L_{fd}\frac{di_{fd}}{d\tau} + L_{md}\frac{di_d}{d\tau} = -R_{fd} i_{fd} + v_{fd} \qquad (10)$$

$$L_{md}\frac{di_d}{d\tau} + L_{md}\frac{di_{fd}}{d\tau} + L_d\frac{di_d}{d\tau} = -R_d i_d \qquad (11)$$

$$L_{mq}\frac{di_q}{d\tau} + L\frac{di_q}{d\tau} = -R_q i_q \qquad (12)$$

With rotor excitation voltage v_{fd} as input variable. Also replacing the stator d-q axis flux linkages, in generalized electromagnetic torque, using correlation (8) and (9) the electromagnetic torque is expressed in terms of current in d-q axis:

$$T_{em} = \frac{3}{2}p(-L_{md} i_{md} i_q + L_{mq} i_{mq} i_d). \qquad (13)$$

The restrictive condition in this case is

$$i_A + i_B + i_C = 0 \leftrightarrow i_0 = \frac{i_A + i_B + i_C}{3} = 0$$
$$v_A = v_B = v_C = 0 \qquad (14)$$

or by applying the direct Park-Gorev transformation;

$$v_d = v_q = 0 \qquad (15)$$

By employing the current-based expressions (8) and (9) to eliminate the flux variables from stator voltage, the following processed voltage equations result:

$$L_d\frac{di_d}{d\tau} + L\frac{di_{fd}}{d\tau} + L_{md}\frac{di_d}{d\tau} = -Ri_d + \omega.(L_q i_q + L_{md} i_q)$$
(16)

$$L_q\frac{di_q}{d\tau} + L_{mq}\frac{di_q}{d\tau} = -Ri_q - \omega.(L_d i_d + L_{md} i_{fd} + L_{md} i_d)$$
(17)

$$\frac{d\gamma}{d\tau} = -\omega$$ (as stated in (4))

$$\frac{d\omega}{d\tau} = -\frac{p}{J}T_{em} \quad \text{...} \qquad (18)$$

Where,

P = Generator pole pairs
T_{em}= The driving turbine torque
J = Equivalent moment of inertia
γ = Rotor lag angle
The short circuit model follows by coupling (15) and (16) with the processed rotor voltage equation (10-12), (13) and (18) given interms of d-q axis current .
In this case, the electro-magnetic torque preserves the general expression given for electromagnetic torque in terms of d-q axis currents . The model incorporates seven differential equations and the vector of state variables includes the stator d-q axis currents, the rotor (field, damper) current, angular velocity and the rotor lag angle.
At each step of numerical integration, the stator phase currents result by means of converse Park-Gorev transform (6) having in view of equation (14) that points the annulment of the zero sequence components.
Thus the three phase short circuit Model is shown below:

$$i_A = i_d cos\gamma + i_q sin\gamma \qquad (19)$$

$$i_B = \frac{1}{2}\left(-i_d + \sqrt{3i_q}\right)\cos\gamma - \frac{1}{2}\left(\sqrt{3i_d + i_q}\right)\sin\gamma \qquad (20)$$

$$i_C = \frac{-1}{2}\left(i_d + \sqrt{3i_q}\right)\cos\gamma + \frac{1}{2}\left(\sqrt{3i_d - i_q}\right)\sin\gamma \qquad (21)$$

4.0 MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL

The three quantities that must be determined in order to describe the generator model are:

1. The relationship between field current and flux (and therefore between the field current I_F and the internal generated voltage E_A);
2. The synchronous reactance;
3. The armature resistance.

The open-circuit test on the synchronous generator is first conducted: the generator is rotated at the rated speed, all the terminals are disconnected from loads, the field current is set to zero first. Next, the field current is increased in steps and the phase voltage (which is equal to the internal generated voltage E_A since the armature current is zero) is measured.
Therefore, it is possible to plot the dependence of the internal generated voltage on the field current – the open-circuit

The SCC is a straight line since, for the short-circuited terminals, the magnitude of the armature current is:

$$I_A = \frac{E_A}{\sqrt{R_A^2 - X_S^2}} \qquad (22)$$

Where I_A is Armature current
R_A is Armature resistance
X_s is synchronous reactance

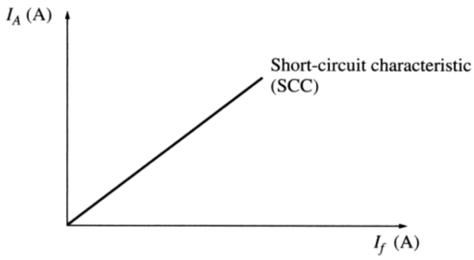

Figure 3 Short circuit characteristics of a turbo generator

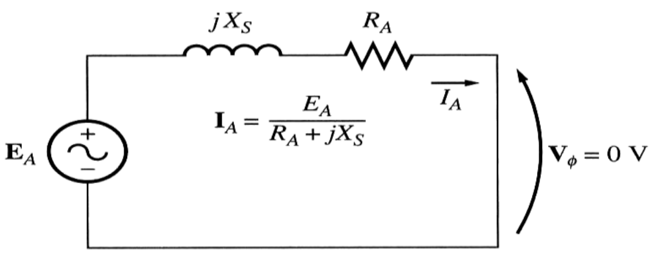

Figure 4 The equivalent generator's circuit during short circuit per phase.

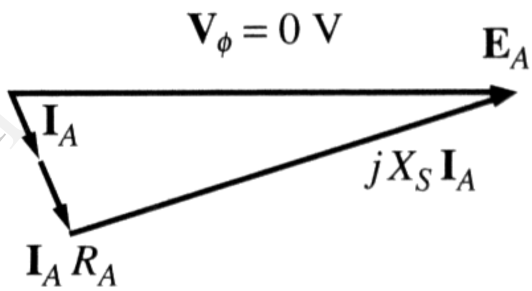

Figure 5 The resulting phasor diagram

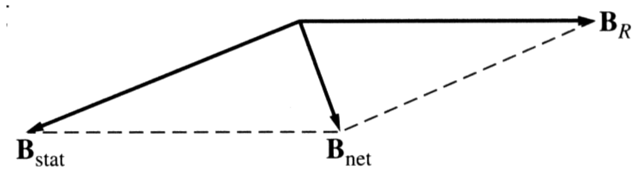

Figure 6 The magnetic fields during short-circuit test

Since B_S almost cancels B_R, the net field B_{net} is very small.

Where:

B_R is the rotor magnetic field

B_S is the stator magnetic field

B_{net} is the net magnetic field

Also since the unsaturated core of the machine has a reluctance thousands times lower than the reluctance of the air-gap, the resulting flux increases linearly first. When the saturation is reached, the core reluctance greatly increases causing the flux to increase much slower with the increase of the mmf.

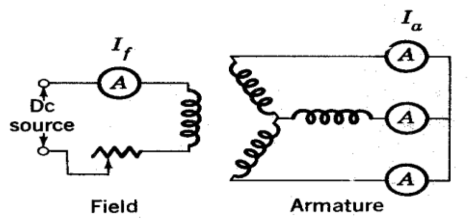

Figure 7 Connection for open circuit test

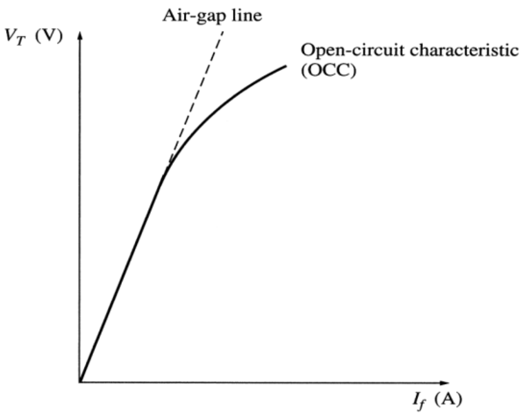

Figure 8 Open circuit characteristics of a turbo generator

We conduct next the short-circuit test on the synchronous generator: the generator is rotated at the rated speed, all the terminals are short-circuited through ammeters, the field current is set to zero first. Next, the field current is increased in steps and the armature current I_A is measured as the field current is increased. The plot of armature current (or line current) vs. the field current is the short-circuit characteristic (SCC) of the generator.

4.1 An Approximate Method to Determine the Synchronous Reactance x_s at a given field current:

1. Get the internal generated voltage E_A from the OCC at that field current.

2. Get the short-circuit current $I_{A,SC}$ at that field current from the SCC.

3. Find X_S from $$\boldsymbol{X_s = \frac{E_A}{I_{Asc}}}$$

Since the internal machine impedance is

$$\boldsymbol{Z_s = \sqrt{R_A^2 + X_s^2}}$$

$$\frac{\textbf{Open circuit per phase voltage}}{\textbf{Short circuit per phase current}} = \frac{E_A}{I_{ASE}} = \boldsymbol{X_s} \quad (23)$$

Under the assumptions that the synchronous reactance *Xs* and the induced *emf Ea* have the same values in both the open and short circuit tests, and that *Xs* >> *Ra*,

4.2 Conclusion

Three-phase synchronous machines account for a high percentage of any country's power generation. Understanding the machine's dynamic characteristics and determining its equivalent circuit and performance characteristics are of prime importance to a power engineer. The main purpose of modelling short circuit characteristics study is to infer the machine's reactance. From time to time it is necessary to develop user models for equipment which do not have representation in commercial software standard libraries for stability assessments. Emerging technologies and new equipment are typical bases for **user models**.

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