Extracting Machine Parameters at Condition of Sudden Short Circuit of a Turbo Generator at Constant Speed

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***Abstract*— This paper present a novel approach of extracting parameters of a turbo generator at constant speed in off line mode under the condition of saturation. The method involves two separately excited DC motors of very low rated value through a gear system that drives the generator. At sudden short circuit, the gear system which is at a ratio of 1:5 of the motor speed and generator speed (600:3000 rpm) keep the prime mover at the rated speed thereby making the generator to run at its synchronous speed. Under the condition of sudden short circuit, the system is simulated and the oscillograms of the armature current i_a, field current I_{fr}, armature voltage v_{as}, voltage at quadrature axis V_{qs}, torsional effect and voltage at direct axis V_{ds}, were captured. The parameters at subtransient, transient and steady state were extracted. This is done at rated voltage of the generator used for the simulation. The result shows a high level of accuracy because there was no deviation of synchronous rotor speed.**

Keywords*— *Constant speed, saturated, short circuit, DC motors, parameters

I. INTRODUCTION

An essential component of an electric power system is the three phase ac generator. These days, almost all power generators are of synchronous type. Machine designers and plant operators have always been interested in the determination of the parameters of synchronous machine since their introduction as the standard means for generation and distribution of electric power. As the need develops for increasing use of simulation for the dynamic system, the parallel need arises for the access to reliable data on machine constants and characteristics.

Parameter extraction of turbo generator has been a topic of interest to many investigators for several decades. Different ratings of synchronous machines have been used and these vary from a few watts to hundreds of megawatts.

Several tests have been proposed along with their implementation methodology over the years. Those tests have had different impacts on the synchronous machine; some of these are applied when the machine is at stand still, while others are applied when the machine is on line.

Unloaded synchronous machines are also often installed in power systems solely for power factor correction or for control of reactive power(KVAr) flow, such machines are known as **synchronous condensers** and may be more economical in the large size than static capacitors [1] Analysis of synchronous machines has been implemented using different approaches such as open circuit step response test [2], time domain test using finite-elements and time domain identification of generator transfer functions [3]

Power system stability concerns the power system's response to disturbances [4]. Synchronous generators play a very important role in these studies.

In carrying out short circuit simulation, and analysis of parameters in problems involving electromechanical transients, slow varying phase is assumed and this assumption is justified considering the high moments of inertia exhibited by turbine generator sets like synchronous generator [5].

Generator parameters are in general not constant throughout the useful life of a synchronous generator. Some parameters such as the magnetizing inductances in the direct and quadrature axes vary at different operating points due to the effect of magnetic saturation. These and other parameters also change because of aging since generator parameters are properties of physical materials in the generator winding that undergo changes in their physical characteristics with time. Further major changes in generator parameters occur after a repair. For example rewinding of rotor of a generator would cause the field resistance to be different from the original design value. For this reason, parameters extraction is necessary to ensure that the parameters used in various power system studies are accurate and to enhance the confidence in the interpretation of the results of such studies.

Traditionally, synchronous generator parameters are obtained by manufacturers data sheets and then verified and enhanced by off-line tests, as described in IEEE standard

II. ARRANGEMENT /DESIGN OF THE SCHEME USED FOR THE STUDY

The scheme uses two separately excited dc machine (motors) and a special spring mechanism to drive the generator. The generator is fully excited so that at no load, rated voltage stands at the terminals of the armature winding.

The Generator's rating used for the study is : 214MVA, 2-pole, 21kv, 50 Hz, 3000rpm. Motor rating 2MW, 600rpm, 1250kg.m^2, 888V, 3040A, 7.3mΩ.

Two identical separately excited dc motors rated at 2MW each are stiffly coupled together and arranged to drive a gear train. The gear then drives the synchronous generator through a flexible spring coupling.

The speed of the DC motor set is 600rpm, and since the required speed of the generator is 3000 rpm, the gear has to be of a 1:5 ratio type.

The armature voltage is connected between the terminals A-B and Rst is the starting resistor usually inserted to limit the high starting current. The field circuit has a very high inductance compared to that of the armature ($L_f >> L_a$). In the process, a short circuit generator is used to initiate the sudden short circuit.

A. Reasons for the Chosen Approach

In off-line sudden-short-circuit test rigs of synchronous machines, Dc motors are used as prime movers owing to their precision in speed. Such tests impress torque loads (generator short-circuit torques) of a time-varying nature on the couplings and shaft, and this is aggravated if the rating of the tested generator is several times that of the driving Dc motor. Dc motors of the separately excited type are favoured for such applications, because the field and armature fluxes can be controlled independently.

During short-circuit tests, speed has to be maintained constant, otherwise, the parameters extracted from the armature current wave form will be inaccurate. So the question is which prime mover can give such a constant speed drive?

It is known that induction motors cannot be used to drive the generator because when the short circuit occurs, the speed must change in accordance with slip changes because of the high air gap torque and high armature current at the terminals of the generator.

The ratings of biggest size Dc machines are between 2 and 3MW while medium sized turbo generators are as high as 200MVA so ordinarily, these cannot be used to drive 214MVA generator because of the high difference in rotor inertia.

Again, SSC tests are usually performed at very low voltages partly due to the inability to find matching sizes of Dc motors and the need to find current collecting gears to absorb the high explosions attending SSC tests.

To this end, the common method is to under excite the machine so that the output voltage, the short circuit current and the air gap torque becomes low then the extracted parameters will be extrapolated to the extent of the excitation .

This method is inaccurate because saturation would not have been considered and it is known that magnetic circuit of synchronous generators is non linear.

When short-circuit occurs at rated conditions, it drives the machine into the deep saturation region and since B-H curves are non-linear, the extrapolated results will naturally be inaccurate. To counteract the wide difference in the inertia of the driving and driven machines, the gear system is shown to uniquely refer inertia from one side to the other in a manner similar to impedance matching using transformers.

III. SYSTEM DYNAMIC MODEL

The system is modelled in parts, but the combined equation describes the entire system behaviour. The DC motor set is represented as a single DC motor with a rating equaling the combined algebraic sum of the rating of the two components DC motors. The generator model is well known from its d-q-o equation in the rotor reference frame P.C. Krause et al, 2002 and the coupling is modeled appropriately in conjunction with gear train.

All equations are given in per unit of the appropriate base quantities

A. The DC Motor

The electrical and mechanical behaviour of a separately excited DC motor with no field control ie (field flux is constant) can be represented with two differential equation in per unit as

$$\frac{di_a(\tau)}{d\tau} = \frac{1}{l_a}\left[V_a - r_a i_a(\tau) - K\psi\omega_m(\tau)\right] \quad (1)$$

$$\frac{d\omega_m(\tau)}{d\tau} = \frac{K\psi i_a(\tau) - T_{SH}(\tau)}{J_{EFF-DC}} \quad (2)$$

Where

$i_a(\tau)$ and $\omega_m(\tau)$ are respectively, the armature current and rotor speed.

τ is per unit time.

r_a and i_a are the machine reactance and inductance in p.u.

ψ is the armature flux.

K is the constant determined by the design of the armature winding.

J_{EFF-DC} is the per unit moment of inertia of the entire moving mass comprising the DC motor rotor and the rotor of the synchronous generator as seen from the motor side.

B. The Turbo Generator

The direct axis (d-axis) and the quadrature axis (q-axis) equation of synchronous generator in the rotor reference frame according to **P.C. Krause et al (2002)** and **C. Concordia (1958)** in p.u. using standard nomenclature are:

$$V_{ds} = r_s I_{ds} + \frac{d\lambda_{ds}}{d\tau} - \omega_r \lambda_{qs} \quad (3)$$

$$V_{qs} = r_s I_{qs} + \frac{d}{d\tau}\lambda_{qs} + \omega_r \lambda_{ds} \quad (4)$$

$$V_{fr} = r_{fr} I_{fr} + \frac{d}{d\tau}\lambda_{fr} \quad (5)$$

$$0 = r_{dr} I_{dr} + \frac{d}{d\tau}\lambda_{dr} \quad (6)$$

$$O = r_{qr} I_{qr} + \frac{d}{d\tau}\lambda_{qr} \qquad (7)$$

Where the flux linkage are

$$\begin{bmatrix}\lambda_{qs}\\ \lambda_{ds}\\ \lambda_{qr}\\ \lambda_{dr}\\ \lambda_{fr}\end{bmatrix} = \frac{1}{\omega_r}\begin{bmatrix} X_{qr} & O & X_{mq} & O & O \\ O & X_{ds} & O & X_{md} & X_{md} \\ X_{mq} & O & Xqr & O & O \\ O & X_{md} & O & X_{dr} & X_{md} \\ O & X_{md} & O & X_{md} & X_{fr}\end{bmatrix} \times \begin{bmatrix}1_{qs}\\ 1_{ds}\\ 1_{qr}\\ 1_{dr}\\ 1_{fr}\end{bmatrix}$$

(8)

Where

$X_{qs} = X_{mq} + X_{ls}$

$X_{ds} = X_{md} + X_{ls}$

$X_{qr} = X_{mq} + X_{lqr}$

$X_{dr} = X_{mq} + X_{ldr}$

$X_{fr} = X_{md} + X_{lfr}$

The speed and torque are related by

$$\frac{d}{d\tau}\omega r = \left(\frac{T_{EX} - T_L}{J_{GEN}}\right) \qquad (9)$$

The torque is given by

$$T_{EX} = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds} I_{qs} - \lambda_{qs} I_{ds}\right) \qquad (10)$$

.

Although the above equations are complete, these cannot be used directly to simulate a stand-alone generator short-circuit condition under no load because the voltage V_{qs}, V_{ds} and V_{fr} are unknown. These state variables can easily be deduced by noting that at no-load condition (or initial condition), the rotor is operating at rated synchronous speed, the rotor and stator currents I_{dr}, I_{qr}, I_{qs} and I_{ds} are nominally zero.

Hence, the flux linkages in equation (8) becomes:

$$\left.\begin{aligned} \lambda_{ds} &= \lambda_{dr} = \frac{X_{md} I_{fr}}{\omega_r} \quad (11) \\ \lambda_{fr} &= \frac{X_{fr} I_{fr}}{\omega_r} \\ \lambda qs &= \lambda qr = 0 \end{aligned}\right\}$$

With equation (11), equation (3) now become

$$V_{ds} = \frac{d}{d\tau}\lambda_{ds} = \frac{X_{md}}{\omega_r}\frac{d}{d\tau} I_{fr} = 0$$ (since I_{fr} is a dc current) (12)

However, under steady-state no-load condition the terminal voltage Vs is 1.0p.u. and is given by

$$Vs = \sqrt{V_{ds}^2 + V_{qs}^2} = 1 \qquad V_{qs} = 1.0 \text{ p.u.} \qquad (13)$$

Applying these initial conditions to equation (4) under steady state open-circuit conditions gives.

$$V_{qs} = \omega_r \lambda_{ds} \quad \text{or} \quad I_{fr} = \frac{V_{qs}}{X_{md}} = \frac{1}{X_{md}} \qquad (14)$$

Similarly, equation (5) becomes

$$V_{fr} = r_{fr} I_{fr} = \frac{V_{qs} r_{fr}}{X_{md}} = \frac{r_{fr}}{X_{md}} \qquad (15)$$

Equation (15) provides a means of determining the value of excitation required to give the p.u. rated voltage on the terminals of the generator under no load conditions.

Equations (3) to (15) are now sufficient to simulate the no-load voltage build-up of a synchronous generator at a constant speed now that V_{qs}, V_{ds} and V_{fr} are known.

IV. CONSTANT SPEED SIMULATION

Constant-speed conditions are most desired because the operational inductances and time constants obtainable from short-circuit current waveforms depend on the speed of rotor. Significant departures from synchronous speed at short-circuit conditions means that the operational reactance and time constant values will be unreliable. For constant speed operation (ω_r = 1.0 p.u.), only the synchronous generator equations are solved, and the results obtained from these will be used as a benchmark. Under this mode of operation, it is assumed that the generator is driven by some ideal means; the SSC test does not lead to speed departure from synchronism. Figures 1 to 6 show the envelope or oscilogram of the simulation done at constant speed condition.

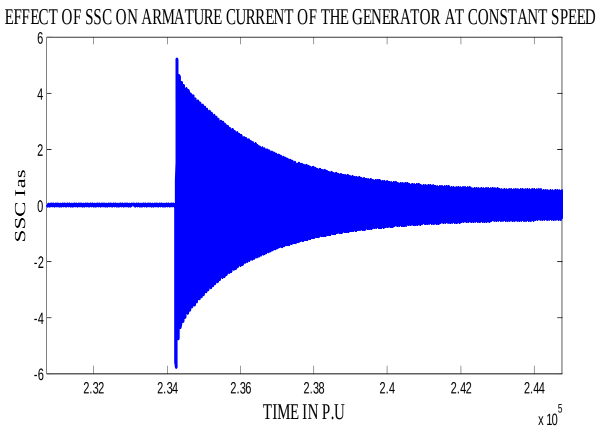

Figure 1 Effect of sudden short circuit on the armature current of the generator at constant speed

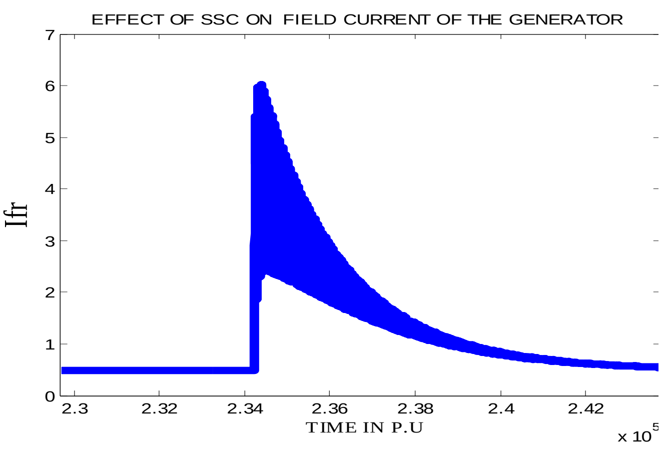

Figure 2 Effect of sudden short circuit on I_{fr} at constant speed.

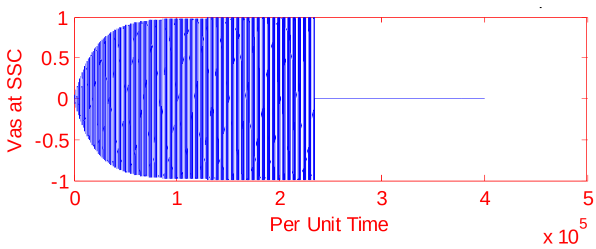

Figure 3 Effect of sudden short circuit on V_{as} at constant speed

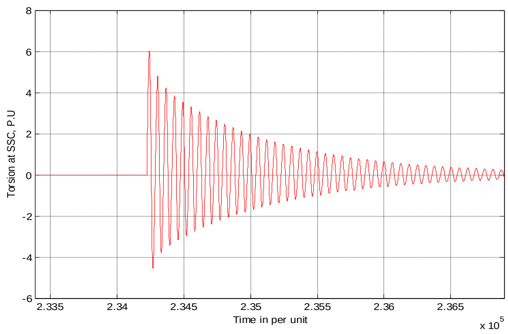

Figure 4 Torsional effect as a result of short circuit at constant speed

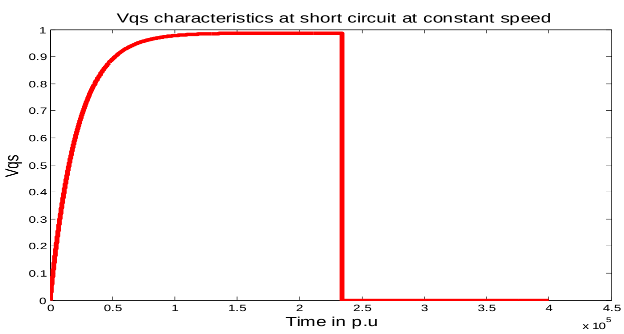

Figure 5 V_{qs} characteristics on short circuit at constant speed

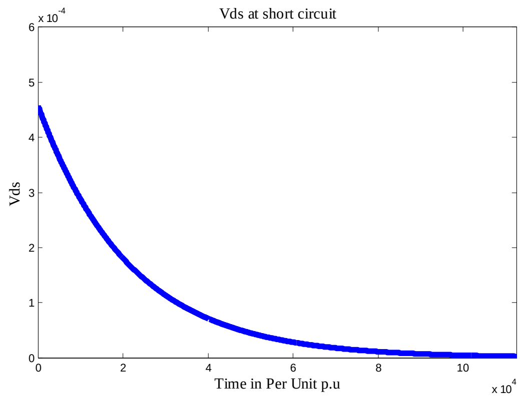

Figure 6 V_{ds} characteristics during short circuit at constant speed

V. EXTRACTION OF PARAMETERS

Considering the three phase generator on no load or off-line mode, running at its synchronous speed, and carrying a constant field current, suddenly, the three phase are short circuited, symmetrical armature current is shown in figure 1. Notice that for the first few cycles, the current I_{as} decays very rapidly . This period is termed **subtransient period.** During the next several cycle, the current decreases somewhat slowly and this area is called **transient period.** After this period, the next period is when the current settled at a **steady state condition** or value. These currents are limited by subtransient reactance $X_d^{''}$, Transient reactance $X_d^{'}$ and synchronous reactance X_d . The subtransient reactance is due to the presence of its damper bars. The transient reactance accounts for field winding and the synchronous reactance is the reactance due to armature winding.

It can be shown that

$i^* = \frac{v_0}{x^*}$ (Short circuit current is obtained by the product of the voltage at the time of short circuit and reciprocal of the machine reactance at the time of short circuit), in all cases V_0 is taken to be at 1 p.u.

In extracting the parameters at constant speed, the oscillogram of figure 1 was considered where the terminal currents I_{as} of the generator at sudden short circuit is considered at a corresponding time interval in p.u.

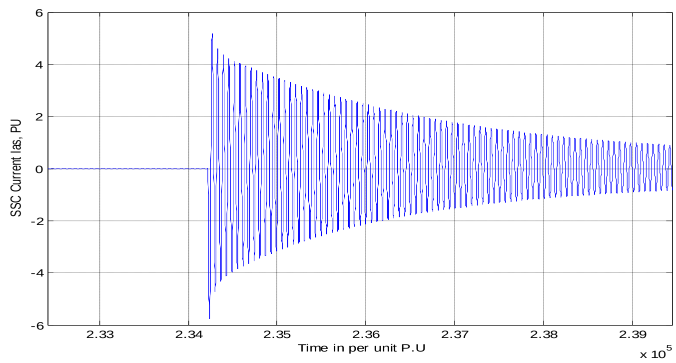

Figure 1 Effect of sudden short circuit on the armature current of the generator at constant speed Used for parameter extraction.

Table 1 Extracted Values at constant speed

$x_d\ (p.u)$	2.1978
$x_d'(p.u)$	0.217
$x_d''(p.u)$	0.1923
$\tau_d'(sec)$	0.021 sec
$\tau_d''(sec)$	0.001
I_{as} (Final)	0.4548
I_{as}' (Transient)	4.600
I_{as}''(SubTransient)	5.200

A. Result Discussion

The stator current waveforms for the constant-speed operation of figure 1, shows that at the point of the short circuit, the current rose spontaneously and decayed rapidly. This point is the sub-transient region which degenerated to the transient period of the oscillogram. The various regions in which the transients occurred are recorded in the section that discussed the extraction of the parameters.

Figure 2 depicts the rotor field current when sudden short circuit occurred at the terminals of the generator driven by the two DC motors. Between the subtransient and the transient region, the oscillogram shows a sharp rise in short circuit current before dropping to steady state condition. Figures 3,4,5, and 6 depicts the armature voltage, generator torsion, Vqs and V_{ds} . Figure 3 actually shows that the generator is maintained under a saturated condition. The generator's torsion envelop is the reaction of the generator when there is sudden short circuit.

VI. CONCLUSION

Synchronous generators are often stressed by short circuit faults being external faults or internal faults. Long-term average statistics indicate that short circuit faults occurring during operation cannot offer sufficient information with a view to fault correct assessment, simply because of the various circumstances in which these faults do practically occur. It should be emphatically stressed that three phase short circuit occurs sparsely but very devastating because of enamours armature current build up. This is why it is recommended that modelling and extracting parameters of a generator should be actually carried out under a three phase condition so that when one is designing for switch gear and other protective devices, the result will be able to withstand other faults like line to ground and line to line. It is pertinent to note that when parameters are extracted for study or recommendations, it is important to carry out such investigation under a constant speed and saturated conditions. This is why the scheme is essential to ensure that speed is maintained constant and at saturated condition.

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