This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.

A Novel and Fundamental Approach towards Field and Damper Circuit Parameter Determination of Synchronous Machine

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Abstract - **In this era of advanced computing where complex algorithms and expensive approaches are used to determine the machine parameters of a synchronous machine, this paper proposes a novel, economical and yet fundamental approach towards estimation of the d- and q-axis field and damper circuit parameters of a low/medium power wound-field synchronous machine. The proposed novel methodology employs fundamental voltage, current, flux linkage relationships of the 3-phase wound-field synchronous machine in a-b-c reference frame theory. Firstly, the proposed methodology has been explained in detail using analytical equations and then employed to determine the aforementioned parameters of a small laboratory synchronous machine. Other equivalent circuit parameters have been determined using conventional tests. Further validation of the proposed methodology was performed using two other larger machines with different nameplate ratings. Moreover, the aforementioned parameters of the larger machines were also experimentally determined using IEEE standard tests. Finally, a comparison of the results obtained employing the conventional and the proposed methodologies were performed and the proposed methodology has been established to be valid as the results are in close agreement.**

Index Terms - **Damper circuit, field circuit, parameter estimation, wound-field synchronous machine.**

I. INTRODUCTION

Many papers have been written since the first ones by Park [1], [2] till today about the definition, characterization and measurement of electrical parameters of synchronous machines [3], [4]. Industrial test and measurement standards by world-renowned North American and European bodies viz. IEEE 115, IEEE 1110, IEC and NEMA MG1-2006 also exist for determination of parameters and stability and dynamic studies [5]-[7]. Although research on parameter determination of wound-field synchronous machines started many decades ago, this topic keeps on receiving active investigation as the need for development of fundamental, less expensive, flexible and yet reliable parameter determination procedures still exist. Knowledge of correct synchronous machine (SM) equivalent circuit parameters permits accurate predictions on power system dynamics, stability studies and real-time input power and exciter control [5]-[8], where the machine acts predominantly in the generator mode. These studies are equally important for similar dynamic studies of large high-power load commutated inverter (LCI) fed synchronous machine drives, where the machine predominantly works in the motoring mode [9] in applications such as pumped storage and ship propulsion. Accurate parameters for dynamic studies for predicting and analyzing changeover of modes with perspective to success of load/induced voltage commutation of the LCI drive thyristors at all loads and transient overvoltage during load commutation across the thyristors are of paramount importance [10]. Small and medium power wound field synchronous machine for drives applications also require parameter information obtained through simple yet reasonably accurate means for high performance parameter-sensitive real-time drive control applications [11]. Studies conducted in the early 1970s [12] showed that, in general, in stability analysis it is more important to use accurate machine data than to use more elaborate machine models. In developing and applying more detailed and accurate models [13], [14], it was found that an economic benefit could be obtained from the increased capability to transmit power generated at a lower cost site. Background literature obtained from [5]-[14] state that the standard tests used to determine the SM parameters are the short-circuit tests, standstill frequency response (SSFR) and time domain tests.

Owing to their simplicity of implementation, off-line tests such as standstill frequency response (SSFR) and standstill time domain (SSTD) tests, have attracted the attention of researchers [15]-[19]. One noteworthy advantage about why SSFR testing has become an acceptable alternative to short-circuit testing is that identification of field winding response is possible. They pose a low probability of risk to the machine being tested, and data in both direct and quadrature axes are available, with little change in the test setup without resorting to special short circuit and/or low-voltage tests.

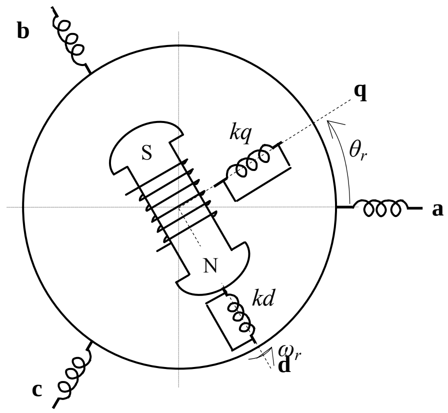

Fig. 1. Winding schematics of a 3-phase wound field synchronous machine demonstrating the winding dispositions, electrical rotor position and the d-q rotor reference frame.

However, the inaccuracy of the results obtained from the SSFR test due to the required nonstandard condition of machine operation still exists. For this reason, the analysis of SSFR test data usually yields models requiring further adjustments to correct for the overly low magnetizing currents that tend to occur during test. Hence, the data obtained from SSFR test is adjusted by data obtained by complementary short circuit tests or the online frequency response tests. Otherwise, the SSFR test requires supplementary tests to be performed along with it in order to provide accurate results, thus, making it complex and time consuming.

Even though the authors reiterate that the SSFR test is a well established process that allows the determination of high-order models on synchronous machines, sophisticated equipment, such as a function generator, a large fundamental frequency AC power source (power converter/amplifier) and a spectrum analyzer, are required. Also the SSFR test is found to be time consuming at lower frequency range of 0.001– 0.01 Hz [20]. Problem noise, probably due to winding heating, in the lower frequency range is a disadvantage of the SSFR test.

Moreover, keeping in view the educational sector, where the synchronous machine is taught as one of the fundamental machines along with the induction and the DC machines, laboratory experiments are usually performed on fractional horsepower machines which do not always obey the IEEE standards of parameter estimation [5]. Also, if experiments are performed on bigger machines, specialized equipment involved such as the function generator, power amplifier and spectrum analyzer might have to be purchased to perform the SSFR tests and cost of obtaining technical specialists would be another issue.

Hence, this research manuscript proposes a novel and yet fundamental approach towards determining the field circuit and d- and q-axis damper circuit resistances and inductances, by employing basic voltage, current, flux linkage relationships of the 3-phase wound field synchronous machine in a-b-c reference frame theory. This proposed methodology rests on the assumption of the presence of one d-axis damper and one q-axis damper winding in the machine and hence is predicted towards use with small or medium sized hydro-alternators or synchronous motors meant for low/medium power machine drives applications. Section II explains in length the derivation of the analytical model of the proposed methodology for parameter estimation. Experiments have been performed on a 120 VA machine, a 1.5 kVA machine and a 5 kVA machine based on the proposed method and results are investigated and validated in section III and IV respectively. Supporting data of other machine parameters such as the armature resistance, armature leakage reactance, d- and q-axis magnetizing reactances, have been obtained through conventional tests [5].

II. The Proposed Methodology and Its Derivation to Determine Field and Damper Circuit Parameters

The voltage equation of phase ‘a’ (Fig. 1) of a three phase wound field synchronous machine is given by:

$$v_{an} = r_a i_a + p\psi_a \tag{1}$$

where, v_{an}, i_a are the armature ‘a’ phase voltage and current respectively, r_a is the armature phase resistance, ψ_a is the total flux linkage of the a-n winding and p is the differential *(d/dt)* operator. For a general three-phase salient-pole synchronous machine with one d-axis damper and one q-axis damper, the time rate of change of the flux linkage of the ‘a’ phase armature winding can be written as [21]:

$$\begin{aligned} p\psi_a = p[&\{L_{la} + L_A - L_B\cos 2\theta_r\}i_a \\ &+ \{-0.5L_A - L_B\cos(2\theta_r - 2\pi/3)\}i_b \\ &+ \{-0.5L_A - L_B\cos(2\theta_r + 2\pi/3)\}i_c \\ &+ L_{mq}\cos\theta_r i'_{kq} + L_{md}\sin\theta_r i'_{fd} + L_{md}\sin\theta_r i'_{kd}] \end{aligned} \tag{2}$$

where, L_{la} is the armature leakage inductance, L_{md} and L_{mq} are the d-axis and q-axis magnetizing inductances, i_b, i_c are the currents of the other two armature phases, θ_r is the rotor position (electrical) as shown in Fig. 1, i'_{kq}, i'_{fd} and i'_{kd} are the currents in the q-axis damper, field and d-axis damper windings respectively, referred to armature, L_A and L_B are inductances related to L_{md} and L_{mq} by the following expressions:

$$L_{md} = \frac{3}{2}\left(L_A + L_B\right) \tag{3}$$

$$L_{mq} = \frac{3}{2}\left(L_A - L_B\right) \tag{4}$$

Motoring condition has been assumed positive here. In the proposed methodology for determining the electrical parameters of the field and dampers of the conventional d-axis and q-axis equivalent circuit, only a controlled single phase AC sinusoidal voltage would be applied to the armature a-phase winding with the rotor held stationary at certain strategic stationary positions. With the rotor at stationary position, $p\theta_r = \omega_r = 0$, where, ω_r is the rotor speed in electrical radian per second. Hence,