3rd International Conference on Electrical & Computer Engineering
ICECE 2004, 28-30 December 2004, Dhaka, Bangladesh

DYNAMIC RESPONSE OF AN ALTERNATOR DURING UNSYMMETRICAL FAULT AT ITS TERMINALS

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ABSTRACT

The transient behaviour of an unloaded alternator under unsymmetrical single line to ground fault condition at its terminals is studied. A mathematical model in per unit system based on a hybrid coordinate system is developed combining the *abc* (stator phase *a*, *b* & *c*) axis and the *dq0* (direct, quadrature & zero) axis. The mathematical model is formulated with inclusion of special physical phenomena which are specific for extremely unbalanced nature of unsymmetrical faults. Although the model is used to study the single line to ground fault it can be used for any type of unsymmetrical fault with proper consideration of initial conditions. The validity of the mathematical model was checked by comparison of its results with the results of tests.

1. INTRODUCTION

Single line-to-ground fault occurs when any one of the three phases of an alternator is connected to the ground with or without impedance. This is unsymmetrical in nature. Current flows only through the faulted phase and the faulted phase voltage drops abruptly to zero. The voltages of the other two phases are not zero and there is no current flow through theses phases. The current and voltage wave shapes deviate from their balanced shape. The single line-to-ground fault is very significant for its zero sequence current. The zero sequence current arises from unbalanced nature of phase currents. Although the fault current of the single line-to-ground fault usually does not exceed that of the three phase short circuit fault, it has a great impact on the whole power generation process for its extreme unbalanced nature. The special feature of this study is that the speed of the rotor is considered as variable throughout the simulation. So the result obtained from the simulation reveals the actual and real condition.

2. MACHINE PARAMETERS

The study was carried out for two machines; a laboratory small capacity 4 pole synchronous machine Machine1 (0.11 KVA, 50 Hz, 0.17 A and 380 V rating) coupled with a 4 pole DC machine having 0.175 KW, 1500 rpm, 1.3 A and 220 V rating and a large capacity 6 pole synchronous machine Machine2 (9 KVA, 50 Hz, 23.6 A and 220 V rating) coupled with a 4 pole DC machine having 10 KW, 1000 rpm, 80 A and 125 V rating. The synchronous machines were unloaded all the time except during measurement of the friction & windage and core loss. All machine parameters required for the fault study are determined at steady state condition. The leakage reactance of armature winding X_l is measured by energizing stator winding with rotor removed and the armature resistance R_a is measured by using bridge and input ac power measurement also with rotor removed. The direct axis synchronous reactance X_d and the quadrature axis synchronous reactance X_q are measured by slip test oscilloscopic plots. The friction & windage loss and the core loss of the synchronous machine are measured at steady state condition loaded with DC motor by existing methods. The loss torque T_m and inertia constant are then measured using their respective equations. The field winding resistance R_f and reactance X_f and damper winding reactances X_D and X_Q and resistances R_D and R_Q in direct and quadrature axis are measured by solving equivalent circuits of the machine during feeding of stator phase by single phase ac supply for stator phase positions in direct (*d)* and quadrature (*q)* axes.

ISBN 984-32-1804-4

3. MATHEMATICAL MODEL

Instead of taking one single coordinate system i.e. either *abc* axis or *dq0* axis, a hybrid coordinate system is considered for the developed mathematical model. The axes are shown in the Fig.1.

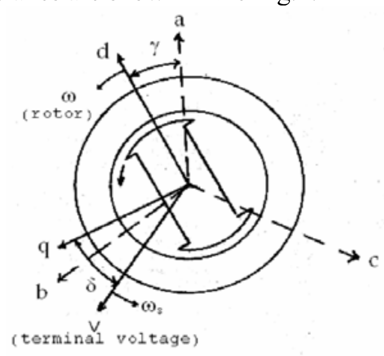

Fig. 1 *abc* and *dq0* axes of the synchronous machine.

The transformation and the inverse transformation of Park's system of equations are used to switch from *dq0* axis to *abc* axis and vice versa. The mathematical model is formulated on the basis of motor convention of signs. The first order differential equations [1] of flux linkages (ψ), angular velocity (ω) and load angle (δ) are the following:

$$\frac{d\psi_d}{dt} = V_d + \psi_q \omega - R_a i_d \tag{1}$$

$$\frac{d\psi_q}{dt} = V_q - \psi_d \omega - R_a i_q \tag{2}$$

$$\frac{d\psi_f}{dt} = V_f - R_f i_f \tag{3}$$

$$\frac{d\psi_D}{dt} = -R_D i_D \tag{4}$$

$$\frac{d\psi_Q}{dt} = -R_Q i_Q \tag{5}$$

$$\frac{d\psi_0}{dt} = V_0 - R_0 i_0 \tag{6}$$

$$\frac{d\omega}{dt} = \frac{T_{em} + T_p - T_m}{H_j} \tag{7}$$

$$\frac{d\delta}{dt} = 1 - \omega \tag{8}$$

These equations are solved in conjunction with the following algebraic equations of flux linkages and currents:

$$\psi_{\mathrm{d}} = x_d i_d + x_{ad} i_f + x_{ad} i_D \tag{9}$$

$$\psi_{\mathrm{q}} = x_q i_q + x_{aq} i_Q \tag{10}$$

$$\psi_o = x_o i_o \tag{11}$$

$$\psi_{\mathrm{f}} = x_f i_f + x_{ad} i_d + x_{ad} i_D \tag{12}$$

$$\psi_{\mathrm{D}} = x_D i_D + x_{ad} i_f + x_{ad} i_d \tag{13}$$

$$\psi_{\mathrm{Q}} = x_Q i_Q + x_{aq} i_q \tag{14}$$

From the first derivative values of ψ_d, ψ_q, ψ_0 the first derivatives of ψ_a, ψ_b and ψ_c are obtained as follows:

$$\psi_a = \psi_d \cos\gamma - \psi_q \sin\gamma + \psi_o \tag{15}$$

$$\psi_b = \psi_d \cos(\gamma - 120^o) - \psi_q \sin(\gamma - 120^o) + \psi_o \tag{16}$$

$$\psi_c = \psi_d \cos(\gamma + 120^o) - \psi_q \sin(\gamma + 120^o) + \psi_o \tag{17}$$

$$\frac{d\psi_a}{dt} = \frac{d\psi_d}{dt}\cos\gamma - \psi_d \omega \sin\gamma - \frac{d\psi_q}{dt}\sin\gamma - \psi_q \omega \cos\gamma + \frac{d\psi_o}{dt} \tag{18}$$

$$\frac{d\psi_b}{dt} = \frac{d\psi_d}{dt}\cos(\gamma - 120^o) - \psi_d \omega \sin(\gamma - 120^o) - \frac{d\psi_q}{dt}\sin(\gamma - 120^o) - \psi_q \omega \cos(\gamma - 120^o) + \frac{d\psi_o}{dt} \tag{19}$$

$$\frac{d\psi_c}{dt} = \frac{d\psi_d}{dt}\cos(\gamma + 120^o) - \psi_d \omega \sin(\gamma + 120^o) - \frac{d\psi_q}{dt}\sin(\gamma + 120^o) - \psi_q \omega \cos(\gamma + 120^o) + \frac{d\psi_o}{dt} \tag{20}$$

Hence the *abc* terminal voltages are determined by the following voltage equations [2]:

$$V_a = \frac{d\psi_a}{dt} + R_a i_a \tag{21}$$

$$V_b = \frac{d\psi_b}{dt} + R_b i_b \tag{22}$$

$$V_c = \frac{d\psi_c}{dt} + R_c i_c \tag{23}$$

Phase currents i_a, i_b, i_c are obtained by *dq0* to *abc* axis transformation as follows.

$$i_a = i_d \cos\gamma - i_q \sin\gamma + i_0 \tag{24}$$

$$i_b = i_d \cos(\gamma - 120^o) - i_q \sin(\gamma - 120^o) + i_0 \tag{25}$$

$$i_c = i_d \cos(\gamma + 120^o) - i_q \sin(\gamma + 120^o) + i_0 \tag{26}$$

Values of V_d, V_q and V_0 are obtained from the inverse transformation of Park's system of equations

$$V_d = \frac{2}{3}\left[V_a \cos\gamma + V_b \cos(\gamma - 120^o) + V_c \cos(\gamma + 120^o)\right] \tag{27}$$

$$V_q = -\frac{2}{3}\left[V_a \sin\gamma + V_b \sin(\gamma - 120^o) + V_c \sin(\gamma + 120^o)\right] \tag{28}$$

$$V_o = \frac{1}{3}(V_a + V_b + V_c) \tag{29}$$

The electromagnetic torque T_{em}, prime mover torque T_p, loss torque T_m and rotor angle γ are obtained by the following equations [1]:

$$T_{em} = \psi_d i_q - \psi_q i_d f \tag{30}$$

$$T_p = a\omega + c \tag{31}$$

$$T_m = c_1\sqrt{\psi_d^2 + \psi_q^2} + c_2\omega \tag{32}$$

$$\gamma = t - \delta \tag{33}$$

4. INITIAL CONDITIONS

It was considered that single line to ground fault occurred on phase *a* (i.e. $V_a = 0$). The angle between the reference phase axis *a* and the position of the rotor or the direct axis is γ and $\gamma = t - \delta$ where *t* is the time in radian and δ is the load angle i.e. the angle between the synchronously rotating terminal voltage *V* and the quadrature axis. The stator current i_a, i_b and i_c will be zero as stator circuit is open; consequently the current i_d, i_q and i_o will be zero. The damper windings do not carry current so $i_D = i_Q = 0$. The field current, $i_f = V_f/R_f$ where V_f and R_f are the applied field voltage and the measured field resistance respectively. The stator coil flux linkages ψ_d (equals $x_{ad}i_f$), ψ_q (equals 0) and ψ_o (equals 0), the field circuit flux linkage ψ_f (equals $x_f i_f$) and the damper winding flux linkages ψ_D (equals $x_{ad}i_f$) and ψ_Q (equals 0) are determined from initial currents and machine parameters by corresponding flux linkage equations [2]. V_d,, V_q and V_o voltages are initialized as 0, $\psi_d \omega$ and 0 respectively using initial values of flux linkages and currents and taking the rate of change of flux linkages $\frac{d\psi_d}{dt} = \frac{d\psi_q}{dt} = \frac{d\psi_o}{dt} = 0$ due to steady state condition at the previous moment of fault. The terminal voltages V_a, V_b and V_c are then initialized as 0, $-V_q \sin(\gamma - 120^o)$ and $-V_q \sin(\gamma + 120^o)$ respectively by *dq0* to *abc* axis transformation [2]. Torque equations [1] are used to initialize electromagnetic torque T_{em}, loss torque T_m and prime mover torque T_p.

5. SOLUTION OF THE MATHEMATICAL MODEL

The first order differential equations (1)-(8) are solved with the help of fourth order Runge-Kutta (R-K) method to obtain the respective values of Ψ, ω and δ. In every step of R-K method new values of currents i_d, i_q, i_o, i_D and i_Q are used which are determined by solving the flux linkage equations (9)-(14). Here again updated values of ψ_d, ψ_q, ψ_o, ψ_f, ψ_D and ψ_Q are used which are obtained from previous step of R-K method. From the first derivative values of ψ_d, ψ_q, ψ_0 the first derivatives of ψ_a, ψ_b and ψ_c are obtained from the equations (18)-(20). Hence the *abc* terminal voltages are determined by the voltage equations (21)-(23). Here the phase current i_b and i_c are equal to zero and phase current i_a is obtained by *dq0* to *abc* axis transformation as by the equation (24). Later new values of V_d, V_q and V_0 are obtained from the inverse transformation of Park's system of equations (27)-(29). The simulation time is then incremented by Δt (0.03 radian) and all calculations were repeated for this time instant. Thus the simulation continues until it covers longer period at the post fault time duration.

6. SIMULATION RESULTS

The transient behaviour of the Machine1 during single line to ground fault was simulated for the rotor positions (γ) at 0, $\pi/2$ and π radian and for the applied field voltages (V_f) 0.826, 1.0344 and 1.7916 in per unit. The alternator shows the most severe transient behaviour for the rotor position $\gamma = 0$ with the applied field voltage 1.7916 per unit (Fig. 2, 3 & 4).

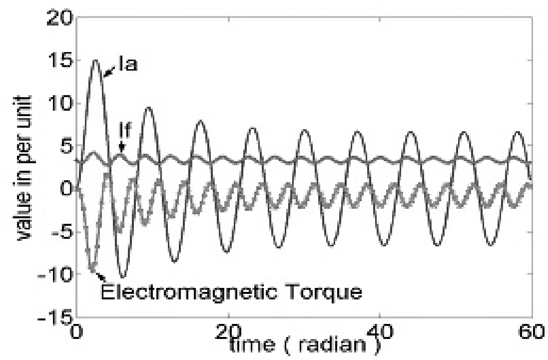

Fig. 2 Variation of I_a, I_f and T_{em} during single line to ground fault for Machine1 at rotor position $\gamma = 0$ with $V_f = 1.7916$ per unit.

The analysis shows that the peak value of the field current is the highest when the armature current shoot is the highest due to the demagnetizing nature of the armature reaction on the field flux. According to the constant flux linkage theory, the highly inductive field coil tends to keep its flux linkage constant by increasing the field current. There is pulsation in the electromagnetic torque and the average torque is negative. Because of the unbalanced nature of the single phase fault current there are effectively two fields, forward and backward; the backward field is responsible for the negative average value of the torque.

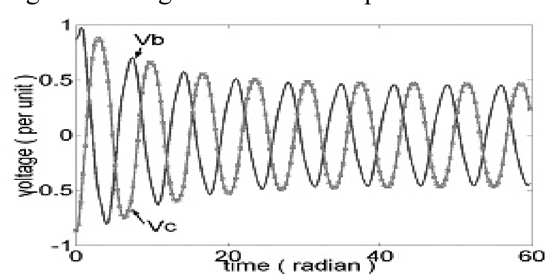

Fig. 3 Variation of terminal voltages V_b and V_c during single line to ground fault for Machine1 at rotor position $\gamma = 0$ with $V_f = 1.7916$ per unit.

The terminal voltages V_b and V_c show a very high peak at transient condition which exponentially decrease to steady state value due to exponential decrease in fault phase current (Fig.3).

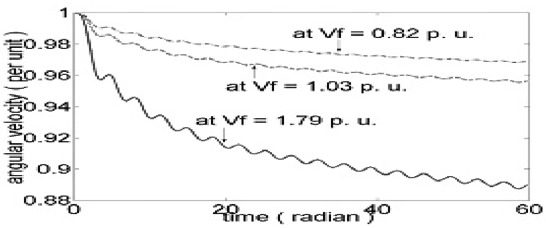

Fig. 4 Variation of angular velocity (ω) during single line to ground fault for Machine1 at rotor position $\gamma = 0$ with different excitation voltage V_f .

The rotor speed (ω) falls very rapidly at the moment of fault and later it decreases gradually. Analysis shows that the load angle (δ) increases with the decrease of the rotor speed due to the speed deviation from the synchronous speed. The analysis shows that the higher the value of applied field voltage the higher the value of fault current shoot as well as the higher the falling rate of rotor speed. The change in speed is reflected in the frequency of the current. At lower speed the frequency of the current becomes lower.

7. VALIDITY OF SIMULATION RESULTS

The validity of the mathematical model was checked by comparison of its results with the experimental results. An experimental setup is done where one phase (phase a) of Machine2 is connected to neutral abruptly. The short circuit current was sampled by series resistance R (0.009818 Ohm) at rotor position $\gamma = \pi$ with $V_f = 0.0084225$ per unit. The fault current in terms of voltage across R, prefault and postfault terminal phase voltages (phase a) is recorded by a storage oscilloscope (Fig.5).

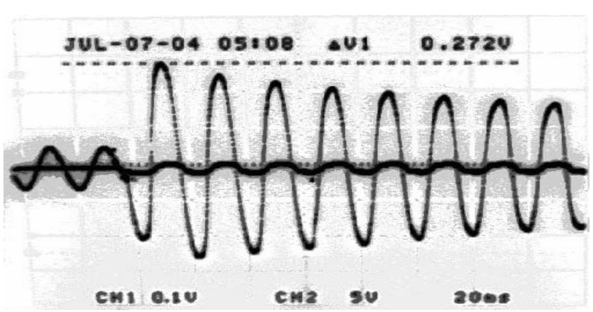

Fig. 5 The storage oscilloscopic plots of the single line to ground fault current of Machine2 (curve with larger amplitude) in terms of voltage across resistance R, pre and post fault voltages of faulted phase.

Fig.5 shows that the highest voltage (across R) shoot is 0.272 V. Dividing by the series resistance R the highest current shoot is found 27.7 A. or 1.174 per unit (base current 23.6 A). The Fig.5 also shows that fault current does not reach steady state condition during recorded time which can be explained by the larger speed change of prime mover (DC motor). The field circuit of the coupled DC motor is controlled by a variable resistor which introduces additional resistance and hence the prime mover torque is deviated from its ideal characteristics. As a result the prime mover takes time to reach steady state condition. The initial low fault current peak is due to the use of circuit breaker as switching device to initiate fault condition.

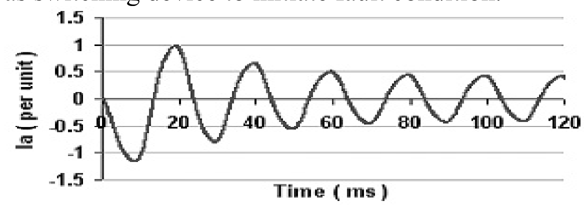

Fig. 6 The Simulated single line to ground fault current (I_a) for Machine2 at rotor position $\gamma = \pi$ with $V_f = 0.0084225$ per unit.

From the simulated plot (Fig. 6) the highest fault current shoot is found –1.174 per unit which completely validates the formulated mathematical model. The current is negative since the mathematical model is formulated on the basis of motor convention of signs as mentioned in section 3.

8. CONCLUSION

The developed mathematical model based on hybrid (combination of *abc* axis and *dq0* axis) coordinate system is used to simulate transient characteristics of an unloaded alternator during single to ground fault at its terminal. Due to the unbalanced nature of the fault current the pulsating rotating field is generated which causes unbalanced phase shift in currents and harmonic distortion in voltages. The transient behaviour is highly influenced by the rotor position and the applied field voltage. The model is useful for generator designing.

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