# ON THE DYNAMIC BEHAVIOUR OF DUAL-EXCITED SYNCHRONOUS MACHINES

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in Partial Fulfilment of the Requirements for
the Degree of Doctor of Philosophy
in the Department of
Electrical Engineering
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by

Mohamad Abd El-Raheim Badr

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TO MAHA, MONIRA AND MY MOTHER

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Head of the Department of Electrical Engineering
University of Saskatchewan
Saskatoon, Canada.

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# "ON THE DYNAMIC BEHAVIOUR OF DUAL-EXCITED SYNCHRONOUS MACHINES"

Student: Mohamad Abd El-Raheim. M. Badr Superivsor: Dr. A.M. El-Serafi

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## ABSTRACT

Investigations reported in the recent past confirm the vastly improved dynamic and transient stability characteristics of dual-excited synchronous machines. In order to utilize more fully the capabilities of these machines, it is of prime importance to understand how they behave under different conditions and to assess their advantages and disadvantages in comparison with conventional synchronous machines.

It is the main objective of this thesis to examine various aspects of the dynamic behaviour of dual-excited synchronous machines. The mathematical treatment involves a series of digital, analytical and analog simulations; both rigorous and simplified. A good deal of this work is devoted to dynamic stability investigations with particular emphasis on the choice of the parameters of the excitation systems for maximum possible capacitive loading. In addition, the limitations imposed on the excitation control of dual-excited synchronous condensers are determined. This involves an analytical evaluation of the relative effectiveness of the different feed-back control signals. Information regarding the phenomenon of self-excitation and electromechanical oscillations of dual-excited synchronous machines, particularly when they are connected through series compensated transmission lines, are also presented. These dynamic stability investigations are followed by a study of the transient stability characteristics of these machines. The main objective of this study is to explore the effect of the different modes of operation, the loading conditions, the possible schemes of excitation control and the parameters of the control loops on their transient stability limits.

Another important aspect is the development of generalized equivalent circuits for these machines, which provide a convenient method for determining their steady-state and transient behaviour. In this respect, expressions for the machine reactances and time constants as well as formulae for the 3-phase short-circuit currents are derived. The equivalent circuits are also utilized in devising a new approach to analog computer simulation of such machines.

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# LIST OF SYMBOLS

| | |
|---|---|
| $e$ | resultant electromotive force before disturbance |
| $e_d$, $e_q$ | d- and q-axis component of e respectively |
| $g_D(p)$ | governor transfer function |
| $g_{R1}(p)$, $g_{R2}(p)$ | field winding 1 and 2 regulator transfer function respectively |
| $g_R(p)$ | d-axis field regulator transfer function (in a conventional synchronous machine) |
| $G(p)$ | field operational function (in a conventional synchronous machine) |
| Im [ ] | imaginary part of [ ] |
| $i$ | infinite-bus current |
| $i_d$, $i_q$ | d- and q-axis component of i respectively |
| $i_{ta}$,$i_{tb}$,$i_{tc}$ | phase a, phase b and phase c armature current respectively |
| $i_{td}$,$i_{tq}$ | d- and q-axis component of armature current respectively |
| $i_o$ | infinite-bus current before disturbance |
| $i_{do}$,$i_{qo}$ | d- and q-axis component of $i_o$ respectively |
| $i_{to}$ | phase a armature current before disturbance |
| $i_{tdo}$,$i_{tqo}$ | d- and q-axis component of $i_{to}$ respectively |
| $i_{f1}$,$i_{f2}$ | field winding 1 and 2 current respectively |
| $i_{fd}$ | field current of a conventional synchronous machine |
| $i_{kd}$,$i_{kq}$ | d- and q-axis damper winding current respectively |
| $K_e$ | exciter constant |
| $K_f$ | ratio between field winding 1 and 2 exciting currents |
| $P$ | active power delivered to the infinite-bus |

| | |
|---|---|
| $p$ | differential operator $\frac{d}{dt}$ |
| $Q$ | reactive power delivered to the infinite bus |
| $Re[\ ]$ | real part of [ ] |
| $R_e$ | external resistance |
| $r$ | armature resistance |
| $r_{f1}, r_{f2}$ | field winding 1 and 2 resistance respectively |
| $r_{fd}$ | d-axis field winding resistance (in a conventional machine) |
| $r_{kd}, r_{kq}$ | d- and q-axis damper winding resistance respectively |
| $t$ | time in seconds |
| $T_e$ | electromagnetic torque |
| $T_f$ | fault clearing time |
| $T_i$ | shaft torque |
| $v_{f1}, v_{f2}$ | field winding 1 and 2 exciting voltage respectively |
| $v_{fd}$ | d-axis field winding exciting voltage (in a conventional machine) |
| $v, v_t$ | bus-bar and machine terminal voltage respectively |
| $v_d, v_q$ | d- and q-axis component of v respectively |
| $v_{td}, v_{tq}$ | d- and q-axis component of $v_t$ respectively |
| $v_{to}$ | phase a terminal voltage before disturbance |
| $v_{tdo}, v_{tqo}$ | d- and q-axis component of $v_{to}$ respectively |
| $x_e$ | external reactance |
| $x_{ad}, x_{aq}$ | d- and q-axis magnetizing reactance respectively |
| $x_d, x_q$ | d- and q-axis synchronous reactance respectively |
| $x_d'$ | d-axis transient reactance |
| $x_q'$ | q-axis transient reactance |

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| $x_{ffd}$ | d-axis field winding self reactance (in a conventional synchronous machine) |
| $x_{ff1}, x_{ff2}$ | field winding 1 and field winding 2 self winding reactance respectively |
| $x_{f1f2}$ | mutual reactance between field winding 1 and 2 |
| $x_{kkd}, x_{kkq}$ | d- and q-axis damper winding self reactance respectively |
| $x_{\ell f1}$ | field winding 1 leakage reactance |
| $x_{\ell f2}$ | field winding 2 leakage reactance |
| $\phi$ | phase angle between the current and voltage of phase a |
| $T_a$ | amplifier time constant |
| $T_e$ | exciter time constant |
| $T_c$ | measuring devices time constant |
| $T_s$ | feed-back stabilizing loop time constant |
| $\mu_a$ | amplifier gain |
| $\mu_c$ | measuring devices gain |
| $\mu_s$ | feed-back stabilizing loop gain |
| $\delta$ | rotor angle |
| $\delta_L$ | power-angle |
| $\delta_o$ | rotor angle before disturbance |
| $\alpha_1$ | angle between the axis of field winding 1 and the d-axis of the rotor |
| $\alpha_2$ | angle between the axis of field winding 2 and the d-axis of the rotor |
| $\psi_d, \psi_q$ | d- and q-axis armature flux linkage respectively |
| $\psi_{f1}, \psi_{f2}$ | field winding 1 and 2 flux linkage respectively |
| $\psi_{kd}, \psi_{kq}$ | d- and q-axis damper winding flux linkage respectively |

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| $p\theta$ | speed of the machine (elect. radians/sec) |
| $p\theta_o$ | speed of the machine before disturbance (elect. radians/sec) |
| Ⓗ | inertia constant of the machine and its prime mover in per-unit |
| $\Delta$ | prefix to denote small changes about the initial operating point |

# 1. INTRODUCTION

## 1.1. General

The operating limits of synchronous generators are of general importance to power systems planning and operating engineers. The limits for lagging power factors had been of particular interest in the past, since synchronous generators were operated mainly in the over-excited region. Recent developments in power systems, such as the establishment of more long high voltage transmission lines, the widespread use of high voltage underground cables and the addition of large numbers of capacitors for power factor improvement, have changed the conditions under which synchronous generators operate. Because of the excessive capacitive power needed in this case, synchronous generators have to work in the under-excited region. The extent to which this is possible is severely limited by stability considerations [1-3]. Moreover, as electric power systems have continued their rate of growth, it has become both economically desirable and technically feasible to use large size generators. In order to obtain more KVA from a given frame size of a generator, designers have developed more efficient methods of dissipating the losses, such as the direct cooled conductors. It follows that the output from the units, which are now under construction, will be much greater than that from conventionally cooled units with the same frame size. This results in machines with higher per-unit reactances and lower inertias causing some apprehension as to their stability limits [2].

## 1.2. Stability Problem

Since the earliest days of conversion of energy from mechanical to electrical form, the problem of power system stability has been of importance and has been under study in both the academic and the industrial fields. The problem results from unbalance between the energy input and the energy output of the synchronous machines in the system during changes of the operating conditions or consequent to the occurence of a disturbance. When such an unbalance develops in one or more of these machines, their speeds of rotation change and synchronism is disturbed and stability of operation of the whole system may be threatened. Whether the system will be unstable or not, depends on the inherent characteristics of the generators and transmission system as well as on the effectiveness of the control and the protective equipment. The stability problems of power systems have been conventionally divided into steady-state and transient stability problems, primarily for expediency of the analysis.

Extending the steady-state stability operating regions of synchronous generators has been receiving considerable attention in recent years. Such an extension can be achieved by controlling the alternator field excitation with a fast and continuously acting voltage regulator [4-20]. The improvement which can be achieved is very nearly equivalent to doubling the short circuit ratio of the generator at full load. This method is less effective at light loading and no improvement is possible at no load. Maintaining system stability under light and no load conditions requires the use of reactive power sources such as shunt reactors and synchronous compensators.