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Controllable d.c. power supply from wind driven Induction generator

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ABSTRACT

This paper presents a system for the control of the output voltage of wind driven self-excited induction generators. The proposed system comprises a squirrel-cage induction machine feeding a 3-phase line commutated controlled rectifier bridge in conjuction with voltage and current controllers of PI type. The effect of the load resistance and thyristor firing angle on the excitation capacitance was examined and a critical value of load resistance have been determined. The parameters of the controller have been optimised in order to give a switching transient performance of 3% maximum overshoot with minimum settling time. As a result, zero voltage regulation is obtained with 33% reduction in wind speed at constant excitation capacitance and normal loading conditions. The effect of sudden reduction in the load on the voltage regulation has also been investigated. The introduction of the current controller, with full-load current limiting, has led to a considerable reduction in the size of the smoothing inductor. Comparison between the results obtained from the theoretical analysis and those obtained experimentally showed good agreement.

The technique of obtaining controllable D.C. power from a self-excited induction generator is especially interesting in applications such as windmills of small hydroelectric power plants without speed control. The d.c. power obtained in these systems can be used directly in d.c. equipment and battery charging or it can be connected to an a.c. network through d.c. link inverters.

The system described in this paper comprises a 3-phase cage rotor induction machine, with self excitation capacitors, which generates a variable-frequency/variable voltage supply. The output voltage is fed through a 3-phase line-commutated controlled bridge rectifier to give a d.c. supply of constant voltage. Two electronic controllers are used to control the voltage and current in an inductive load by a suitable adjustment of the thyristors firing angle.

2. MATHEMATICAL ANALYSIS:

2.1 Variation of the generator voltage with R_L and α

Fig. 1 shows the proposed system in which 3 capacitors are connected to a 3-phase 4-pole, 200 V, 50 50 Hz, 1 KW squirrel cage induction machine. A d.c. motor is used as the variable speed drive.

The power output was fed into 12 pulse transformer-connected S.C.R. converter. Reliable tests showed good converter performance at generator voltage and frequency above 150 V and 25 Hz respectively.

The following analysis assumes no ripples in the output current i_a very large smoothing inductance and negligible commutation time.

NOMENCLATURE

α : thyristor firing angle
i_a; I_d : generator line current and load current
i_{act}, i^* : actual load current and required load current
K_{P1}, K_{P2} : gain of the voltage and current controller
R_L, X_L : load resistance and reactance
R_e, X_e : equivalent resistance and reactance of the load
R_{Lc}, X_{cc} : critical load resistance and excitation reactance
T_{n1}, T_{n2} : reset time of the voltage and current controller
T_c : converter time constant
v_a : generator voltage per phase
V^*, V_{act} : desired and actual value of load voltage
V_L : line voltage of the generator

1. INTRODUCTION

In recent years, owing to the increased emphasis on renewable energy resources, development of suitable isolated power generators driven by wind, has assumed greater significance [1-6]. The capacitor self excited and wind driven induction generator is usually a suitable generator for isolated power sources due to its reduced cost and small size when compared with synchronous or d.c. generators. It is also advantageous because of the brushless rotor construction, the absence of a separate excitation source and the self-protection against short circuits. However, the generator has a relatively poor voltage and frequency regulation and methods to control the terminal voltage are therefore of considerable interest.

The fundamental component i_a of the converter input current is given by [7]

$$i_a = (2\sqrt{3}\ I_d / \pi) \quad \sin (wt - \alpha + 30) \tag{1}$$

The steady state output current I_d may be obtained by dividing the converter output voltage by R_L,

$$I_d = (3\sqrt{2}\ V \cos \alpha) / \pi R_L \tag{2}$$

Equation (1) may be rewritten as

$$i_a = [\cos (\alpha - 30) \sin wt - \sin (\alpha - 30) \cos wt]\ 2\sqrt{3}\ I_d / \pi \tag{3}$$

The two terms of equation (3) represent the active and reactive components of i_a. The load and converter can be then considered as equivalent to a resistance R_e and a reactance X_e connected in parallel. The generator output voltage is
given by

$$v_a = \sqrt{2/3}\ \ V_L \sin wt \tag{4}$$

Dividing equation (4) by the two components of equation (3) gives the star connected equivalent resistance and reactance. The following two equations give their equivalent delta-connection (R_e and X_e) and may be written as:

$$R_e = \pi^2\ R_L/6 \cos^2 (\alpha - 30) \tag{5}$$

$$X_e = \pi^2\ R_L/3 \sin (2\alpha - 60) \tag{6}$$

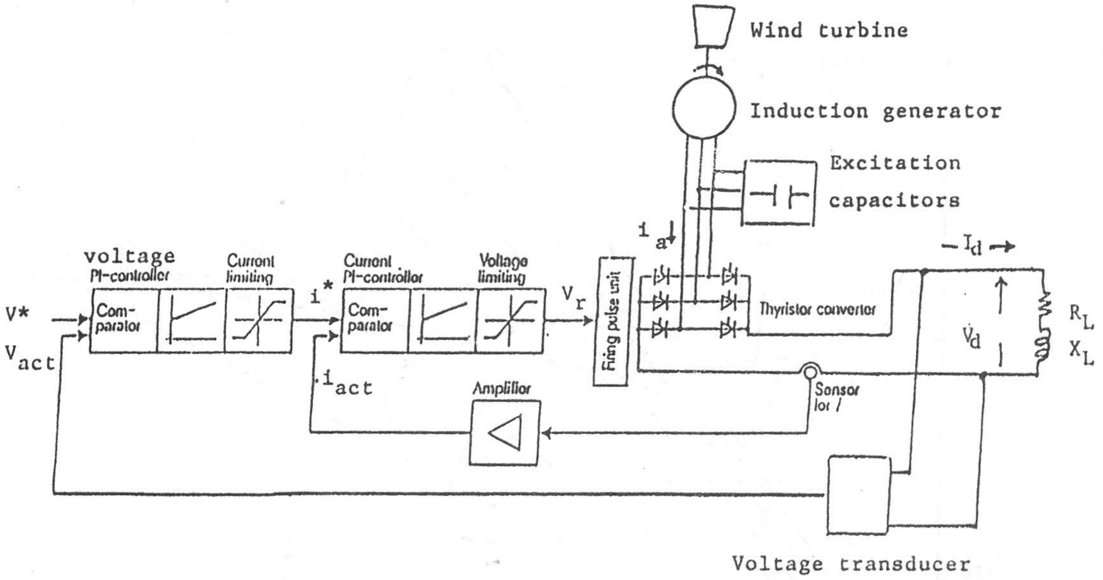

Fig. 1 Induction generator control system

Thus, the induction generator is loaded by an equivalent resistance R_e which changes with the thyristors firing angle α as shown by equation (5). Also, the excitation capacitors are greatly affected by the load resistance and α as indicated by equation (6). The total capacitive reactance is then given by

$$X_{ct} = X_c X_e/(X_c - X_e) \tag{7}$$

Fig. 2 shows the variation of the no-load generator voltage with the excitation capacitive reactance at a normal speed of 1500 r/min. The generator voltage on load can be approximated by a rectilinear drooping characteristic as indicated by the non continuous line in Fig. 2. Practical experience showed that this approximation is acceptable up to 125 % of full load. It should be noted that the reduction in R_L must be limited to a value at which $X_{ct} = X_{cc}$ where X_{cc} is the critical value of the excitation capacitive reactance at normal speed andfrequency and is given by $X_{cc} = X_{mu}$, where X_{mu} is the sum of the unsaturated magnetising reactance and leakage reactance of the machine at normal frequency. The critical value of load resistance R_{Lc} at constant α and speed is then given by

$$R_{LC} = 3X_{cc}\,X_c \sin(2\alpha - 60)/\pi^2(X_{cc} + X_c) \qquad (8)$$

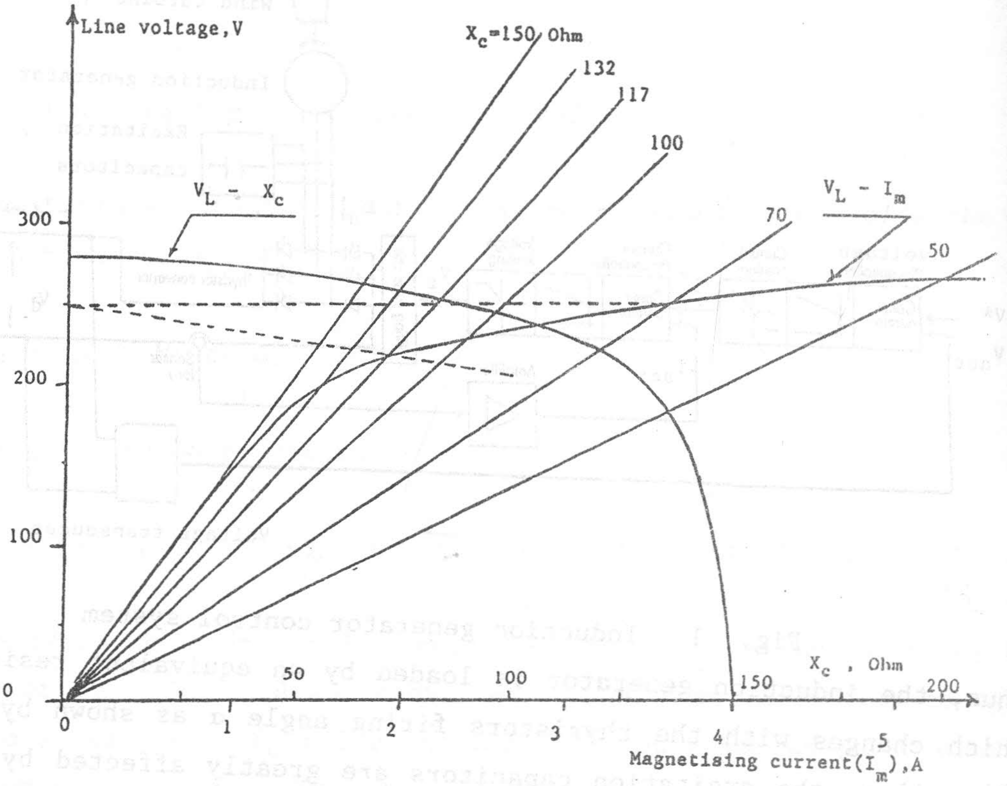

Fig. 2 Variation of the no-load voltage with excitation capacitor

Fig. 3 gives the variation of R_e, X_e, X_{ct} and the generator voltage with α at R_L = 70 and 50 ohms. It shows a significant reduction in V_L and

X_{ct} at $\alpha = 75^{o}$ at which X_e is minimum.

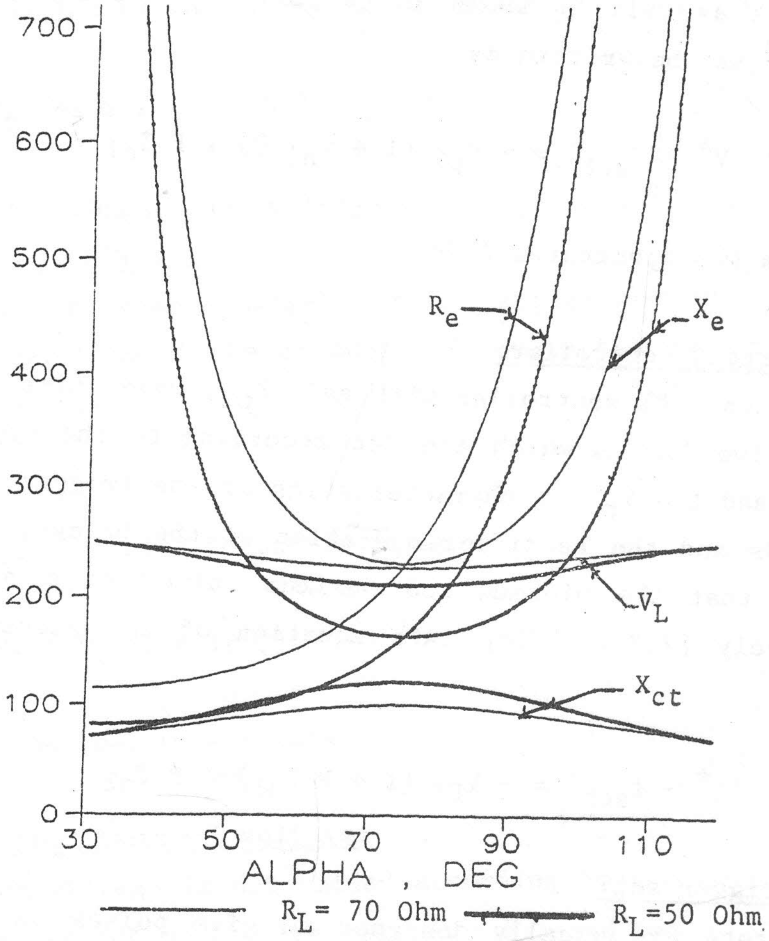

Fig. 3 Variation of R_e, X_e, X_{ct} and V_L with α

2.2 The system equations:

* The voltage controller:

This is an operational amplifier of PI type and characterised by gain K_{P1}, reset time T_{n1} and positive and negative limits. These limits are set according to the maximum current required by the load while K_{P1} and

T_{n1} are set to optimised values in order to give the desired transient performance as will be shown in section 3. The state equation of PI controller may be written as

$$i^* / (V^* - V_{act}) = - K_{p1} (1 + T_{n1} P) / P T_{n1} \tag{9}$$

Where P is the operator d / dt.

* <u>The current controller:</u>

This is also a PI controller with gain K_{p2}, reset time T_{n2} and positive and negative limits which are set according to the type of the bridge employed and the V_r - α characteristics of the trigger set. For inductive loads and the rectifier operation of the bridge, these limits are set such that the minimum and maximum values of α are 30° and 110° respectively [7,8]. The state equation of the current controller is given by

$$V_r / (i^* - i_{act}) = - K_{P2} (1 + P T_{n1}) / P T_{n2} \tag{10}$$

* <u>The trigger set:</u>

Trigger sets are usually designed to give pulses to thyristors gates with a state equation of straight line relation between α and V_r which may be written as

$$\alpha = M V_r + A \tag{11}$$

where M and A are constants dependent on type and limits of the set [8].

* the Converter bridge:

The state equation of the bridge may be written as [7]

$$V_d = V_p \cos \alpha / (1 + T_c P) \tag{12}$$

where V_d : the output load voltage

V_P : $3 \sqrt{2}\ V_L / \pi$

T_c : is the time constant of the bridge and is taken as the normal periodic time of the ac supply / double the number of thyristors in the bridge [7].

* The load:

The state equation of R-L load is given by

$$i_d = V_d / R_L (1 + T_L P) \tag{13}$$

where T_L is the load time constant.

* The generator terminal voltage:

The generator voltage is determined according to the operating value of the total equivalent capacitive reactance X_{ct} and can be written as

$$V_L = V_o - K.I_a \tag{14}$$

where V_o is the no-load voltage and K is a constant.

Equations (9) to (14) have been solved numerically using the Range - Kutta - Merson method and programmed to obtain the transient performance for a step input function.

3. OPTIMIZATION OF CONTROLLER PARAMETERS:

The gain and reset time of each controller has to be set to values such that the time response of the system should have minimum overshoot and settling time. Starting form semi empirical values for K_{P1}, T_{n1}, K_{P2} [8], these parameters have been varied individually and the effect of each parameter has been investigated. As a result groups of points have been plotted in Fig. 4 and the controller

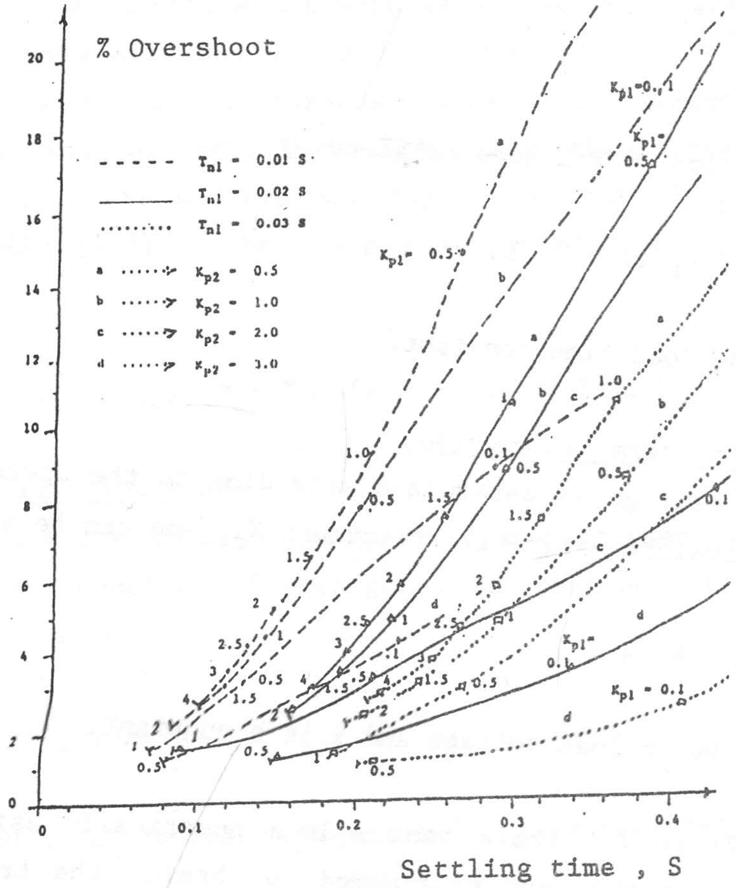

Fig. 4 The effect of controller parameters on the time response

parameter can be chosen according to the desired percentage overshoot and settling time. As a common practice, the reset time of the current controller is taken equal to the largest time constant in the current control loop which is usually the load time constant T_L. It should be noted that the controller parameters must be set far enough above the values at the end of each curve in Fig. 4, since below these values the system suffers sustained oscillation during which the system will be operating between the limits of each controller. Fig. 4 shows the range in which the parameters should be set to give an overshoot and settling time about 3% and 100 ms respectively.

4. TIME RESPONSE:

Fig. 5 shows the computed and experimental transient characteristics of the system in terms of generator line voltage V_L, load voltage V_d and load current I_d. After the generator is accelerated, with normal excitation capacitors, to full speed and voltage, the load is suddenly subjected to a step input function V^*. The switching transients are characterised by an overshoot of about 3% and a settling time in the load voltage of 0.1 s. The settling time is defined here as the time required by the system to reach ± 2% of target. After attaining steady state conditions, the speed of the generator is suddenly dropped to 67% of its normal value. This reduction in the generator speed, with the corresponding variation is generator frequency and excitation reactance, reduces the steady state terminal voltage V_L by about 48% while the load voltage V_d is kept unchanged with zero current regulation. A comparison between the computed and experimental characteristics shows good agreement and demonstrates the validity of the model.

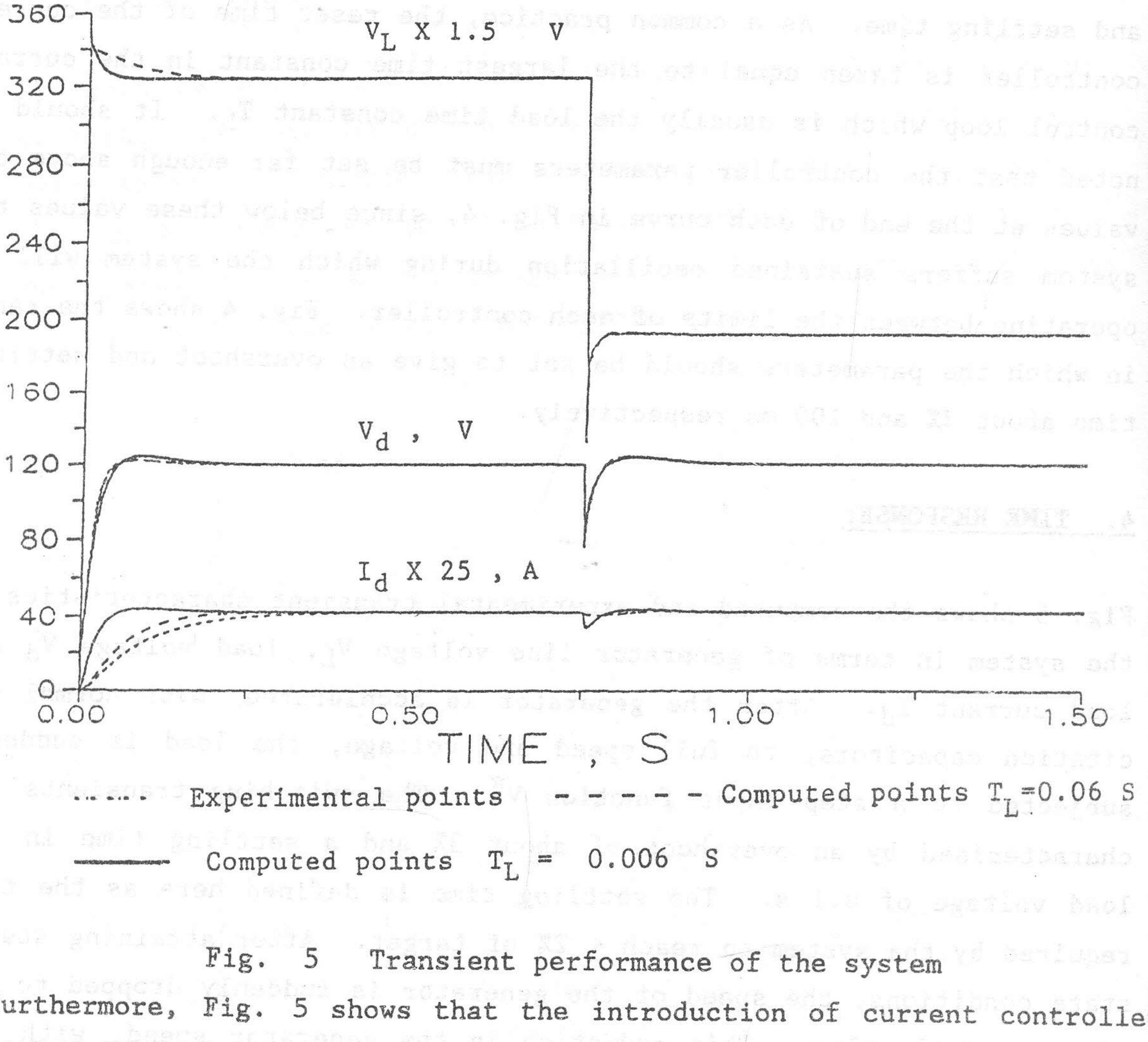

Fig. 5 Transient performance of the system

Furthermore, Fig. 5 shows that the introduction of current controller with full-load current limiting produces a significant reduction in the size of the smoothing inductor. Thus a decrease of smoothing inductance from 4.2 H to 0.42 H with the same controller parameters produces no significant change in the characteristics. Fig. 6 gives the transient behaviour of the system when the load is suddenly increaed by about 30%. As a result, the equivalent capacitive reactance increases by 11% and the generator terminal voltage drops by 7%. The corresponding trancritical value of the load resistance has been determined. The parameters of the controller have been optimised and set to values such that the maximum overshoot and settling time of the load voltage are 3% and 0.1 s respectively. In addition, at constant excitation capacitance and normal loading canditions zero voltage regulation is obtained up to 33% reduction in wind speed. Switching in more capacitance at lower wind speeds will keep the zero voltage regulation. The sudden reduction in the load resistance is associated with zero voltage and unsignificant change in the transient voltage and current. The introduction of the current controller, with current limiting, leads to a significant reduction in the size of the smoothing inductor which may be ten times smaller than the normal value. The analysis has been supported by experimental results and comparison between computed and tested performance showed good agreement.

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