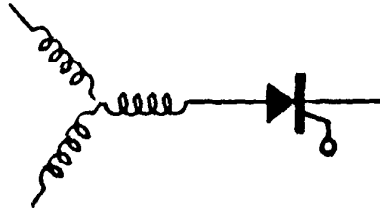


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for Induction Generators

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A PULSE WIDTH CONTROLLED THREE SWITCH EXCITER FOR INDUCTION GENERATORS

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Abstract - A static exciter for stand-alone induction generators is proposed and a computer model for the generator-exciter system is described. The exciter uses static switches to apply sequential short circuits on the generator terminals to control its excitation. The generated voltage is regulated by adjusting the frequency of this rotating short circuit under feedback. It is shown that the duration and pattern of the short circuits are additional control parameters that can be varied on-line to reduce losses and distortion in the system.

INTRODUCTION

Over the years, several methods of exciting isolated induction generators have been studied. The best known, and the oldest of these, is excitation by means of fixed capacitors connected to the stator terminals. The method is relatively well understood [1 to 5], is efficient and, generates low-distortion waveforms. However, fixed capacitor excitation is fundamentally limited since the magnitude of the generated voltage is not directly under control.

Excitation methods that seek to regulate the generated voltage can all be considered as having, directly or otherwise, an adjustable capacitance at the generator terminals. A direct approach to varying the terminal capacitance is the use of an array of capacitors in which all or a portion of the capacitors are switched in and out using static switches [6,7]. However, this approach requires a fairly large number of capacitors and switches to obtain a reasonably smooth control of the voltage in a three-phase generator. One method of continuously varying the terminal voltage is to have a fixed capacitor equal to the maximum capacitance required under expected operating conditions and then use a thyristor controlled inductor (TCI) to tune out the excess VARS at a given instant of operation [8,9]. A drawback of this approach is that both the capacitor and the inductor have to be sized to their maximum expected value and tend to be large.

Static inverters have been used successfully as induction generator exciters [10,11,12]. Novotny [10] has shown that the switching action of a VSI or a CSI must automatically meet the excitation needs of the generator since the dc link itself cannot supply the associated reactive power. The mechanism of this automatic excitation is best illustrated by the operation of a 6-step VSI. The topology of a VSI changes every 60 degrees of the ac waveform but during any one of these 60-degree intervals, two of the machine terminals are short circuited by being connected to the same side of the dc link. The current within the short circuit is not constrained by the inverter but is determined by the excitation need of the machine at the given instant. Since the inverter action is

in effect resulting in a rotating short circuit the following question can be posed. Is the presence of the dc link essential to this method of excitation control? Can the excitation needs be met simply by applying direct sequential short circuits to the generator? The work reported by Studtmann [14] and our own experimental work conducted over the last two years indicates that excitation by application of direct short circuits to the generator terminals is feasible. However, absence of the dc link makes it difficult to handle the energy existing in the machine at the instants of switch openings. Experimental work has shown that the simple implementation in the manner of [14] results in large spikes and high exciter losses.

This paper describes an exciter that uses static switches to apply direct short circuits to the generator terminals but permits the circulation of the machine leakage energy so that reasonable values of exciter efficiency and distortion are realized. The paper describes the development of a computer model of the generator-exciter system that can be utilized in the study and the design of this type of systems. It is shown that operation with fixed, 60 degree short circuit intervals is not essential. In fact, easy control of the short circuit widths permitted by the three-switch topology can be utilized to reduce the short circuit durations when a smaller range of effective capacitance is adequate. This reduces the distortion and losses in the exciter. Additional, significant improvements in the distortion are obtained by splitting the short circuits into appropriately selected subintervals.

PULSE-WIDTH CONTROLLED EXCITER

Exciter Power Circuit

Figure 1 shows the schematic diagram of the proposed pulse-width controlled (PWC) exciter for induction generators. The exciter consists of three static switches each in parallel with a capacitor, C. This capacitor is less than half the value needed for an uncontrolled excitation to occur at a given speed by the capacitor action alone. In fact, the capacitor can be omitted from the circuit if other means of handling the machine leakage energy are provided. The value of C is chosen in terms of the desired speed range and the waveform distortion requirements. Figure 2 shows a realization of the static switch that uses a power darlington and a diode bridge to control conduction in either direction. This configuration has the advantage that prior knowledge of the current direction is not required. Alternate realizations using SCR's, transistors, GTO's and power MOSFETs or combinations of these are possible. A current limiting capability is built into the switch to ensure quick and safe discharge of C at switch turn on. L_s is a di/dt limiting inductance of a few hundred microhenries required to slow down the extremely rapid discharge from the capacitor till it can be controlled by the current limiting circuit. C_s , R_s and the diode D_s form a snubber circuit that is sized to handle the small storage energy of L_s provided that a parallel capacitor is present to absorb the much larger leakage energy of the machine.

[#] Habib Rehaouia was on leave from the University of Tunis, Tunisia.

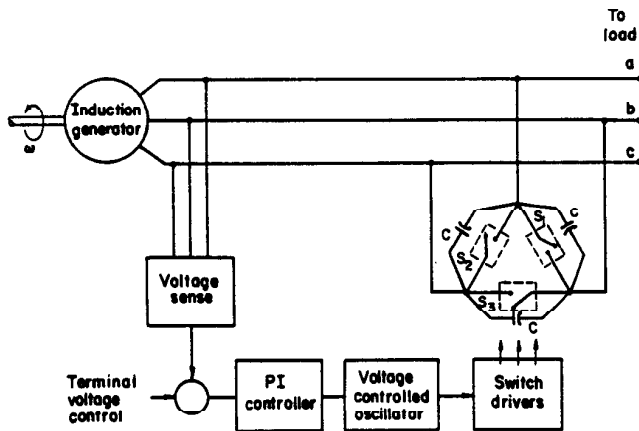


Fig. 1. Schematic of the pulse-width controlled three-switch exciter for induction generators.

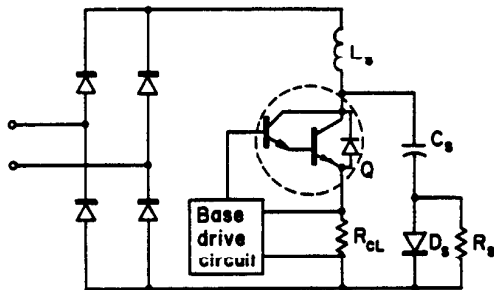


Fig. 2. Power circuit of one switch.

Alternate circuit configurations are possible that apply line-to-line short circuits to the machine terminals but do not require three controllable bi-directional switches. An interesting example is the circuit of Fig. 3.

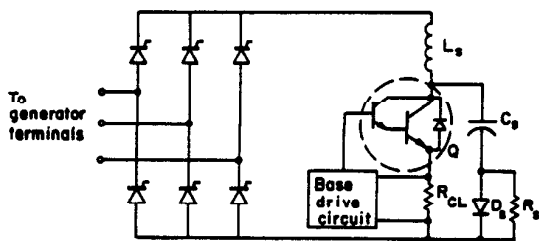


Fig. 3. Alternate arrangement of static devices for application of line short circuits. Only one device is forced commutated.

Basic Operation of the PWC Exciter

To understand the operation of the PWC exciter of Fig. 1 consider its steady state operation. Assume that the switches are being closed, one at a time, in a sequence determined by the direction of the shaft rotation. The frequency of the generated voltage, which is one half the frequency of the switch closings, is below the frequency corresponding to rotor speed. The resulting negative slip corresponds, in the steady state, to the value of the slip required to meet machine and switch losses and, any load that is present.

A drop in the voltage due to changes in the load or the shaft speed is sensed by the error amplifier which feeds a PI controller. The controller responds by decreasing the switching frequency and hence, the frequency of the generated voltage. As a result, the magnitude of the negative slip is increased and the generated voltage is once again restored to the desired value provided that the new operating point does not fall in the unsaturated region of the machine characteristics. If the operating point is in the unsaturated region, the machine voltage will collapse to a zero value. Similar statements hold when the voltage change is in the other direction or if the reference voltage is changed. Figure 4 shows a typical set of waveforms recorded under steady state operation of the PWC exciter.

Line voltage, v_{ab}
250 V/div.
Line current, $-i_a$
2.5 A/div.
Switch current, i_{sa}
5 A/div.
Switch drive, S_1

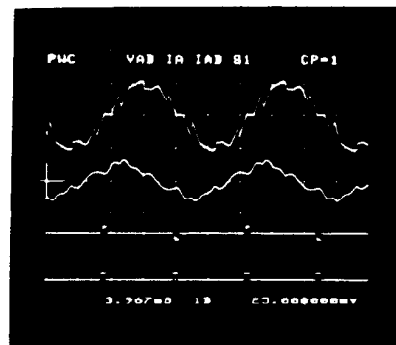


Fig. 4. Typical set of circuit waveforms observed on the PWC exciter-generator system.

COMPUTER MODEL OF THE GENERATOR-EXCITER SYSTEM

In the development of the computer model described below, a hybrid computer implementation has been emphasized. However, considerations that are special to an entirely digital simulation are discussed at the end of this section. The exciter model is developed separately from the generator model. This approach permits easy adaptation of the given model to systems using a different type of exciter.

Induction Generator Model

The nonlinear nature of the air-gap flux characteristics of the machine forms the basis of the self-excited operation of an induction generator. Unlike a motor model where this nonlinearity might be sometimes ignored or only crudely approximated to obtain first order results, an induction generator model must always incorporate the nonlinear characteristics and do so fairly accurately. Also in a generator, the stator voltages are not known a priori as they are for the motor operation. Stator voltages of a generator are determined by writing additional equations for the exciter and the load. Finally, unless the prime mover itself is under study, the rotor speed can be taken as an independent quantity and the torque equation can be eliminated from the model.

The starting point for deriving equations for the generator model are the machine equations transformed to an orthogonal $d-q-n$ reference frame, rotating at an unspecified angular speed ω , the so called arbitrary reference frame. The actual transformation of the machine equations from their phase variable form, where inductances are dependent on rotor position, to this generalized reference frame has been adequately described in the literature, e.g. [15]. The transformation used here is summarized by the following matrix representation.

$$f_{qdn} = [T(\theta)] f_{abc} \quad (1)$$

where

$$[T(\theta)] = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

and $\theta = \int \omega dt + \theta_0$. The vector f represents voltage, current or flux quantities. The transformed equations are of the form

$$v_{qs} = r_s i_{qs} + p \lambda_{qs} + \omega \lambda_{ds} \quad (2)$$

$$v_{ds} = r_s i_{ds} + p \lambda_{ds} - \omega \lambda_{qs} \quad (3)$$

$$v_{ns} = r_s i_{ns} + p \lambda_{ns} \quad (4)$$

$$v_{qr}' = r_r' i_{qr}' + p \lambda_{qr}' + (\omega - \omega_r) \lambda_{dr}' \quad (5)$$

$$v_{dr}' = r_r' i_{dr}' + p \lambda_{dr}' - (\omega - \omega_r) \lambda_{qr}' \quad (6)$$

$$v_{nr}' = r_r' i_{nr}' + p \lambda_{nr}' \quad (7)$$

where $p \triangleq d/dt$ and the primes denote rotor quantities referred to stator. The flux linkages above are related to currents in the following manner

$$\lambda_{qs} = L_{ls} i_{qs} + \lambda_{mq} \quad (8)$$

$$\lambda_{ds} = L_{ls} i_{ds} + \lambda_{md} \quad (9)$$

$$\lambda_{ns} = L_{lns} i_{ns} \quad (10)$$

$$\lambda_{qr}' = L_{lr}' i_{qr}' + \lambda_{mq} \quad (11)$$

$$\lambda_{dr}' = L_{lr}' i_{dr}' + \lambda_{md} \quad (12)$$

$$\lambda_{nr}' = L_{lnr}' i_{nr}' \quad (13)$$

and

$$\lambda_{mq} = L_m (i_{qs} + i_{qr}') \quad (14)$$

$$\lambda_{md} = L_m (i_{ds} + i_{dr}') \quad (15)$$

where L_m is the magnetizing inductance which in general is flux dependent. Equations (8) to (12) can be rewritten to express currents in terms of the flux linkages. For example

$$i_{qs} = \frac{(\lambda_{qs} - \lambda_{mq})}{L_{ls}} \quad (16)$$

Using (16) and similar expressions for the other current terms, currents can be eliminated from (2) to (7). The resulting equations are written in terms of reactances and modified flux linkages, e.g. $X_{ls} = \omega_b L_{ls}$ and $\psi_{qs} = \omega_b \lambda_{qs}$ where ω_b is the base angular speed of the system. Note that the modified flux linkages have units of voltage.

$$v_{qs} = \frac{r_s}{X_{ls}} (\psi_{qs} - \psi_{mq}) + \frac{p}{\omega_b} \psi_{qs} + \frac{\omega}{\omega_b} \psi_{ds} \quad (17)$$

$$v_{ds} = \frac{r_s}{X_{ls}} (\psi_{ds} - \psi_{md}) + \frac{p}{\omega_b} \psi_{ds} - \frac{\omega}{\omega_b} \psi_{qs} \quad (18)$$

$$v_{ns} = \frac{r_s}{X_{lns}} \psi_{ns} + \frac{p}{\omega_b} \psi_{ns} \quad (19)$$

$$v_{qr}' = \frac{r_r'}{X_{lr}'} (\psi_{qr}' - \psi_{mq}) + \frac{p}{\omega_b} \psi_{qr}' + \frac{(\omega - \omega_r)}{\omega_b} \psi_{dr}' \quad (20)$$

$$v_{dr}' = \frac{r_r'}{X_{lr}'} (\psi_{dr}' - \psi_{md}) + \frac{p}{\omega_b} \psi_{dr}' - \frac{(\omega - \omega_r)}{\omega_b} \psi_{qr}' \quad (21)$$

$$v_{nr}' = \frac{r_r'}{X_{lnr}'} \psi_{nr}' + \frac{p}{\omega_b} \psi_{nr}' \quad (22)$$

When (17) to (22) are specialized to a stationary reference frame, i.e. $\omega = 0$, and rewritten in integral form suitable for analog simulation, they take the form

$$\psi_{qs} = \int [\omega_b v_{qs} - \frac{\omega_b r_s}{X_{ls}} (\psi_{qs} - \psi_{mq})] dt \quad (23)$$

$$\psi_{ds} = \int [\omega_b v_{ds} - \frac{\omega_b r_s}{X_{ls}} (\psi_{ds} - \psi_{md})] dt \quad (24)$$

$$\psi_{ns} = \int [\omega_b v_{ns} - \frac{\omega_b r_s}{X_{lns}} \psi_{ns}] dt \quad (25)$$

$$\psi_{qr}' = \int [\omega_b v_{qr}' - \frac{\omega_b r_r'}{X_{lr}'} (\psi_{qr}' - \psi_{mq}) + \omega_r \psi_{dr}'] dt \quad (26)$$

$$\psi_{dr}' = \int [\omega_b v_{dr}' - \frac{\omega_b r_r'}{X_{lr}'} (\psi_{dr}' - \psi_{md}) - \omega_r \psi_{qr}'] dt \quad (27)$$

$$\psi_{nr}' = \int [\omega_b v_{nr}' - \frac{\omega_b r_r'}{X_{lnr}'} \psi_{nr}'] dt \quad (28)$$

The voltages in (23) to (28) come from the exciter simulation to be discussed in the next section. The shaft speed, ω_r/ω_b is an independent variable. This leaves the air-gap flux components, ψ_{mq} and ψ_{md} to be determined in order to solve (23) to (28). Lipo and Consoli [15] have shown a method for calculating the instantaneous values of these flux components using the air-gap saturation characteristics of the machine. The method utilizes a flux dependent saturation function defined as

$$K_m(\hat{\psi}_m) = \frac{(\hat{\psi}_m - \psi_m)}{\hat{\psi}_m} \quad (29)$$

where ψ_m and $\hat{\psi}_m$ are the total air-gap flux linkages in the machine with and without saturation.

Figure 5 illustrates a method of obtaining the saturation function K_m from experimentally determined machine terminal characteristics at no load. First, the air-gap characteristics are derived from the terminal characteristics by accounting for the stator leakage drop. The linear portion of this curve determines the unsaturated value of the magnetizing reactance, X_m . Then for each value of the unsaturated flux linkage, $\hat{\psi}_m = X_m i$ the saturation function is computed using (29) and plotted against $\hat{\psi}_m$ as shown. The deviation from the linear characteristics, indicated by a nonzero value of K_m , is seen both at the high and very low flux levels. The saturation function can be modelled using curve fitting techniques. When only analog components are available, a limited number of linear segments may be used to approximate K_m . Also, if the excitation build up mechanism is not under study,

then further simplification is achieved by ignoring the low flux values of K_m . Figure 6 shows an implementation using analog components that approximates the saturation function in the high flux region using two linear segments.

To use the saturation function in the calculation of the actual values of flux components assume, first, that their unsaturated values are known. Then the total unsaturated value of the air-gap flux is given as

$$\hat{\psi}_m = \sqrt{\hat{\psi}_{mq}^2 + \hat{\psi}_{md}^2} \quad (30)$$

Since K_m is known as a function of $\hat{\psi}_m$ then

$$\Delta\psi_{mq} \triangleq \hat{\psi}_{mq} - \psi_{mq} = K_m(\hat{\psi}_m) \hat{\psi}_{mq} \quad (31)$$

then

$$\psi_{mq} = \hat{\psi}_{mq} - \Delta\psi_{mq} \quad (32)$$

This form of (31) and (32) is particularly convenient for hybrid computer simulation. Similarly for the d -axis

$$\Delta\psi_{md} \triangleq \hat{\psi}_{md} - \psi_{md} = K_m(\hat{\psi}_m) \hat{\psi}_{md} \quad (33)$$

$$\psi_{md} = \hat{\psi}_{md} - \Delta\psi_{md} \quad (34)$$

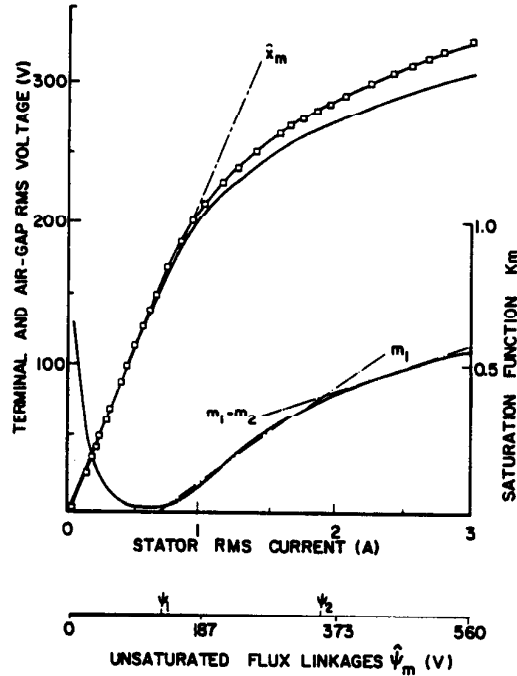


Fig. 5. Derivation of the saturation function $K_m(\hat{\psi}_m)$ from the no load terminal characteristics of the machine.

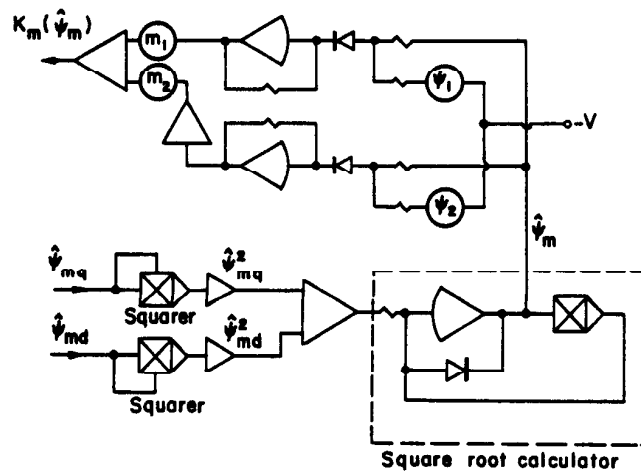


Fig. 6. Two-segment analog approximation of the saturation function in high flux region.

Expressions for the unsaturated values of the flux components, assumed above as known, can now be derived as follows. By definition

$$\hat{\psi}_{mq} = \hat{X}_m (i_{qs} + i'_{qr}) \quad (35)$$

but from (16) and (32)

$$i_{qs} = \frac{\psi_{qs} - (\hat{\psi}_{mq} - \Delta\psi_{mq})}{X_{ls}} \quad (36)$$

and similarly

$$i'_{qr} = \frac{\psi_{qr} - (\hat{\psi}_{mq} - \Delta\psi_{mq})}{X'_{lr}} \quad (37)$$

substituting for currents in (35) and rearranging

$$\psi_{mq} = \frac{\hat{X}}{X_{ls}} \psi_{qs} + \frac{\hat{X}}{X'_{lr}} \psi'_{qr} + \hat{X} \left(\frac{1}{X_{ls}} + \frac{1}{X'_{lr}} \right) \Delta\psi_{mq} \quad (38)$$

Similarly for the d-axis

$$\psi_{md} = \frac{\hat{X}}{X_{ls}} \psi_{ds} + \frac{\hat{X}}{X'_{lr}} \psi'_{dr} + \hat{X} \left(\frac{1}{X_{ls}} + \frac{1}{X'_{lr}} \right) \Delta\psi_{md} \quad (39)$$

where $\frac{1}{\hat{X}} = \left(\frac{1}{\hat{X}_m} + \frac{1}{X_{ls}} + \frac{1}{X'_{lr}} \right)$.

Figure 7 shows the resulting simulation diagram for the induction generator. A squirrel cage rotor has been assumed. Therefore, the rotor voltages v_{qr} , v_{dr} and v_{nr} and the rotor neutral current i'_{nr} are all zero.

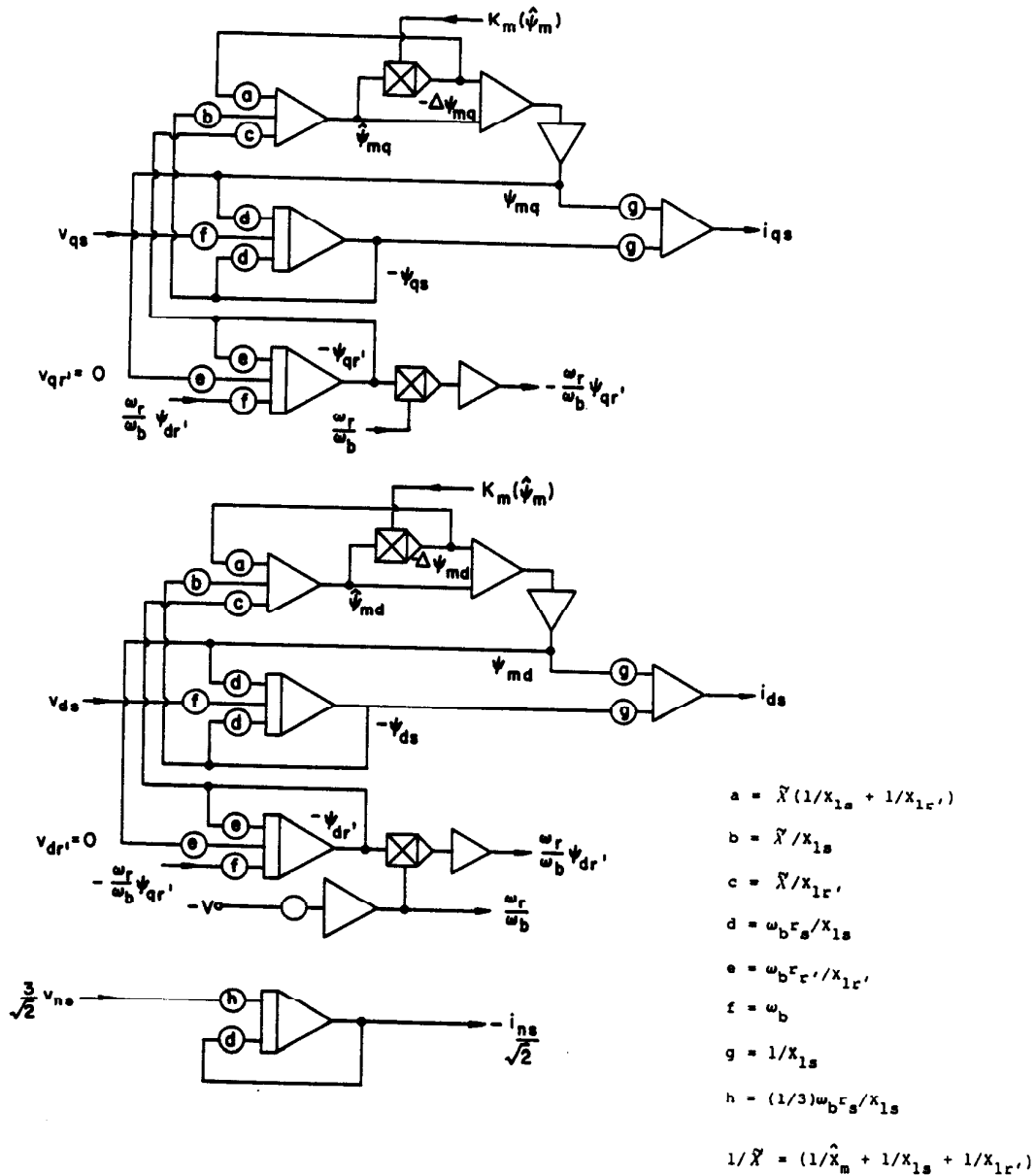


Fig. 7. Hybrid computer model of the induction generator.

Exciter Model

Figure 8(a) shows a simplified representation of the PWC exciter. Capacitor C is the actual value of the line capacitance in the circuit. Resistor R represents the load and the iron losses in the exciter and the machine. A controlled switch in series with inductance L_s is used as a simplified representation of the bidirectional switch. The inductance value is the same as the actual value used in the switch. Under this representation, the current through L_s is zero when the switch is open.

To obtain a model of the exciter, the $d-q-n$ currents from the generator simulation are first transformed to their phase variable form using the inverse transformation relation with $\theta = 0$

$$i_{abc} = [T(0)]^{-1} i_{qdns} \quad (40)$$

Assuming that the line voltages have been solved, the current in switch S_1 is

$$i_{sa} = \begin{cases} 0 & S_1 \text{ off} \\ \frac{1}{L_s} \int v_{ab} dt & S_1 \text{ on} \end{cases} \quad (41)$$

Equations for i'_a , i'_b and i'_c are obtained by summing currents at the respective nodes. At node a, for example

$$i'_a = -i_a - i_{sa} + i'_c + i_{sc} \quad (42)$$

To solve uniquely for i'_a , i'_b and i'_c flowing in a delta, an additional constraint is necessary. This comes from the observation that the charges on the capacitors sum to zero at all times. Hence, under balanced conditions

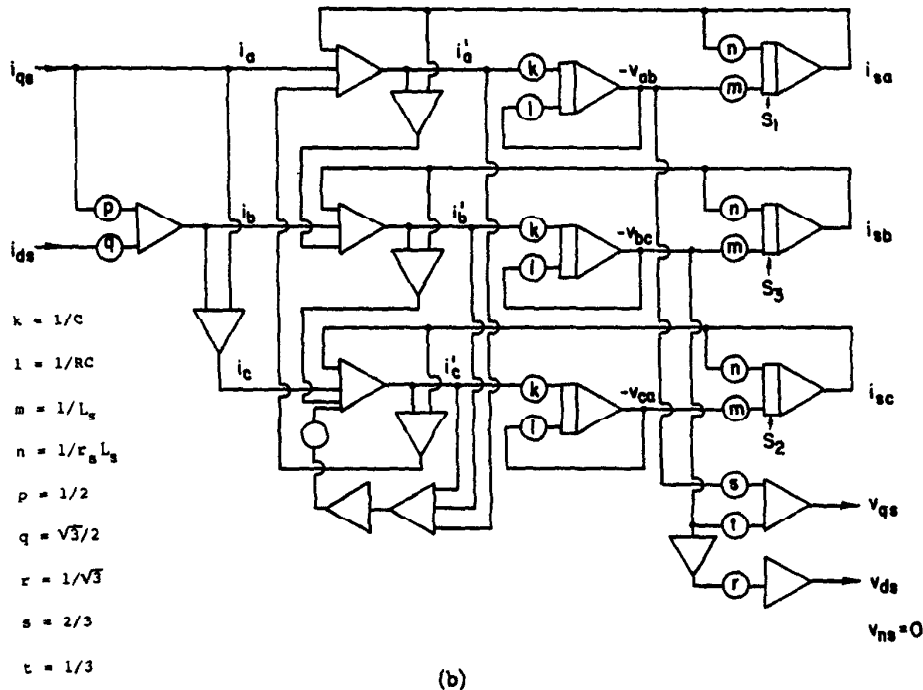
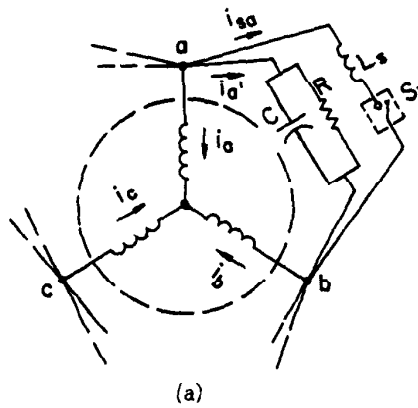


Fig. 8. PWC exciter model. (a) Simplified circuit representation. (b) Hybrid computer model.

$$i_a' + i_b' + i_c' = 0 \quad (43)$$

Equation (43) can either be used to obtain explicit expressions for i_a' , i_b' and i_c' or the constraint may be imposed on the solutions obtained for these currents. The resulting values of i_a' , i_b' and i_c' can then be used to solve for the line voltages.

For example, line voltage v_{ab} is given as

$$v_{ab} = \frac{1}{C} \int [i_a' - \frac{v_{ab}}{R}] dt \quad (44)$$

Line voltages are then transformed to $q-d-n$ voltages using the transformation relations

$$v_{qs} = \frac{2}{3} v_{ab} + \frac{1}{3} v_{bc} \quad (45)$$

$$v_{ds} = -\frac{1}{\sqrt{3}} v_{bc} \quad (46)$$

The voltage v_{ns} is zero since line voltages are being used. Figure 8(b) shows the resulting hybrid computer model for the PWC exciter. Switch closing patterns are established through the logic signals S_1 , S_2 and S_3 . A separate program, implemented on the digital portion of the hybrid, is used to generate and control the logic signals. Negative feedback is used to ensure (43).

Digital computer model: The generator model for a digital computer can be developed without major modifications of the approach outlined above for the hybrid. However, in modeling the exciter it becomes necessary to write a separate set of constraints created by each of the three cases of line short circuits, i.e. $a-b$, $b-c$ and $c-a$. These constraints are then transformed to equations in the $d-q-n$ reference frame where they are solved sequentially as the short circuits are rotated.

SYSTEM OPERATION

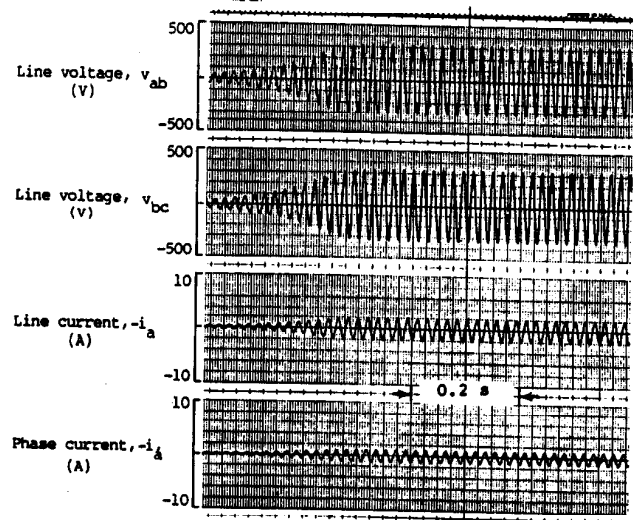
The generator-exciter system model developed above is tested and then used to investigate some of the characteristics of the PWC exciter.

Operation as a Fixed Capacitor Exciter

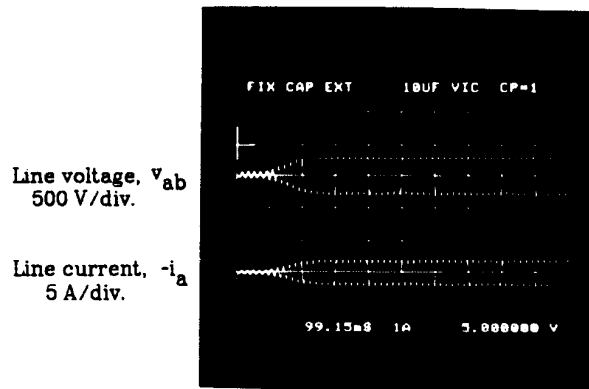
Note that fixed capacitor excitation is automatically included in the model of Fig. 8(b) as a special case with all switches inactivated. If fixed capacitor excitation were the only mode under study then a model much simpler than that of Fig. 8(b) is possible by transferring the exciter equations to the $d-q-n$ reference frame. Because of its total symmetry, the fixed capacitor excitation mode provides a useful first check of the generator model. Figure 9 compares the simulated and experimental results for this mode of operation. In both cases, the self-excitation process is started by placing an initial charge on the capacitors.

Excitation with Short Circuits

When logic signals S_1 to S_3 are reapplied the model simulates the exciter operation with short circuits. Figure 10(a) shows a set of simulated waveforms at no load. For this example, unbroken short circuits of 28 degree duration have been used. Resistor R is selected to approximate the iron losses and the losses in the switches. The capacitor value is $4 \mu F$ which is about half the value required to sustain excitation at the given speed if no switching is done. Figure 10(b) shows the corresponding circuit waveforms from an experimental system constructed in the laboratory. These and the results of the fixed capacitor excitation together establish the validity of the computer model developed for the PWC exciter-generator system.



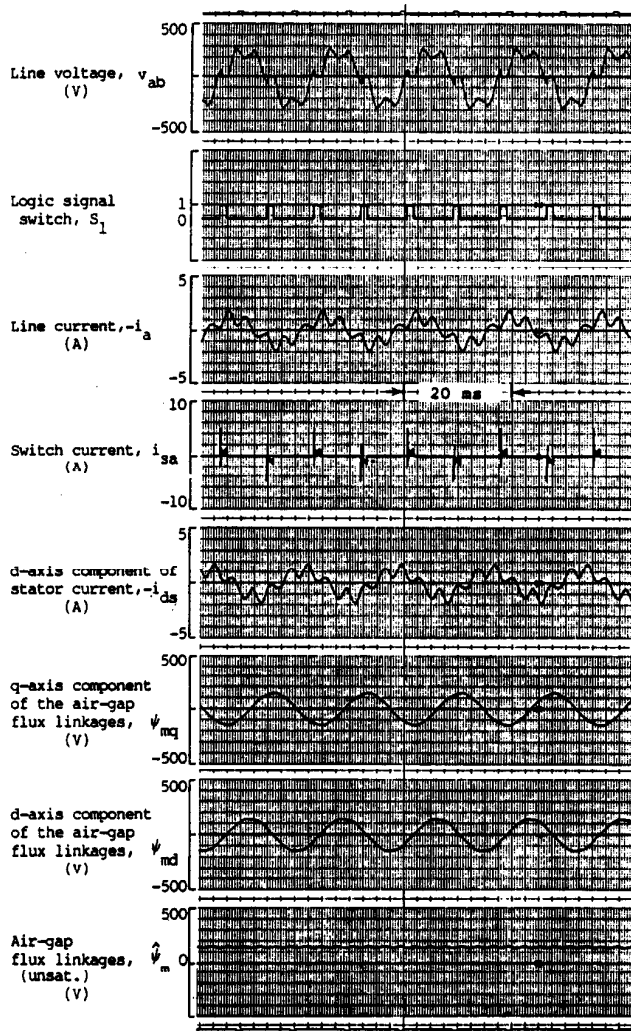
(a)



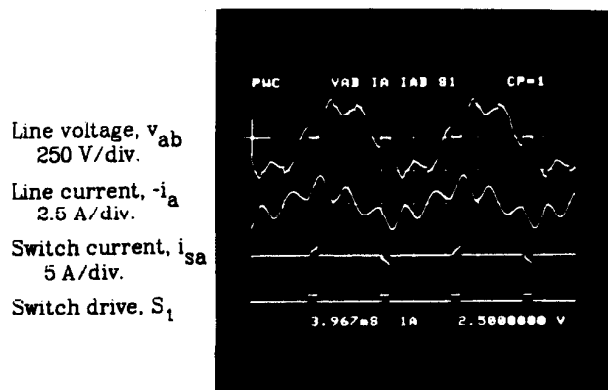
(b)

Fig. 9. Fixed capacitor excitation. (a) Simulated waveforms. (b) Waveforms from the laboratory model.

The generated voltage waveform is the result of the symmetrical switching action of the exciter on the air-gap flux in the machine. Note that the fundamental component of the switch current, i_{sa} is leading with respect to the fundamental component of the generated line voltage, v_{ab} which is also the voltage across switch S_1 . Thus, at the output frequency the switch appears as a variable capacitor. The exciter steady state operation can be seen as varying the total effective capacitance at the generator terminals in order to regulate the generated voltage. It is easy to see that this total capacitance is larger than the physical capacitance, C



(a)



(b)

Fig. 10. Circuit waveforms of the generator-exciter system. Switch closings consist of a single pulse of 26 degree duration. (a) Simulated waveforms. (b) Waveforms from the laboratory system.

since excitation is not sustained if the switches are inactivated leaving only C in the circuit.

Capacitor, C supplies a fixed portion of the excitation. However, its major contribution is in the effective handling of the energy in the machine leakage inductances at instants of switch openings. It absorbs this leakage energy but in a way that keeps the energy available for circulation. As noted earlier, excitation control is possible with no capacitors directly connected across the switches but with comparable capacitors being present within the switches for snubber or commutation action. However, such an arrangement leads to large spikes in the generated voltage. Also, the leakage energy of the machine is routed to these capacitors at each opening of the switch where it can get trapped. This results in a poor efficiency for the exciter.

Subdivided Short Circuits

Experimental and simulation work has shown that significant additional reductions in the distortion are obtained by splitting the short circuits into appropriately selected subintervals. Figure 11, for example, shows the simulated waveforms with short circuit pulses split into a 16-degree and a 4-degree pulse. In other respects the waveforms are similar to those of Fig. 10 and the two can be compared directly. Harmonic measurements of the generated voltages for the two cases confirms the improvement apparent in the voltage and air-gap flux waveforms. Note that the distortion levels are much better than would be possible using a VSI or a CSI type exciter.

Pulse-width Control of the Short Circuits

Short circuit width, measured in degrees of the generated cycle, is an important parameter of the PWC exciter. It is easy to see that a larger width creates increased distortion in the generated waveforms. Large pulse widths also increase the exciter losses because of the increased amount of current in the switches. But on the other hand, a large value of the pulse width produces a wider range of the effective capacitance and hence, a wider range of control for the system. However, these requirements are not entirely conflicting because the dynamic conditions that require a large control range are generally transient conditions when distortion and losses are not a critical issue. Similarly, in normal steady state operation when low distortion and losses are desirable, the control range requirements are not as large. Thus, it is advantageous to employ a controllable rather than a fixed value of the short circuit width. A pulse width range between 20 to 60 degrees should be adequate in most applications.

No attempt has been made to use multiple switching with any pulse width modulation scheme. In fact any such attempt is not likely to achieve improvements of any greater order of magnitude. It may, however, add to the exciter losses considerably. This is because the improvement in distortion becomes relatively smaller with additional switchings but the losses increase almost proportionately. For this reason, the number of subintervals into which the short circuits are split should be kept small.

The considerations that apply in starting and loading of this system are essentially the same as for capacitor or inverter excited system and have been reported to a large extent in the literature. For starting, an initial voltage either induced from a remnant rotor flux or placed externally by precharging of capacitors is required and the build up is highly dependent on machine magnetizing characteristics at low flux levels. With respect to loading, an induction generator handles a unity power factor load with the greatest ease. However, motor loads or passive loads of nonunity power factor can be accommodated to some extent by building such a capability in the exciter design.

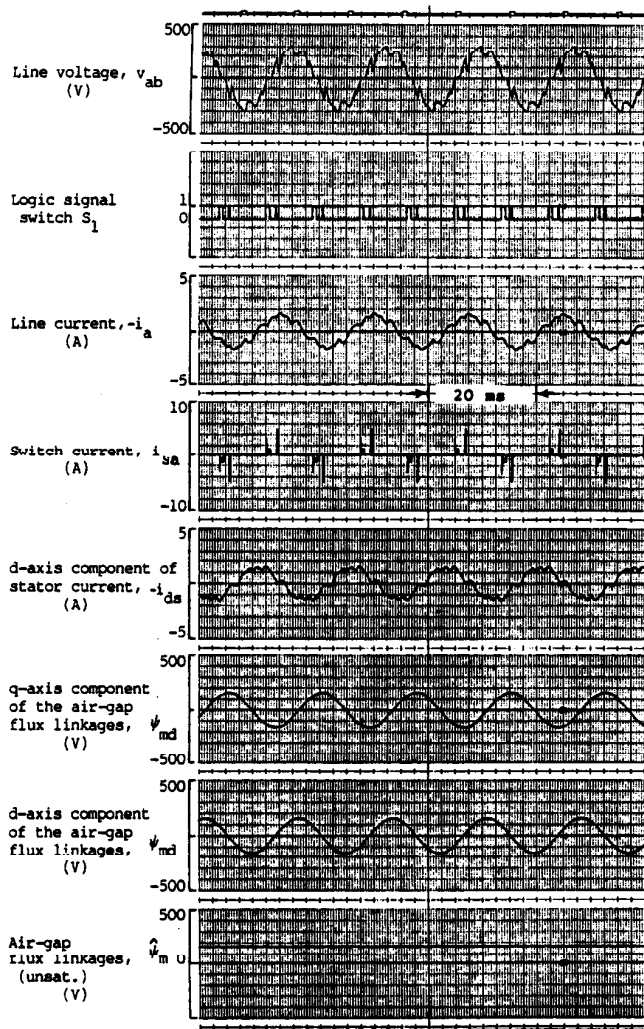


Fig. 11. System waveforms with each switch closing consisting of a 18 degree and a 4 degree pulse separated by a 22 degree null period.

CONCLUSIONS

Excitation of an isolated induction generator by the method of rotating short circuits is possible without requiring the dc link of an inverter. Use of fixed line capacitance, besides supplying a portion of the excitation, permits free circulation of the machine leakage energy which might otherwise be trapped in the switch snubber or commutation circuits. It is shown that on-line adjustments of the short circuit widths allows the designer to meet the conflicting requirements of a large control range during starting or other dynamic conditions and lower levels of distortion and losses during normal steady state operation. The PWC exciter is capable of achieving further reductions in the distortion by simple alterations of the short circuit forms. Finally, a computer model for the exciter-generator system has been developed and verified. The model can also be widely adapted to study other known methods of self-excitation.

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