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SMALL HYDRO-DRIVEN INDUCTION GENERATOR

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SUMMARY

The demand for cheap, reliable micro-hydrolectric systems has caused a search for better generators than the automotive equipment initially used. Induction generators are ideal for the purpose. They are cheap, have only one moving part, good efficiency and torque characteristic, and interface well with power transmission systems, whether AC or DC. Their only weakness is a potential failure to self excite when spun up to speed. The factors affecting excitation are discussed and a strategy for avoiding the problem is presented.

MAIN TEXT

An induction generator is simply an induction motor driven faster than synchronous speed. This is well illustrated by considering the full torque curve of a squirrel cage machine connected to a power supply of frequency w.

Just as a motor can stall under excessive torque, as a generator it can run away with too much torque from a turbine. The various trade-offs in an induction motor to obtain specified starting torque are of course unnecesssary in a generator. Also the starting windings can be omitted. This allows efficiency to the be the dominant criterion for selection, making low resistance rotors and three phase windings the best choice. Slightly higher efficiency is achieved in the generation mode as the shaft carries the windage, tooth and bearing losses which predominate in a fractional horsepower frame. Better than 75% efficiency is attained when copper and iron losses are well balanced.

An induction motor at full load will take a lagging current, often as much as 60 degrees behind voltage. This current can be considered as composed of two almost independent parts; the magnetising current lagging nearly 90 degrees, and the load current which lags varying amounts because of the winding inductance. The lagging part of the total current must be supplied by the line, whether the machine is generating or motoring unless it is supplied by power factor correction capacitors wired in parallel with the motor. With reactive current so taken care of the remaining current can be actually brought to zero (and reversed) by speeding the rotor up so the wires can be disconnected and the machine left running self excited. The question of stability of course remains.

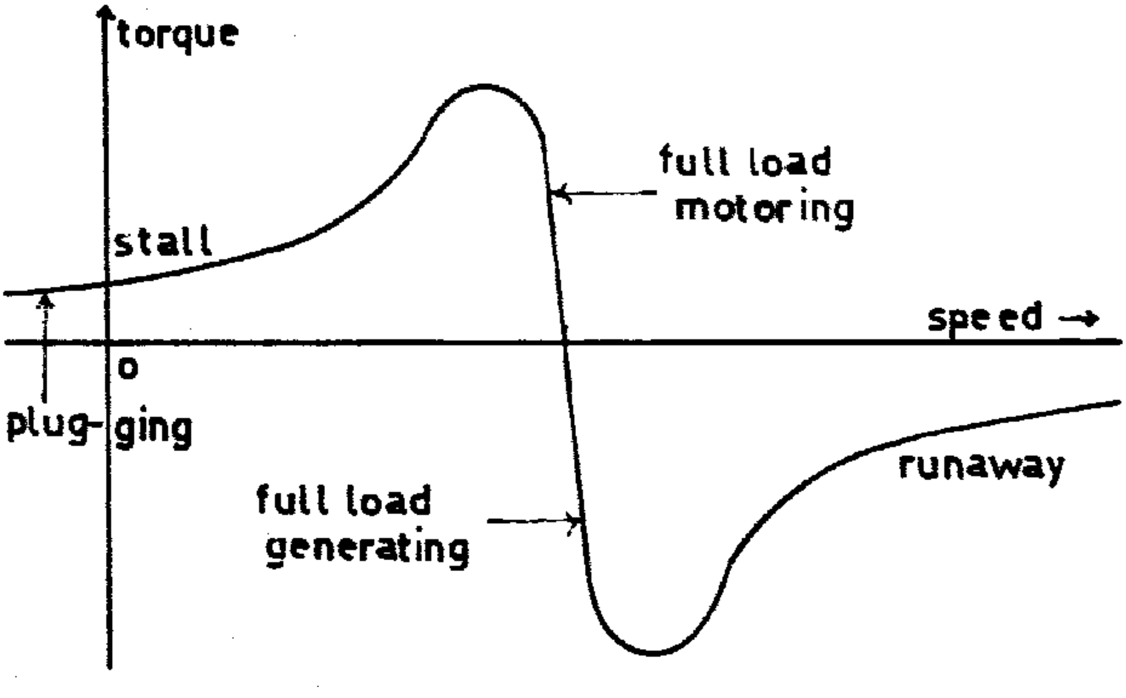


Illustration 1: Full Torque of Generator

When an induction generator is running self-excited its voltage and frequency are both free to vary and the actual operating point is very dependent on load and prime mover characteristics. With constant speed drive the voltage rises until the onset of saturation which increases the magnetising current past what the capacitors can supply and this limits excitation. The equivalent circuit is useful for finding the optimum operating point of a machine.

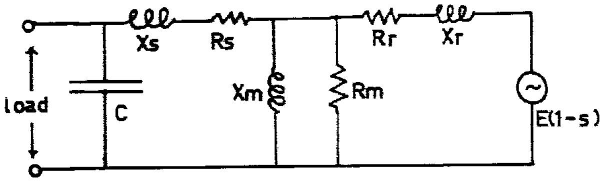


Illustration 2: Equivalent Circuit

The equivalent circuit also helps visualisation of the self excited induction generator as a feedback oscillator. The capacitor in series with Xs and Xm obviously form a high Q resonant circuit with feedback from the rotor circuit maintaining oscillation, so long as the slip is sufficient to make up losses in Rm and the load. Metal foil and polypropylene capacitors are almost lossless, Rs is small, and air gaps typical of induction motors are almost optimal for an iron cored inductor. Iron losses in the rotor are minimlsed as the frequency is so low. The result is a Q of 10 to 5O at fields around 1 Tesla. The resonant frequency of this L/C network defines the operating frequency of the induction generator by providing the 180 degree phase shift for oscillation. The resonant frequency w0 is inversely proportional to the square root of the capacitance.

This is very convenient as the speed of a generator can be matched to a directly connected turbine and optimised on site by variation in the capacitors. Australian Pelton wheels come no smaller than 4" so in practice induction generators are run at a great variety of speeds from 600 RPM to 4000 RPM depending on water pressure. Voltage of operation must of course be taken into account as must power level when designing a particular winding. The procedure is the same as for a motor.

LOADING THE INDUCTION MOTOR

A self excited induction motor drive from a "soft" prime mover like a turbine will carry many types of load, reacting to changing load current and power factor with changing voltage and frequency. Beyond a certain load the generator de-excites so there is never need for over-current protective devices. For a fraction of a second, depending on the rotor time constant, the generator will maintain current past the steady state maximum and so start loads like cold light bulb filaments and even small induction motors.

In general however the machine can only be described as unstable. There are also some very nasty peculiarities. The start up can be slow enough to allow the turbine to reach runaway speed before the volts come up. The inertia of the turbine can then drive a power pulse several times normal which blows filaments, semiconductors and capacitors. The only good thing to be said of the induction generator as a voltage source is that the waveform is beautifully sinusoidal.

A variety of shunt regulators have been used with limited success. The simplest arrangement averages the generator voltage with a filter, compares this derived voltage with a reference and controls power to a load sink such as a water heater or high wattage lamp. The controlling device is typically a triac which must be rated for high voltage and protected from the high dI/dt resulting from the large capacitors.

This simple circuit malfunctions in to revealing ways. The first is "mode jumping" wherein the triac ceases firing on every half cycle and starts catching only every second, fourth etc. half wave. This problem is solved in practice by the use of multiple triacs successively bringing in multiple loads, ideally with zero switching for RFI suppression. This solution indicates that the problem may be due to the very non-linear relationship between theta, firing angle, and power shunted in a phase control circuit.

PHASE CONTROL REGULATION

A switching regulator circuit running at 20KHz was found successful. Its action was linear and looked to the generator like a resistor.

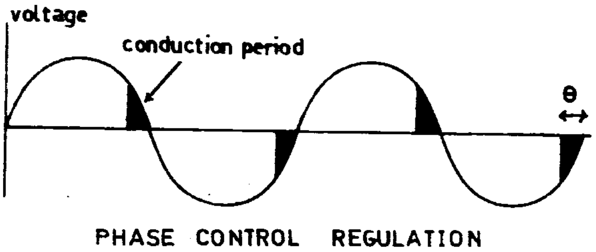


Illustration 3: Phase Control Regulation

The second common malfunction is hunting - something one would expect a squirrel cage to eliminate! Induction motor cages are usually deeply buried for lower tooth loss and starting current and so Xr is considerable. The cage does not act to damp oscillations of the rotor about a mean position when they are much faster than the rotor time constant. The combined delays in changes of the cage current, rotor speed (particularly with heavy turbine attached), and the response of the voltage averaging circuit make the 180 degrees phase shift for oscillation happen at quite low frequency. The high gain of the voltage/speed relation causes hunting at quite low regulator gain and typically 240 volts +/- 20 volts is the best possible.

D.C. SYSTEM

The solution to all these stability problems with A.C. systems is to use a D.C. link between generator and load. By rectifying the generator output to float charge a battery the voltage is clamped and the load power factor unity, so stabilising speed and frequency at the best operating point for the turbine. Some low level hunting may still occur with current fluctuations of up to 10% but this has minimal effect on efficiency and actually carries useful information.

The D.C. link can be easily shunt regulated with a fast acting circuit like the one drawn below.

SWITCHMODE LINE CLAMP

Much of the load of a small system can be D.C. with solid state inverters supplying any remaining A.C. load like refrigeration and appliances. Inverters are now cheap and reliable enough to fill all but the most excessive requirements for 240v, giving a well conditioned supply, better than the mains in every way except ironically, waveform - the forte of the generator.

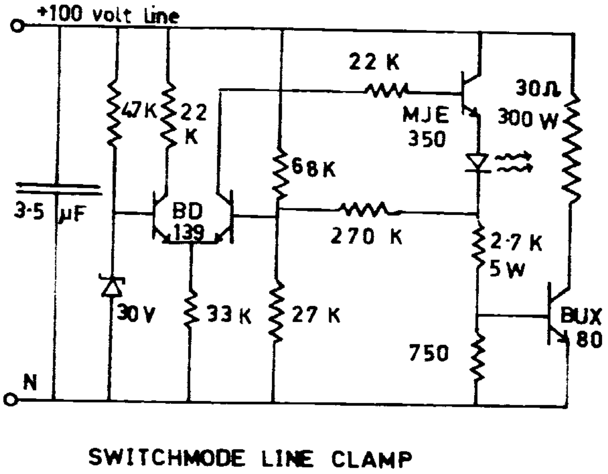


Illustration 4: Switchmode Line Clamp

TRANSMISSION

Sites for micro-hydroelectric development typically require power transmission over several hundred metres of country that is almost impossible for either overhead or buried cable because of rock, steep gradients, and trees. Rectifying the generator output to 100 volts D.C. can allow the transmission line to fall under ELV regulations and so be buried shallow, cemented to rock, or run in conduit on fences. The cost of the extra copper required is small compared to the cost of safety provisions with higher voltages. The D.C. line can be either series connected to several typically 24 volt consumers or can fed to switching regulators to float charge storage batteries at load centres. There must of course be a voltage clamp at the generator to stop the line voltage soaring in the event of an open circuit. The same clamp protects the system from start up surges.

RECTIFICATION

An induction generator driving a 2 or 3 phase bridge is forced to deliver a flat topped voltage wave causing considerable harmonic currents in the windings. Small induction motors are often driven from square wave inverters for speed control purposes and the losses increase only moderately. It is reasonable to extrapolate this to induction generators under similar voltage waveforms. The harmonic currents clearly will vary with winding pattern, winding inductance and power distribution transformers before rectification. The full effect of harmonic currents remains to be analysed. They may play an important role in the action of shunt regulators. The typically slow diodes used in bridges have a marked reverse recovery time and the snap off can cause severe MW radio interference from the transmission line if filters are not included.

SELF EXCITATION

If the speed of an induction generator drops below a critical speed, dependent slightly on load, the voltage will drop quickly to almost zero. Because this happens quickly compared to the slip frequency the residual magnetism left in the rotor is that corresponding to a quite large field. To see why the voltage drops quickly and does not de-gauss the rotor it is necessary to examine the curve of resonant frequency vs field for the machine. A curve of this type will exist for any gapped iron cored inductor with parallel capacitor.

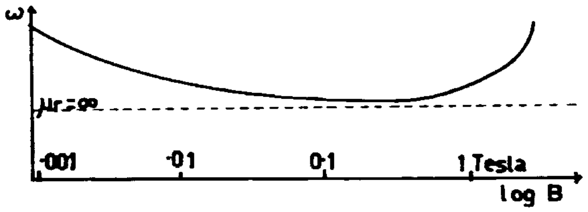


Illustration 5: Resonant Frequency vs Field Stength

Frequency rises at low and high fields as the permeability of the iron has a significant effect on the magnetic circuit. The actual operating speed Vs field will be almost the same curve as slip is small. All points to the right of the minimum are stable operating points whereas all points to the left of he minimum are unstable and even constant speed will result in a rapid de-exitation caused by slip reversal. The residual field can be calculated using Br=lHc/G where the value of Hc is that obtained from the hysteresis curve with tips at the field existing at the time of de-excitation. Meanwhile the stator Br' will be reduced to a small level by the decreasing rotating field present in it during de-excitation, which cannot be shorter than a few cycles because of rotor inductance. Remnant fields present in the stator play no part in the subsequent buildup of the machine in any case as they are incapable of de-gaussing the rotor and currents they induce are small and cannot create any larger field than the remnant. The situation is like an alternator with short circuit stator.
The residual field in the rotor however is sometimes able to re-excite the machine if the speed is increased sufficiently. The cut-in speed is typically about 1.4 times operating RPM which is no problem if the prime mover is a turbine. There is however an undesirable power surge as the surplus kinetic energy of the apparatus is exhausted.

The snag is that not all machines will reliably re-excite. Some will only re-excite if accelerated quickly, and some not at alt. To explain and predict these vagaries in behaviour a detailed analysis is necessary.

EXPERIMENTAL METHOD

A test bed was set up with various generators driven with a flexible coupling from a variable speed D.C. motor with low inertia. The voltage from the test machine was fed to a zero crossing detector firing a strobe light which illuminated marks on its shaft. The frequency and voltage of the generator were also measured concurrently and slip was recorded with a stop watch.

RESULTS

At below synchronous speed the induction generators all ran as synchronous machines excited by the residual magnetism in the rotor. With no capacitors connected voltage was proportional to speed and indicated a field of around 5O Gauss but varying very widely. With capacitors connected the voltages rose and as speed was increased some generators built up and some failed. After failure these generators were found to have very much reduced residual field. There was a marked phase shift in these generators as synchronous speed was passed.

The onset of slip accompanying buildup showed different forms.

Some machines [eg Newman 7.5 HP] showed a smooth commencement of slip, some [repulsion induction Motor] shoved a jump in phase of rotor on buildup, and some [Crompton Parkinson] showed an exponentially growing rocking of phase. Frequency seemed to depend most on the size of the machine when there as no electrical load. In all cases the slip seemed to be almost independent of field in the range of operation between stability and saturation, ie 0.1 Tesla to 1.2 Tesla. As friction and windage are carried by the shaft the slip was only that required to carry the iron and copper loss and varied from 2Hz to 0.2 Hz. The most adverse conditions for buildup were very slow accelerations, often encountered in Hydroelectric systems with malfunctioning plumbing. Surprisingly, very fast accelerations were never a problem although the rotor often reached speeds three times normal.

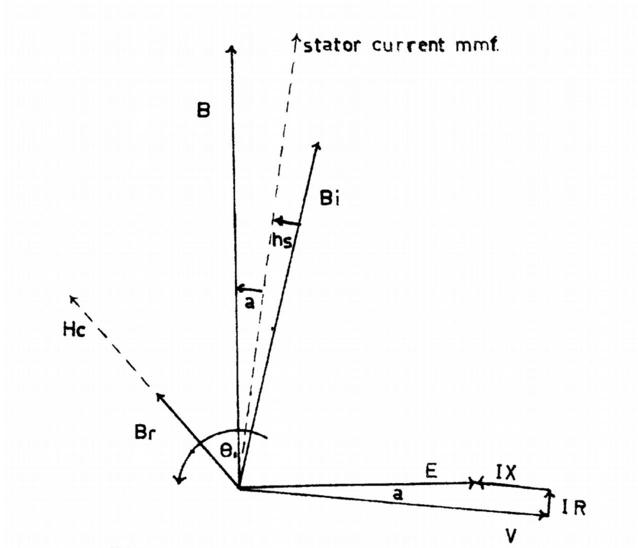


FIG 6 SYNCHRONOUS OPERATION

Illustration 6: Alternator Phasor Diagram

THEORY OF BUILDUP

The simplest reason for a failure in self excitation is the inability of the residual field in a generator to create a large enough field to cause a change in Br, leaving it frozen in direction and magnitude with respect to the rotor. To analyse this situation the phasor diagram of the alternator is used. In this diagram, h is the angle of lag of Bi behind the MMF caused by stator hysteresis. It is a function of B. Eddy current loss is ignored because it is small compared to hysteresis and is carried mainly by the shaft as tooth loss.

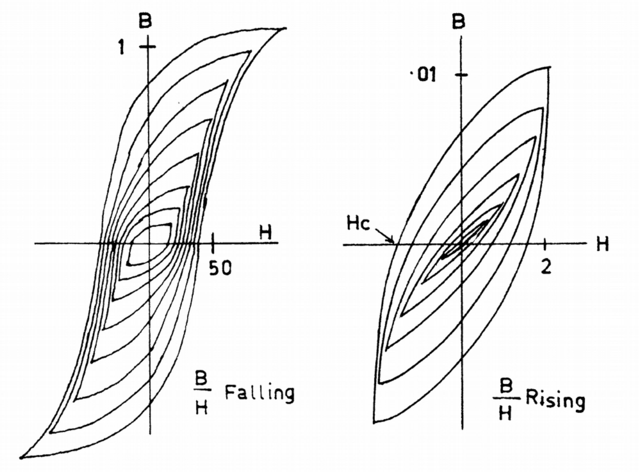
ln FIG 6
Br + Bi = B
E is perpendicular to B
MMF is perpendicular to V Taking the slight liberty of calling |V| = |E| + |X| (as a=3 degrees)

the formula on the right relates B to the MMF creating it, Hc.

$$\frac{B}{H_c} = \frac{l}{G\sqrt{1 - 2\left(\frac{\omega}{\omega_p}\right)^2 \mathrm{Cos}(a+hs) + \left(\frac{\omega}{\omega_p}\right)^4}} \quad \ldots.1$$

This expression is not very useful for predicting whether Hc will be altered by B as the size of B depends on Q. Also, Wp, G and h all are a function of B. However, it is very revealing of the way B varies with w to form a high Q resonance at w = Wp whose peak is determined by a + h.
Also this formula emphasises the importance of small G and large l.
B/Hc can be estimated from the proportions of the hysteresis loop.
The loop area represents energy lost per cycle, so hysteresis loss Vs B curves can be used to deduce the trend of B/Hc.

The Steinmetz relation gives loop area proportional to the 1.6 power of B so the loop actually gets fatter in shape as B decreases. This trend fails however at small fields, and at very small fields such as 100 Gauss the Raleigh law states that loop area is proportional to the cube of B, making the loop thinner again. A thin hysteresis loop requires relatively more B to reverse Hc. The RH side of [1.] is complicated but does not change very much with B as the dependence on h, which decreases with B (Raleigh's Law), is approximately counteracted by changes in G caused by Ur decreasing.



Hysteresis Loops for Large and Small Fields

This change in the loop proportions explains why any generator can have its residual magnetism reduced to the point where buildup will not occur.

Spiral Condition

Even if Hc can create a large enough B to rotate it there is still no assurance that it will not result in a decreasing Hc. Consider a rotating field extnally impressed on a rotor.

Br will dragged around by B with a certain size and angle relationship depending on the size of B. If the size of B depends on the size of Br then this would be the point of unstable equilibrium vhere Br creates B just sufficient to rotate Br with unchanging amplitude. Larger ratios of B/Br vould cause Br to increase and smaller would extinguish Br in a decreasing spiral.

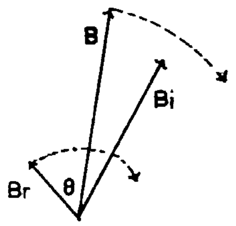


Illustration 7: Spiral Condition

Hence the spiral criterion presents itself:
When B leads Br by the angle needed to rotate Br vith unchanging amplitude it must be bigger than that value which would leave Br the same size. To further analyse this condition for increasing B consider the phasor diagram of a rotating field in an induction motor with an open circuit cage. The field Bi is created by the current in the stator windings.
The assumption here is that Brr and Brs both lag B by the same angle which is strictly true only if the laminations are of the same material.

fig 6 gives $\mathrm{Sin}\,\theta_1 = \dfrac{\mathrm{Bi\ Sin}(a + hs)}{\mathrm{Br}}$ 2

fig 8 gives $\mathrm{Sin}\,\theta_2 = \dfrac{\mathrm{Bi\ Sin}(hs + hr)}{\mathrm{Brr} + \mathrm{Brs}}$ 3

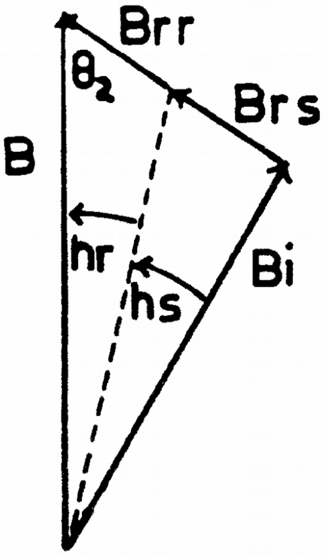


Illustration 8

In fig6 (above) theta1 will increase with speed until it is as large as theta2. At this point B/Hc must be such as to cause an increasing spiral if the machine is to build up.

now $\mathrm{Brs} = \dfrac{\mathrm{Hc'\,ls}}{\mathrm{Gr}}$ and $\mathrm{Brr} = \dfrac{\mathrm{Hc'\,lr}}{\mathrm{Gs}}$ 4

the spiral condition requires $\dfrac{B}{\mathrm{Hc}} > \dfrac{B}{\mathrm{Hc'}}$ 5

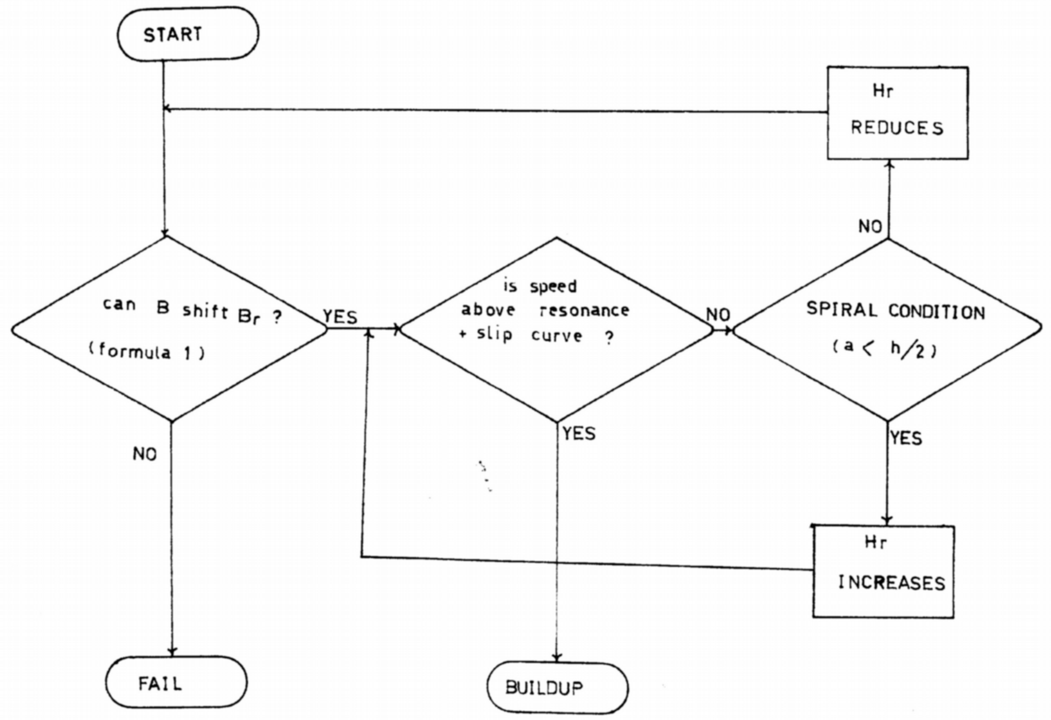
using symmetry to simplify 2 3 4 & 5 gives:

$a < \dfrac{h}{2}$ 6

This criterion gives a clear and useful indication of which features of an induction generator are beneficial to builldup:
1/ A high Q stator circuit
2/ High hysteresis loss at low field (in rotor laminations)

The upward spiralling of Hc and B must get into the area above the resonance + slip curve and so initiate induction generator action as currents are established in the cage. This could take many cycles however as the rotor time constant is often more than 0.2 seconds. Interaction between the upwardly spiralling Br and the rotor cage may be responsible for the peculiar movement of the phase of B at buildup as mentioned in "Results". There is a good analogy between the movement of the field with respect to the rotor, and the sliding of surfaces under friction. First Br remains stuck to the rotor. Then on the point of buildup a stick/slip behaviour commences, followed by a viscous sliding as slip sets in and the rotor carries torque. With increasing torque the linearity eventually breaks down as the field loses its grip on the rotor like a slipping clutch.

The flow chart below is a convenient representation of the sequence of events possible when an induction generator is spun up.



CONCLUSION

Induction generators offer high output per dollar, environmental resistance, and reliability. The potential problems of self-excitation can be avoided by using those machines that posess the important qualities defined in this paper. Modern metallised polypropylene capacitors have become so cheap and reliable as to present far less problems than slip rings.

Competing machines in this application include permanent magnet, alternators, brushless alternators, and inductor type alternators. These are all either more expensive than induction generators or simply unavailiable. Induction generators are cheap enough to allow high output machines to be left lying idle much of the time, for example in wind electric systems where they are commonly used in a grid excited manner.It is likely that they would be useful in small isolated wind plants where the frequency/output curve could be adjusted withh inductors to match the rpm/output curve of a fixed pitch aeroturbine.

SYMBOLS	
B	magnetic field
Hc	coercive force
Hr	field resulting from Hc
l	magnetic path length of rotor
a	loss angle due to the stator resistance
h	loss angle due to hysteresis
Q	quality factor
ur	relative permeability of iron
G	((effective airgap times * 2) / µ0) + ((path length) / (µ0 * µr))

POSTSCRIPT

33 years have past since this publication. There have been enormous breakthroughs in technology such as cheap supermagnets. Still there is one great advantage induction generators hold - the simplicity of controlling flux so as to balance iron and copper losses and to achieve power point tracking. Hundreds of small turbines were manufactured and some return for repairs after thirty years of service!

Globalisation of electric motor manufacture has been a problem. As self excitation is hardly a design specification, substitution of motors carrying the same brand has caused grief. The loss of excellent machines like ASEA has forced use of ABB, Baldor, WEG etc which have excellent characteristics. A quick acceptance test has been to short circuit the machine while generating.
Even more of a challenge to re-excitation is a sudden overload sufficient to kill excitation.

This paper will now have a home on the WWW, something that did not exist when it was written!

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