B. McCOLLUM.
ALTERNATING CURRENT MOTOR.
APPLICATION FILED DEC. 22, 1909.

984,582. **Patented Feb. 21, 1911.**

2 SHEETS—SHEET 1.

Fig 1

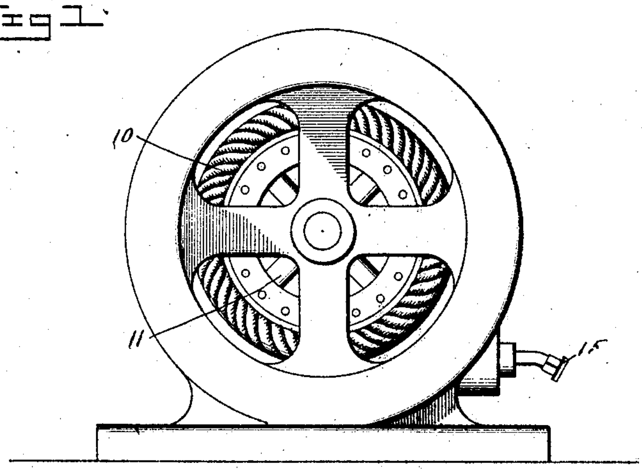
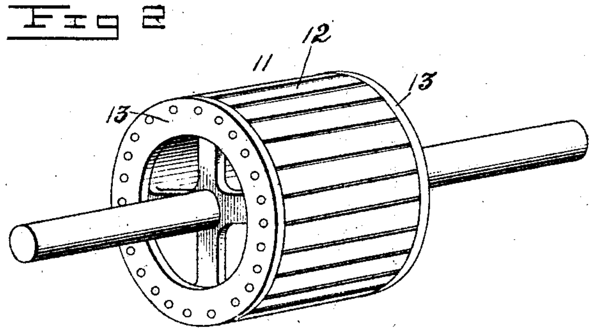


Fig 2



Inventor
Burton McCollum

Witnesses
H. A. Robinette
[illegible]

By Meyers Cushman & Rea
Attorneys

B. McCOLLUM.
ALTERNATING CURRENT MOTOR.
APPLICATION FILED DEC. 22, 1909.

984,582. Patented Feb. 21, 1911.

2 SHEETS—SHEET 2.

Fig 3

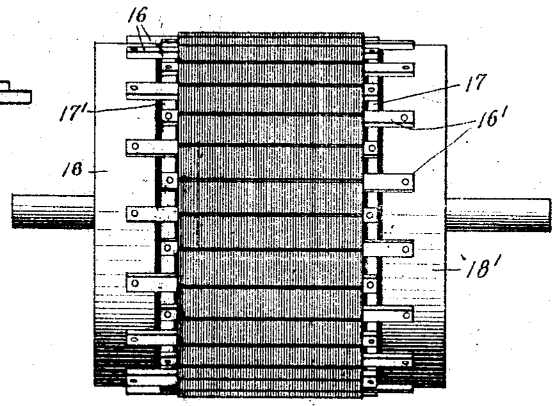


Fig 4

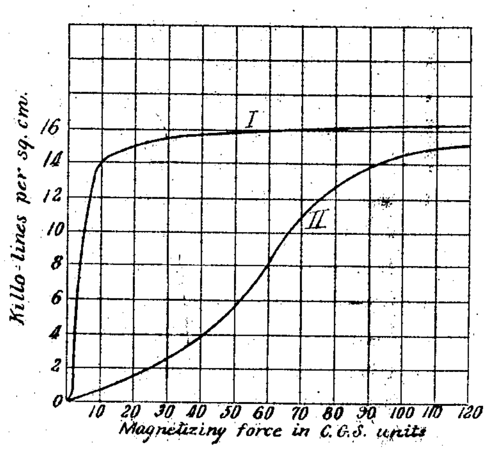
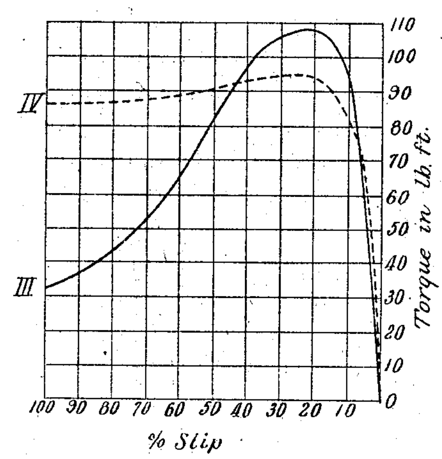


Fig 5



Witnesses

Inventor

Burton McCollum

By Meyers Cushman & Rea

Attorneys

UNITED STATES PATENT OFFICE.

BURTON McCOLLUM, OF LAWRENCE, KANSAS.

ALTERNATING-CURRENT MOTOR.

984,582. Specification of Letters Patent. Patented Feb. 21, 1911.

Application filed December 22, 1909. Serial No. 534,561.

To all whom it may concern:

Be it known that I, BURTON McCOLLUM, a citizen of the United States, residing at Lawrence, in the county of Douglas and State of Kansas, have invented new and useful Improvements in Alternating-Current Motors, of which the following is a specification.

My invention relates particularly to induction motors of the squirrel-cage type, and has to do with the starting of these motors. However, as will appear hereinafter, my invention is not limited to its application to squirrel-cage motors, it being practicable to apply it with facility, and a great resulting advantage, to coil wound rotors of induction motors, and in other ways.

The starting torque of squirrel-cage induction motors is, as is well known, very poor when such motors have good running constants. Motors of the squirrel-cage type possess, however, many very excellent features, especially adapting them for use in many situations. Chief among these features is their good mechanical construction, and the absence of moving contacts of any sort. The absence of all moving contacts at which a possible spark may occur, makes these motors particularly desirable for use in mines and in factories where there is danger of fire, while the absence of these contacts, and sturdy mechanical construction of the squirrel-cage motor, makes them least liable to break down, and adapts them to stand usage under the hardest conditions. But owing to their poor starting torque, their use has been much limited.

It is well known to those skilled in the art that an induction motor requires a high resistance in the secondary circuit, if it is to have good starting torque, but this resistance must be low if the motor is to have good running constants, such as high efficiency, good speed regulation, and low temperature in operation. In order to accomplish this numerous devices have been proposed, most of which contemplate the use of a rheostat resistance in series with the secondary winding, which is cut in in starting and cut in when the motor is running. These are open to the objections that they usually are provided with movable contacts, are expensive, mechanically complicated, and require a coil wound rotor, all of which conditions it is desirable to avoid. Most of the devices proposed are also subject to the objection that they are non-automatic in starting the motor. Attempts have been made to produce a motor free from these objectionable features, and which would operate automatically in starting. One of these features is the making of the short-circuiting ring of the squirrel-cage out of iron in order to take advantage of the skin effect. I have found that this means gives good starting torque, but operates satisfactorily only in motors of small size, so small as two or three horse-power. The motors of large size equipped with this means of starting automatically may have a good starting torque, but poor speed regulation and poor efficiency. The reasons for this will be apparent upon a little study of the curves of Figure 4 of the accompanying drawing. The curve numbered I on this sheet, is the saturation curve of the average grade of iron employed in the manufacture of machines in the electrical art. This curve is drawn between kilo-lines of flux per square centimeter and the magnetizing force in c. g. s. units. It will be observed that the iron rapidly becomes saturated, the greatest change in flux density occurring before the magnetizing force has reached 20 c. g. s. units. Thereafter there is only the very slightest change in the flux density, the saturation curve becoming an approximately straight line substantially parallel to the horizontal axis. In fact, after a magnetizing force of ten c. g. s. units has been applied, there is relatively little change in the flux density. Now variations in skin-effect depend directly upon variation in flux density, as well as upon variations in the frequency of the circuit including the iron conductor. Speaking generally and by approximate formulæ let e_0 be the total electro-motive force impressed upon a portion of a conductor. This will be the same at a given instant for every element of that portion of the conductor. Let e' be the counter E. M. F. in any element of the conductor used at alternations of magnetism that surround that element. The resultant E. M. F. e, acting on that element, will, of course, be the difference between the impressed and the counter E. M. F.'s, or,

$$e = e_0 - e' \quad \text{(1)}$$

But e' equals $2\pi f \phi$ where f is the frequency of the impressed E. M. F., and ϕ, is the maximum value of the flux that links with the element under consideration, as, for simplicity, the center of the conductor. Hence, we have

$$e=e_0-2\pi f\phi \text{......} (2)$$

At points near the surface of the conductor, there will be only a negligible counter E. M. F., and hence, we may consider that here the resultant E. M. F. is equal to e_0. Therefore the ratio of the resultant E. M. F.'s near the surface and at the center, respectively, which will obviously be the ratio of the currents, will be

$$\frac{e_0}{e}=\frac{i_0}{i}=\frac{e_0}{e_0-2\pi f\phi} \text{......} (3)$$

From this equation we see that if e_0 is constant and ϕ is constant, which would be the case with well saturated iron, then as the frequency f increases the denominator decreases, thus increasing the ratio between the current near the circumference and that near the center, producing a greater inequality in the distribution of current and increasing the resistance. Obviously, from the equation, and the assumption made in regard to constant impressed E. M. F., e_0 and constant flux ϕ, the resistance would increase indefinitely with increasing frequency. Now let us apply these facts to an induction motor. If such a piece of iron is made a part of the secondary circuit of an induction motor as described above, the impressed E. M. F. is not constant as assumed above, but varies with the frequency. In a constant potential motor the flux remains nearly constant, and such being the case the E. M. F. e_0 is equal to Ef, where E is the E. M. F. at unit frequency, and is constant. Putting this in equation 3, we have

$$\frac{i_0}{i}=\frac{Ef}{Ef-2\pi f\phi}=\frac{E}{E-2\pi\phi} \text{......} (4)$$

We see therefore, that the ratio of the current near the surface to that near the center is independent of the frequency and therefore the same distribution of current, and hence the same resistance, will result at all frequencies and at all speeds. Hence, if it is desired to secure an increase of resistance with decrease of speed we must make ϕ in the denominator increase as the speed falls off. That this is a physical impossibility where soft iron is used, is seen from the following consideration. The working current in the rotor of a squirrel-cage motor, must of necessity be quite large in order that the motor have the necessary power for which it is designed. Thus, in a ten-horse-power motor the normal load current in a rotor is such as to produce in a short-circuiting ring a magnetizing force of about tweney-five or thirty c. g. s. units, and for larger motors would be still larger. As we have seen, iron under this force is already well saturated, and any further increase of current cannot increase appreciably the value of ϕ. Hence, when iron rings are used for the purpose stated, the resistance will be practically independent of the frequency, and the skin effect will not change appreciably from no load or low speed to full load or high speed. The fact that there is the same skin effect as at full speed at starting, gives rise to a large slip, poor speed regulation, and low efficiency, giving a motor of a horse power above two or three, or a motor of the very smallest size, very poor running constants.

Another device used in connection with induction motors to accomplish the same ends as are accomplished in the use of ohmic starting resistances, and make the motor automatic, is an inductive resistance used in connection with a coil wound rotor, the inductive resistance being closed circuited and free from moving contacts, and having a core of a hysteresis material. The inductive resistance then varies with the variation of current in the coil wound rotor of the motor, varying in degree as the frequency of the rotor E. M. F. varies, and the action of the inductive resistances being magnified by the presence of the core of hysteresis material. The core of hysteresis material in this instance forms no part of the electric circuit of the rotor, being simply a part of the magnetic circuit of the inductive resistance. This device is open to the objection that unless it is placed on or within the rotor itself, movable contacts have to be provided in order to get the taps away from the motor. Necessarily the induction resistances with heavy hysteresis material cores are very heavy, and are too bulky to be placed within the core of the rotor and out of the way, where the taps can be led to them without the use of moving contacts.

It is the object of my invention to produce an induction motor which starts automatically, which has good starting characteristics, good running characteristics, and good starting torque, good running torque, and a good efficiency, and which at the same time is free from moving contacts which are liable to produce sparks or undue heating of some parts, and which has the sturdy mechanical features of the squirrel cage motor under the hardest and most severe conditions. After many experiments I have succeeded in producing a motor which possesses all these features, and which operates in an entirely satisfactory manner in both small and large sizes.

In the accomplishment of my invention I provide the rotor of the squirrel-cage motor with short-circuiting rings of a material having a relatively high hysteresis resistance. By using a short-circuiting ring of this material, I obtain three-fold advantageous results. In the first place, I get a high skin effect, which varies greatly between low speed and high speed of the motor. I have found that a material having a relatively high hysteresis resistance, also has a marked skin effect, which varies greatly with the variation in the magnetizing force. This, I find, is peculiar to materials having a high hysteresis resistance. In the second place a conductor of this material presents primarily a relatively high effective resistance due to the hysteresis of the material itself, the passage of the current directly through the conductor giving rise to this resistance. This hysteresis resistance also varies with the variation in the magnetizing force of the current passing through the conductor. And in the third place the two preceding advantages are obtained in the most simple manner imaginable, the resistance being inherent in the conductor of relatively high hysteresis material which is used as the short-circuiting ring of the squirrel-cage rotor. This structure is extremely simple and most efficient.

As regards the first of the advantageous results just mentioned, referring to curve II of Fig. 4, a simple examination of this curve in connection with what has been said above as to skin effect in conductors and particularly in iron conductors, will suffice to show the existence of this advantage. Curve II is the saturation curve of a material having a relatively high hysteresis resistance. Instead of rising abruptly, as is the case with curve No. I, this curve rises gradually and approximates a straight line from the zero point clear up to and past the 150 c. g. s. units point to approximate saturation. The flux density per square centimeter ϕ, of a material of this nature, thus varies widely with varying magneto motive force, and does not remain substantially constant as is the case with material such as iron. With reference to the resulting equation No. 4 above given, it is quite clear that a skin effect is had in a conductor having a relatively high hysteresis resistance, which skin effect is not approximately constant, but which is high at low speed of the motor when the magneto motive force is high, and low at high speed of the motor when the magneto motive force is low. That the second advantage mentioned above follows primarily from the employment of a material having a relatively high hysteresis resistance as a short-circuiting ring, is striking and easily discernible from inspection of the curves of Fig. 4. The loss of energy due to hysteresis magnetic material is expressed by the formula:

$$P_h = nfB^{1.6} \text{------} (5)$$

where P_h is the power lost due to the hysteresis effect in the iron, n is a constant depending on the quality of the material and size and shape of the magnetic circuit, f is the frequency of the alternations of current, and B is the magnetic flux density in the circuit. This energy loss may be supposed to be expended in an additional resistance inserted in the circuit, in which case the power lost would be given by the equation,

$$P = I^2 r \text{------} (6)$$

where I is the current flowing and r is the equivalent resistance necessary to produce the same energy loss as the hysteresis effect. Equating (5) and (6) we have

$$I^2 r = nfB^{1.6} \text{------} (7)$$

Therefore

$$r = \frac{nfB^{1.6}}{I^2} \text{------} (8)$$

Equation (8) gives the effective resistance of the circuit due to hysteresis. As has been heretofore stated, the induction motor necessarily has a high magneto motive force in its secondary circuit. For example, a ten-horse-power motor, on which I performed many experiments, took a working current under normal full load conditions corresponding to a magneto motive force of about twenty-five c. g. s. units, and since in the squirrel cage rotor there is but one effective turn, the current carried by the short-circuiting rings were of necessity very large, as they are in all induction motors. When starting the magneto motive force was the equivalent of 100 c. g. s. units. Both starting and load currents are therefore large, and the starting current may be said to be four times the full load running current. This motor also had a slip of about 5 per cent. Applying formula No. 8 to this particular motor we may write the formula with zero subscripts, numerals, etc., writing r_0 as the effective starting resistance of the rotor as follows:

$$r_0 = \frac{nf_0 B_0^{1.6}}{I_0^2}$$

Subscript characters represent variable factors at the starting of the motor. We may likewise write the value of the effective resistance r at full load, as follows:

$$r_1 = \frac{nf_1 B_1^{1.6}}{I_1^2}$$

In this equation the subscript r_1 is used to indicate the value of the variables at full load. Now let us substitute in this equation the value of the variables as we know them. I_0 equals I_1 multiplied by 4, and f_0 equals $20f_1$. Dealing first with the induction motor equipped with the shortcircuiting ring of iron, and referring to curve No. I of Fig. 4, we find that the value B does not change materially between the values 25 and 100 of the magnetomotive force. We may therefore treat this quantity as a constant one for the purpose of this equation. Substituting these values, we have—

$$r_1=\frac{\frac{nf_0.B_0^{1\cdot 6}}{20}}{\frac{I_0^2}{16}}=\frac{16.n.B_0^{1\cdot 6}f_0}{20.I_0^2}=\frac{4}{5}r_0$$

Therefore, for a motor equipped with an iron shortcircuiting ring r_1 equals $.8r_0$. Hence the value of the running resistance is nearly as large as the starting resistance, and unless this value is made low the machine could not attain so small a slip as was assumed. But when we make the value of the resistance low, the starting torque of the machine will be only slightly better than the ordinary squirrel cage rotor with copper or brass rings. Since the resistance of the iron short circuiting ring is reduced only about 20 per cent. between low speed and high speed of the motor under load, and about half of the total resistance of the rotor is due to the copper bars, the total resistance is changed only about 1/10 or 10 per cent. Consider now the case of this same motor provided with shortcircuiting rings of a material having a relatively high hysteresis resistance, which material is that I use in the accomplishment of my invention. Referring to curve No. II, which is the saturation curve of a material of this character used by me, it will be found that the value of B, when the magneto motive force is 25 c. g. s. units is about 2,000 lines per square centimeter, while the value when magneto motive force is 100 c. g. s. units is 14,500 lines. B_0 equals 7-1/4B_1, from which $B_0^{1.6}$ power equals $24B_1^{1.6}$. Substituting these values in our preceding equation we have,

$$r_1=\frac{nf_1B_1^{1\cdot 6}}{I_1^2}=\frac{\frac{nf_0}{20}\cdot\frac{B_0^{1\cdot 6}}{24}}{\frac{I_0^2}{16}}=\frac{16}{480}\frac{nf_0B_0^{1\cdot 6}}{I_0^2}=\frac{1}{30}r_0$$

The running resistance of the material having the relatively high hysteresis resistance, therefore, is only 1/30th of the starting resistance. Here, as before, the copper resistance constitutes about one-half of the total, giving the total starting resistance about fifteen times the running resistance, as compared with the change of only about ten per cent. when an iron ring is used. It is this most advantageous result which may be said to be pronounced in degree, taken in connection with the result from the greatly augmented skin effect which has secured to me the accomplishment of my invention, and enabled me to attain its objects. That I have attained the objects of my invention will be readily apparent from inspection of the curves III and IV of Fig. 5. Curve numbered III is the torque curve of a squirrel-cage motor equipped with copper shortcircuiting rings, while curve IV is the torque curve of a motor equipped with the shortcircuiting rings of my invention. More than double full load torque is available at starting in my motor. The torque increases slightly at the point of twenty-five per cent. slip, and then decreases to the full load point where its slip is quite one per cent. smaller than the slip of the motor with the copper shortcircuiting rings.

In the accomplishment of my invention I have experimented with many materials. I have found that not all substances or materials which have a relatively high hysteresis resistance are adapted for use in the electric circuits of motors. Besides having a relatively high hysteresis resistance, it is necessary that the material used should have a low ohmic resistance at full load. It is also desirable that the resistance of the material used as a conductor should be very low. Ordinary carbon steel when hardened to present a relatively high hysteresis resistance, I found has too high an ohmic resistance. Likewise manganese steel and numerous others have too high a resistance or reactance. Among the various materials with which I have experimented, I have found several which are most admirable for the purpose, chief among which are steels alloyed respectively with chromium, molybdenum, and tungsten, or combinations of these, and of these I have found tungsten steel to be the best. It is characteristic of these materials that they have a relatively high skin effect and hysteresis resistance at low speeds of the motor, and a skin effect and hysteresis resistance relatively lower than cast iron at higher speeds of the motor, and have a relatively lower ohmic resistance. All of these steels I temper very hard and then draw the temper until the best results are secured. Curve No. II of Fig. 4 is the saturation curve of a tungsten steel having a percentage of tungsten greater than two and a half per cent., which proportion I have found to be most desirable for motors of ordinary size. Curve No. IV is the torque curve of a motor equipped with tungsten steel rings. This material has an extremely low ohmic resistance, and as has been seen, fulfils admirably the conditions of service. That the third of the three-fold advantageous results mentioned, namely, simplicity and hardiness, or mechanical sturdiness and safety, results from the use of this particular material, will be apparent from a consideration of the accompanying drawings, and particularly of Figs. 1 to 3.

Of the drawings, Fig. 1 is an end view of an induction motor of the squirrel-cage type, equipped with a shortcircuiting ring of the material of my invention. Fig. 2 is a perspective view of the rotor of this induction motor. Fig. 3 is a side elevation of a modified form of rotor, and Fig. 4 is a figure in which is delineated the saturation curves of the several materials above mentioned. Fig. 5 is a figure in which is delineated torque curves of a motor equipped with ordinary copper rings and with the rings of my invention above mentioned.

10 indicates the stator winding of this motor, while 11 indicates the squirrel-cage rotor. This rotor is provided with the usual copper bar conductors 12. Instead of the usual copper shortcircuiting rings, however, it is provided at its ends with shortcircuiting rings 13 of a material having a relatively high hysteresis resistance, such as tungsten steel of the grade mentioned above. All that is necessary in starting the motor equipped with these rings is to connect the leads 15 to a source of power by a suitable switch. The motor will then start under load, and have throughout its operation the good characteristics of a motor of this type. There are no moving contacts, all the connections of the motor being mechanically and electrically secure and permanent. As the stator of the induction motor has no movable contacts, the induction motor of this invention is entirely free from them. That the use of this material as a shortcircuiting ring is at once the simplest, neatest, and most efficient arrangement, is clearly apparent. The combined skin effect and hysteresis resistance is had at one and the same time in this shortcircuiting ring, which forms a part of the electric circuit of the rotor.

When it is desired to build motors of large size, the current in the rotor circuit may become so great that, as above described, the normal full load current will produce practically a condition of saturation of rings of normal proportions, so that with increasing current due to decreasing speed the valve of ϕ in equation (4) will be nearly constant, as is the case with iron rings in very small motors, and hence there will not be nearly as great a tendency for the resistance to increase with decreasing speeds. In order to overcome this defect, and avoid using abnormally heavy rings, when very large motors are to be built, I make use of the modified squirrel-cage construction, as shown in Fig. 3. It is made up of two intermeshed cages, preferably electrically independent, one of them being composed of the bars 16, the copper short circuiting ring 17, and the ring of relatively high hysteresis resistance material 18; and the other of the bars 16′ and the rings 17′ and 18′. By using this construction half the working current is made to flow in one ring 18′ and half in the other, and hence much larger working currents may be employed before the normal load current produces a condition of approximate saturation. In this type of construction, therefore, it is possible to make use of the principles hereinabove set forth, in motors of much larger size than is possible with a single squirrel-cage, without unduly increasing the size and weight of the shortcircuiting rings for the most advantageous normal operation. It is, of course, evident that I may form both rings 17 and 18 as rings of relatively high hysteresis resistance material. The prime feature of this modification is the division of the working current by the use of the double squirrel-cage construction. Obviously the cage could be made in a multiple number of intermediate sections greater than two.

While I have described the best form and embodiment of my invention now known to me, I desire to have it understood that in the annexed claims it is intended that all modifications not departing from the generic spirit of my invention be covered.

What I claim is:

1. In an induction motor of the squirrel cage type, a short circuiting ring of a material having a high hysteresis resistance and a high skin effect at low speeds of the motor and having a hysteresis resistance and skin effect relatively lower than cast iron at higher speeds of the motor.

2. An induction motor comprising primary and secondary windings, said secondary winding having parts of its electrical circuit formed of a conductor of magnetic material which has a lower ohmic resistance than cast iron, and a relatively high hysteresis resistance and skin effect at low speeds of the motor and hysteresis resistance and skin effect relatively lower than cast iron at higher speeds of the motor.

3. In an induction motor having primary and secondary members, a conductor of fixed dimensions forming part of the secondary of said motor and which has high hysteresis resistance and high skin effect at low speeds of the motor and has a hysteresis resistance and skin effect relatively lower than cast iron at higher speeds of the motor.

4. In an induction motor, primary and secondary members, one of said members being provided with a conductor of tungsten alloy steel forming a part of the electric circuit of said member.

5. In an induction motor, primary and secondary members, one of said members being provided with a conductor of tempered alloy steel of low ohmic resistance forming a part of the electric circuit of said member.

6. In an induction motor, primary and secondary members, one of said members being provided with a conductor of tungsten alloy steel forming part of the electric circuit of said member, said conductor containing two and one half per cent. or over of tungsten.

7. In an induction motor, primary and secondary members, one of said members having permanently in its electrical circuit a conductor of a magnet material having a saturation curve which approximates closely a straight line between zero point on the curve and approximate saturation.

8. In an induction motor, primary and secondary members, one of said members having two windings of low ohmic resistance disposed around the member and each winding being permanently short-circuited by a conductor having a relatively high hysteresis resistance at low speeds of the motor, and a hysteresis resistance relatively lower than cast iron at higher speeds of the motor.

9. In an induction motor, a squirrel cage rotor formed of two electrically independent cage sections, each of which is provided with two short circuiting rings, one at each end, one of the short circuiting rings of each cage section being composed of a material having a relatively high hysteresis resistance and skin effect at low speeds of the motor and having a hysteresis resistance and skin effect relatively lower than cast iron at higher speeds of the motor.

10. In an induction motor, a squirrel cage rotor comprising a magnetic core provided with slots, and two intermeshed cage sections composed of bars in said slots, and two sets of short-circuiting end rings, the bars in some of said slots being connected to one set of end rings, and the remaining bars to the other set of end rings, the bars of one set overlapping an end ring of the other.

In testimony whereof I have hereunto set my hand in presence of two subscribing witnesses.

BURTON McCOLLUM.

Witnesses:
J. R. TARBOX,
ARTHUR L. BRYANT.