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SUMMARY OF PROPOSED PAPER

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Soft Commutated Direct Current Motor

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Abstract

A novel soft commutated direct current (DC) motor is introduced. The current of the commutated coil is intentionally drained before the brush disconnects the coil. This prevents the spark generation that normally occurs in conventional DC motors. A similar principle can be applied for DC generators.

I. INTRODUCTION

DC motors having brushes and commutators are not totally obsolete in industry. The advantage of DC motors is that the commutation is taken care of by the motor. Essentially, no power electronic commutation for the main armature current is required as compared with a brushless motor; however, the brush and commutator produce sparks or possible flashovers. Maintenance is a major concern with DC commutator motors. Alternatively, homopolar motors do not require commutation, but they have the low-voltage and high-current drawbacks. The novel soft commutated DC motor has the advantages close to both the conventional and the homopolar DC motors. For consumer products, such as electric vehicle motors, a long brush life expectancy will attract the consumers to choose a low-cost, brush-type motor that does not require a costly inverter to run it.

1.1 Commutation of a Conventional DC motor:

Fig. 1 shows a simplified circuit of a conventional DC motor. The coils and the commutator are moving in the indicated direction and the brush is stationary. The coil currents of both the left- and right-hand sides point to the brush.

Fig. 2 focuses on a small portion of Fig. 1 at the brush to explain the four steps of commutation in a conventional DC motor. It begins with Fig. 2(a) where a coil is going to be commutated. Commutation starts when the brush shortcircuits the coil as shown in Fig. 2(b). The shortcircuited current, caused by the trapped magnetic energy associated with the residual current, goes through the coil, commutator segments, and the brush. Fig. 2(c) shows that the residual current in the coil has attenuated. The connections to the adjacent coils still provide current paths. The left- and right-hand side currents can flow through the coil in various portions, but the total current that the brush collects remains unchanged.

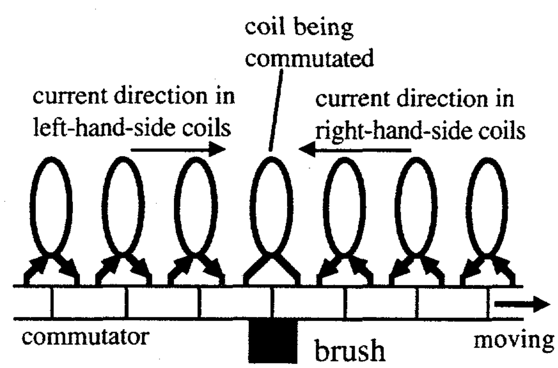

Fig. 1 The brush shortcircuits the coil being commutated

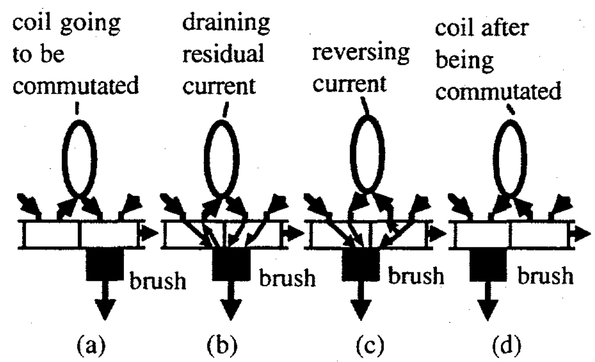

Fig. 2 Four steps of commutation

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DISCLAIMER

Fig. 2(d) shows that when the brush leaves the shortcircuiting position the coil current must be in the opposite direction to that before shortcircuiting. The brush always collects two coil currents coming from the left- and right-hand side coils.

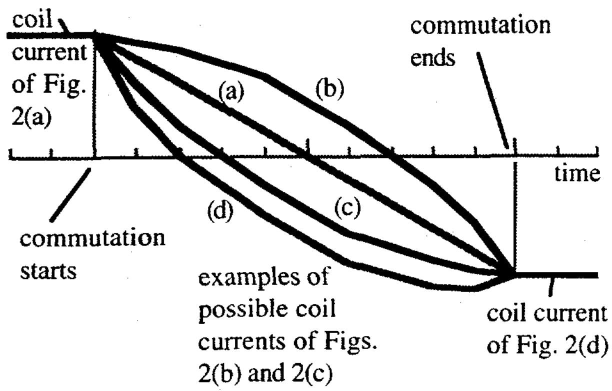

Fig. 3 Examples of possible currents of coil being commutated

The compulsory opposite directions of the coil currents before and after commutation as shown in Figs. 2(a) and 2(d) are again shown in Fig. 3. The coil current referring to the shortcircuited situation shown in 2(b) and 2(c) can follow many different patterns [1]. The desirable one is the straight line commutation shown by (a). The patterns are affected by the electromotive forces (emfs) produced by the self inductance of the coil, the mutual inductances with other coils, the field flux, and the compole flux. Therefore, changing the gap or the ampereturns of the compoles or shifting brush center lines can be used to influence the emfs induced in a coil being commutated. The major factor to ensure a good commutation is that the brush current density at the beginning and the end of commutation should be low, and the voltage difference between the brush and the in-coming or the out-going commutator segment should also be low. However, even under a straight-line commutation, the energy associated with the residual current must be dissipated before the current can reverse. The commutator and brushes act as the heat sink to absorb this energy, which provides the high temperature that shortens their life expectancies.

1.2 Homopolar Motor:

Because a homopolar motor does not require any commutation, the attendant problems such as dissipation of heat associated with residual commutationcurrent are eliminated. The technological advancements in brushes [2], such as the copper fiber brushes [3] and copper foil brushes, offer the improvements of very low contact voltage drops and long life expectancies. On the other hand, the disadvantage of a homopolar motor is its low voltage and high current. The arrangement of a homopolar motor with multiple slip rings may increase the voltage, but the additional voltage drops between the rings and brushes, and the extra space requirement may not be attractive. In addition, the flux path of a homopolar motor requires axial, radial, and peripheral directions. A motor having a three-dimensional flux path is more bulky than a conventional two-dimensional-flux-path motor.

1.3 Soft Commutated DC Motor:

The property of the novel soft commutated DC motor introduced here is good brush performance due to soft commutations and a higher voltage than that of the homopolar motor. Unlike the conventional DC motors, the armature coils of a soft commutated DC motor are dynamically (not permanently) connected in parallel. This is similar to the homopolar motor armature conductors that are permanently (not dynamically) connected in parallel. Each coil's commutation of a soft commutated DC motor can be controlled independently. The soft commutated DC motor is robust with a high degree of tolerance. It still can run with a partial armature and without the attenuation circuit. A compensating winding may be used if the field flux is distorted severely by the armature reaction.

II. BASIC PRINCIPLE OF SOFT COMMUTATED DC MOTORS

2.1 Switching Off:

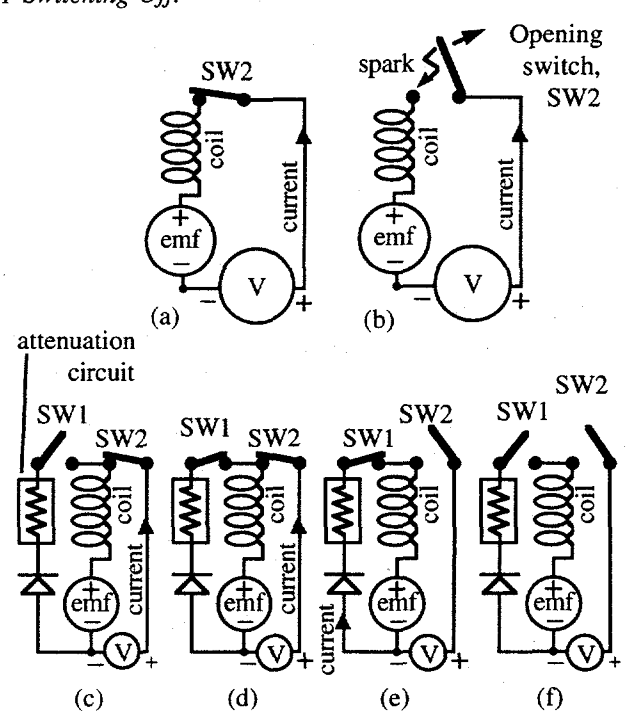

Fig. 4 Basic principle of soft commutated DC motors

The basic principle of a coil's commutation is described here before going into the motor construction. For turning off the current of a coil, Figs. 4(a) and 4(b) show the circuit diagram of a coil without soft commutation. A DC supply voltage, V, under a normal operating situation shown in Fig. 4(a) overcomes the back emf and resistance voltage drop of the coil and results in a load current in the coil. Fig. 4(b) shows that if the switch, SW2, is opened when the current is not zero (i.e., having a residual current), a spark may be generated to release the magnetically stored energy that equals half of the product of inductance times current squared of the coil.

The lower four figures of Fig. 4 show the basic turning-off principle of a soft commutated motor. Fig. 4(c) shows a similar situation as 4(a), but with a branch that contains an attenuation circuit that may incorporate a feature of feeding the coil's magnetically stored energy back to the DC supply. The attenuation circuit may also be designed to simply drain the energy without feeding back to the supply. A diode connected in series as a part of the attenuation circuit prevents unwanted current flow. Fig. 4(d) shows that when the coil is about to be commutated the switch, SW1, is on. Because of the diode, there is no current in the attenuation circuit. Fig. 4(e) shows that when the switch, SW2, is open, the residual current in the coil does not need to force through the gap of SW2 by means of a spark. It seeks the path through the attenuation circuit that can be viewed as a variable impedance. The initial impedance value right after SW2's open should be low to reduce the potential difference across SW2. The impedance value changes for a sufficiently short attenuation of the current. Finally, when the residual coil current is drained, the switch, SW1, is opened, and the potential difference across SW1 should be small. The switching-off of a soft commutation is thus accomplished. The following simple tests confirm the principle.

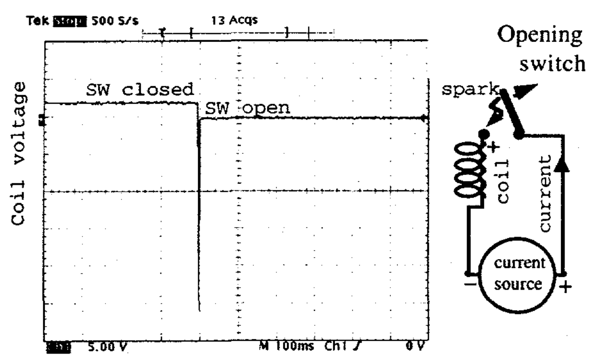

Fig. 5 Experimental high-voltage spike of a coil while opening circuit

Fig. 5 shows the experimental trace of a significant voltage spike generated across the coil when the circuit of the current carrying coil is suddenly opened. However, if a free wheeling diode path is provided to the coil, as shown in Fig. 6, the residual current can go through the diode. The current attenuation and the voltage across the coil can be controlled in the diode circuit. The diode circuit can be removed without causing any spark when the current is completely drained in the diode circuit.

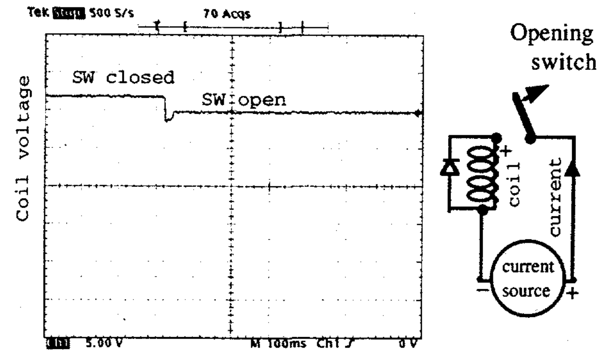

Fig. 6 Voltage spike is eliminated with a diode circuit

2.2 Turning On:

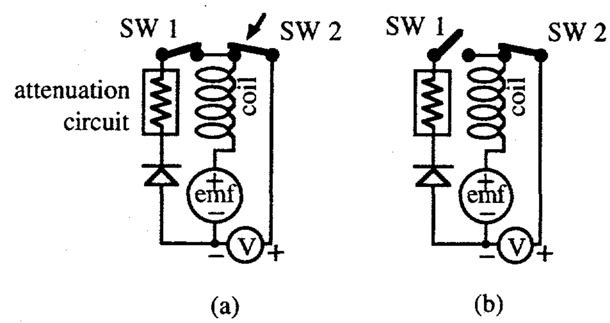

Fig. 7 Turning-on situation of a coil

Fig. 7(a) shows a coil of a soft commutated DC motor turning on. The attenuation circuit of the left-hand side does not draw any current when turning on switch SW2. The coil has a back emf that is close to the DC supply voltage, V. The coil current goes up from zero according to the inductance of the coil and becomes stable when the current equals $\frac{(V - emf)}{R_a}$, where R_a is the coil resistance. Because the inductance of the coil slows the rising time of the current, the turning on can be viewed as a soft turning on. The soft turning on and turning off constitute the soft commutation.

Fig. 7(b) shows that the attenuation circuit can be switched off. It does not affect the conduction of the coil when the coil is being energized. Fig. 7(b) is the same as Fig. 4(c), where the coil is conducting before its commutation.

III. A SAMPLE SOFT COMMUTATED DC MOTOR

3.1 Parallel Coils and Motor Structure:

Fig. 8 shows the spread-out view of the armature of a sample 2-pole soft commutated DC motor. It shows only the electrical connections of the armature coils to demonstrate a sample implementation of the soft-commutation principle. Detailed mechanically symmetrical arrangement is not included in this diagram. The two field poles are similar to a conventional 2-pole DC motor. The magnetic flux paths are two dimensional as compared with the three-dimensional paths of a homopolar motor. A compensating winding that may produce quadrature magnetomotive force (mmf) to counter the armature reaction is incorporated. Each coil may have greater than or equal to one turn. For this 2-pole sample, an individual coil rotating under the pole of field flux generates a back emf. The two leads of a coil are connected to the opposite (i.e., 180 degrees apart) commutator segments. For example, the two commutation brushes A and A' are connected to a coil. So are the commutator brushes B and B'. The commutator segments are separated by the non-conducting segments presented in gray color. Alternatively, the non-conducting segments can be made of the same metal as the conducting segments but with more than one small segment to prevent the re-energizing of a coil after its current has been attenuated during commutation. However, for simplification sake, the non-conducting segment is used in the following explanation.

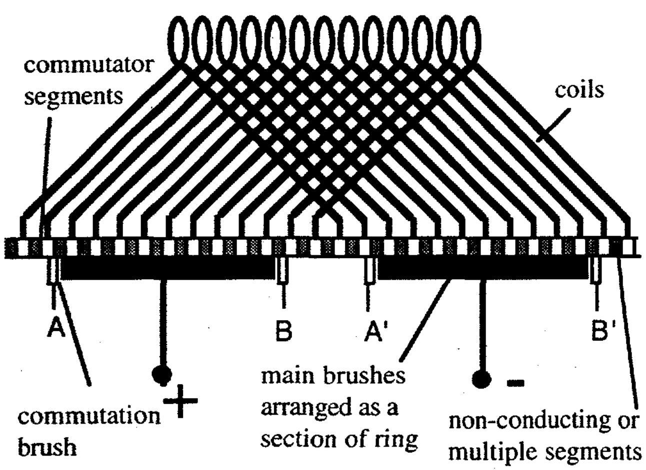

Fig. 8 A sample 2-pole soft commutated DC motor

The commutation brush does not short any coils when it rides on the commutator. The main brushes are arranged in two sections of a ring marked with + and – signs. It clearly shows that the coils are not permanently but temporarily connected in parallel through the main brushes. The main brush and commutator segment correspond to the switch, SW2, shown in Fig. 4. The commutation brush and the commutator segment correspond to the switch, SW1.

3.2 Applying Principle Illustrated in Fig. 4 to a Soft Commutated DC Motor:

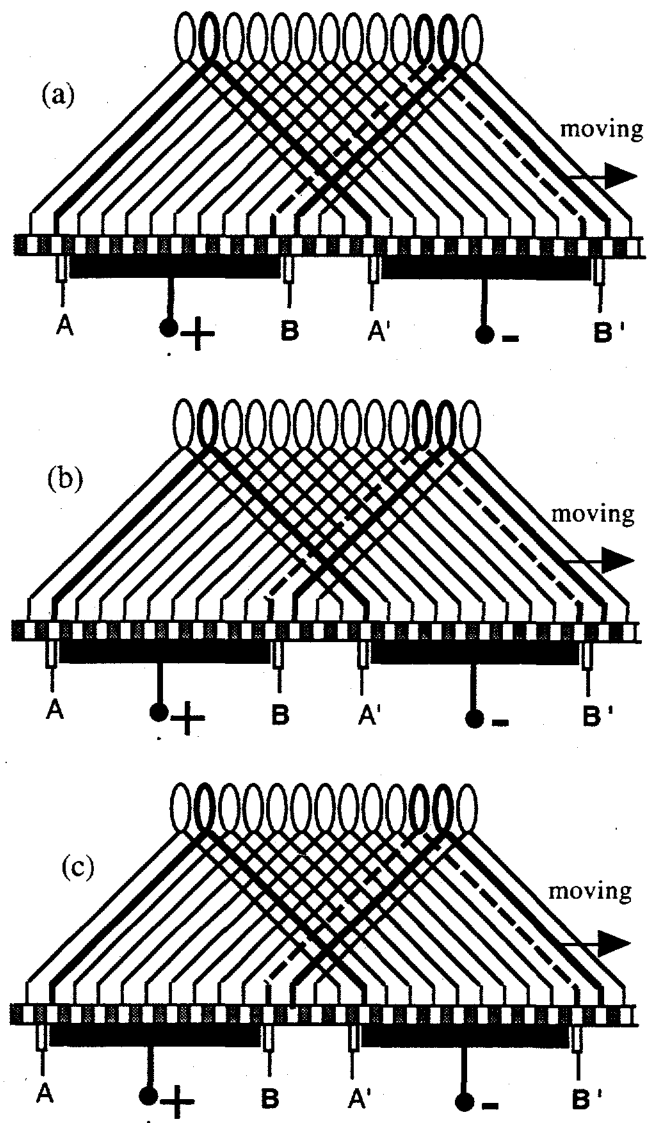

Fig. 9 Relative locations of brushes and coils

Fig. 9(a) shows that the coils in thick solid lines are connected to the commutation brushes, B, B', and A, A', respectively. The main brushes are electrically isolated from the two coils connected to the commutation brushes. This refers to the situation shown in Fig. 4(e). The dashed-line coil is connected to the main brushes only. This refers to the situation shown in Fig. 4(c).

As the rotor that consists of the coils and the commutator moves, the relative positions between brushes and commutator segments change. Fig. 9(b) shows that the thick, solid-line coil originally connected to B, B', is not connecting to any brush. This is corresponding to the situation shown in Fig. 4(f). A coil in dashed line is connecting to both the main brushes and the commutation brushes, B, B'. This corresponds to the commutation brushes, B, B' turning on situation shown in Fig. 4(d). The thick solid-line coil on the left-hand side starts its connection to the main brushes. This corresponds to the turning-on situation shown in Fig. 7(a).

Fig. 9(c) shows that the dashed-line coil connects to the commutation brushes, B, B'. The main brushes are not connecting to the coil. This corresponds to the situation shown in Fig. 4(e). The thick, solid-line coil on the left-hand side is continuously connected to the main brushes.

The soft commutation process depicted in Figs. 4(c) to 4(f) is accomplished step-by-step as follows: A coil is connected to the main brushes through contacts of the commutator segments and brushes. The coil travels under the field-pole air-gap flux and needs to be commutated before leaving the field-pole air-gap flux. At this moment, the commutation brushes (SW1) are contacting the coil before the main brushes disconnect the coil [see Fig. 4(d)]. The attenuation circuit connected to the commutation brushes provides a path for the residual current of the coil to flow when the main brush (SW2) disconnects the coil [see Fig. 4(e)]. The attenuation takes place once the main brushes are not contacting the coil. The residual current of the coil is drained and the attenuation circuit is recovered from any temporary energy stored in its components. This is completed before breaking the contact of the commutation brushes and the coil [see Fig. 4(f)].

IV. TWO ELEMENTS OF SOFT COMMUTATION

The two elements of soft commutation are the attenuation of the residual coil current and the building up of coil current when the coil is connected to the DC supply through the contact of commutator segments and brushes. The objective of attenuation is to drain the residual current of the coil that is being commutated before the coil is open circuited. The potential difference across the open contacts should also be as low as possible. Various attenuation circuits can be built. An attenuation circuit may also have an energy recycle feature to channel the residual energy of the coil back to the DC supply. The recycle feature is not discussed in detail in this paper.

The power rating of components in an attenuation circuit is a small fraction of the motor rating. This helps to keep the cost of the motor-and-drive package down.

4.1. Attenuations of Coil Current through Sample Attenuation Circuits:

A simple attenuation circuit is shown in Fig. 10. The coil consists of an inductance, *La*, resistance, *Ra*, and the coil emf induced from the field-pole magnetic flux. The coil has a residual current, *Io*, that needs to be drained before the coil's contact slides away from the commutation brushes.

The energy associated with the initial residual current is transferred mainly to the capacitor, *C*, and dissipated in time through *R*2. The simulated trace of coil current, *I*(coil), illustrates the attenuation. The capacitor takes care of the very initial current of the coil. When the residual current is attenuated the voltage, *V*coil, is quite different from the voltage, *Vc*. This might cause a potential difference problem when the commutation brushes slide away from the commutator segments connected to the coil.

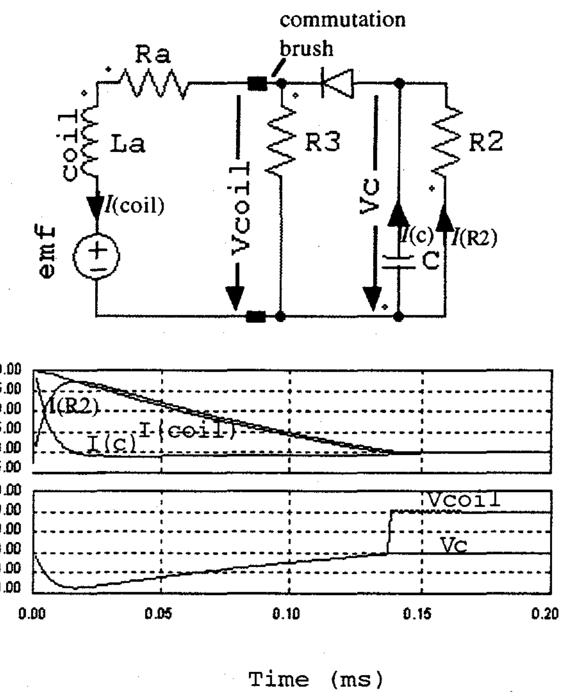

Fig. 10 A sample attenuation circuit

Fig. 11 shows that the potential difference problem can be solved by introducing an adjustable potential, *V*emf, between the capacitor voltage and the coil voltage. The magnitude of *V*emf is slightly lower than the coil's back emf to prevent any unwanted current flow. The attenuation of the residual coil current may take a longer time as compared with the circuit without the *V*emf. The longer time is illustrated by the simulated coil current trace, *I*(coil), shown in the figure.

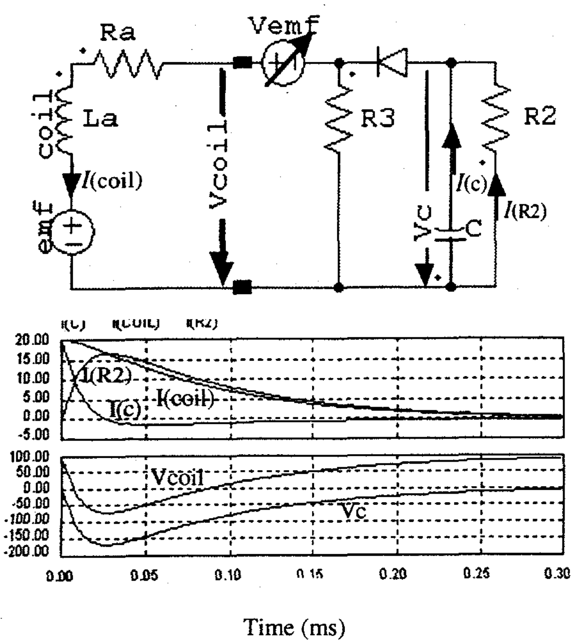

Fig. 11 Adding Vemf in the attenuation circuit

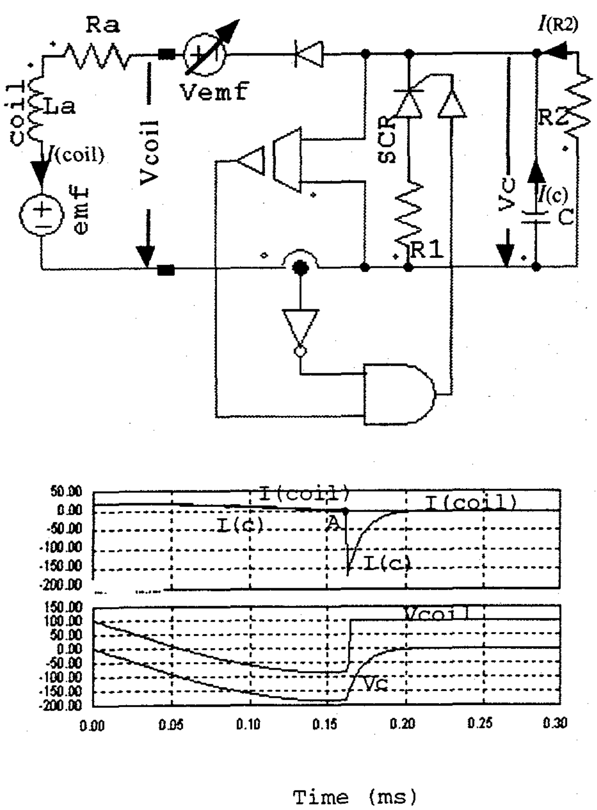

Fig. 12 Rapid capacitor discharge

The longer attenuation time can be solved by introducing a rapid discharge through the silicon controlled rectifier (SCR) and R1. Fig. 12 shows the simulated attenuation of a coil's residual current. When the coil current goes to zero at point A, the rapid discharge of the capacitor I(c) enables the circuit to be ready quickly for the next coil's commutation. The permissible upper speed limit of the soft commutated motor is affected by the time required by the soft commutation. The soft commutation must be completed between the time the commutation brush contacts and leaves an active commutator segment.

4.2 Building up Coil Current after Turn on:

When the main brushes contact the coil with no residual current, the coil current arises from zero according to the following equation.

$$i_a = \frac{V - emf}{R_a}\left(1 - e^{-\frac{t}{\left(\frac{L_a}{R_a}\right)}}\right) \tag{1}$$

The coil current builds up according to the time constant L_a / R_a. Fig. 13 shows an example of the current of a coil versus time. The current builds up softly.

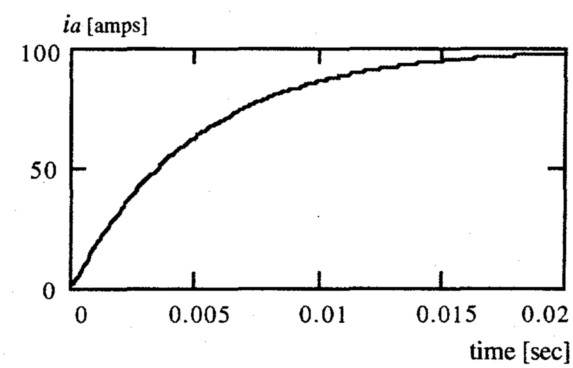

Fig. 13 Coil current builds up softly. (coil resistance Ra=0.2 Ohms, inductance La=0.001 henry, V=100 volts, emf=80 volts)

V. PROTOTYPE MOTOR

A surplus GE, 5 hp, 1750/2400 rpm, 240 volt, shunt wound DC motor was modified for the prototype motor. The surplus motor had two main field poles and two compoles. The compoles were removed, and the air gap of the main poles was machined to make the gap uniform for the prototype motor. A shim was placed in the back of each pole to make the new air gap 1.65 mm (0.065") per side, which is the same as the old gap measured at the pole center. The bore diameter is 120.9 mm (4.760"), and the core length is 152.4 mm (6").

The surplus motor had 20 armature slots and 80 commutator bars. Eight coil layers were in each slot. The armature had a total of 320 turns connected in the two- parallel circuits. The coil pitch was 1–11 slots. Each commutator segment had two coil leads connected to it.

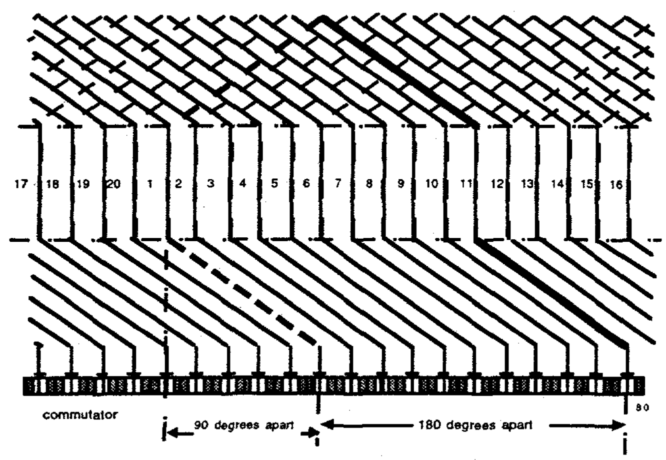

Fig. 14 Partially shown armature coils of the prototype motor

Fig. 14 shows that the prototype motor modified from the surplus motor has a total of twenty double-layer, full-pitch coils. The number of turns percoil is 48 turns for a lower terminal voltage of 72 volts. The center of a slot is 90 degrees apart from the corresponding center of two small commutator segments that are electrically connected together. The main brush center line is located between the main poles. The new motor does not require as many segments as the old motor. The segments shown with gray shadow immediately adjacent to these two small segments are not connected to any coils. They act as the non-conducting segments shown in Fig. 8.

The distance between the main brush and the commutation brush is 1.5 times the width of the small commutator segment. The width of the commutation brush is also 1.5 times the width of the small commutator segment.

The prototype motor with its brush assembly is shown in Fig. 15. The motor starts and runs smoothly. The concept of dynamically connecting the armature coils in parallel through the main brushes is proven to be working perfectly. No sparks are noticeable with a simple commutation circuit, similar to that shown in Fig. 10, connected to each pair of the commutation brushes. The motor can remain running without connecting the commutating brushes to an attenuation circuit or without the commutating brushes entirely. This illustrates the robustness of the motor.

The prototype motor demands a continuous contact between the main brushes and the commutator segments without unwanted disconnection and bouncing. In order to meet this requirement, the main brush should be made of multiple brushes with self adjusting segments in each brush.

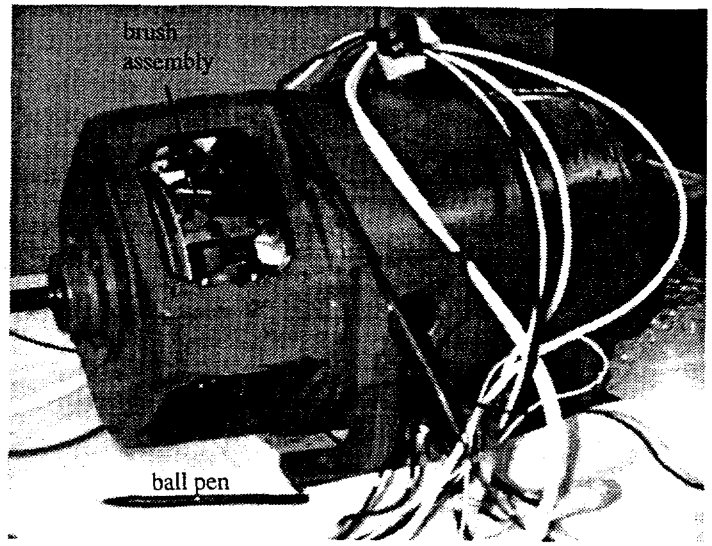

Fig. 15 Prototype motor

VI. CONCLUSIONS

- A new soft commutated DC motor is introduced.
- Advancement in brush technology gives a new potential for brush-type motors.
- Coils of the new motor are dynamically connected in parallel through the main brushes.
- Bouncing brush and partially contacted brush should be absolutely prevented for good conduction.
- No sparks are noticeable.
- Voltage can be higher and current can be lower than those of a homopolar motor.
- Two-dimensional flux path enables a smaller structure than a homopolar motor.
- Unlike a conventional DC motor, the energy associated with the residual current of the commutated coils is dissipated through an attenuation circuit. This energy can be recycled back to the DC supply.
- Unlike a conventional DC motor, the commutator and brushes of the soft commutated DC motor are not used as a heat sink to absorb the energy associated with the residual current.
- The soft commutated DC motor is robust. It still runs with partial coils and without attenuation circuit. It should also run without partial armature coils.
- Commutation of a coil can be controlled independently. Many options can be used through power electronic controls. The rating of power electronic circuit is only a small fraction of the motor rating.

- The motor runs without a power electronic inverter. The cost of the drive package that normally includes both the inverter and the motor is significantly lower.
- Further extensive investigation on this new type of motors will be conducted. Different options of the motor structures and brush assemblies are conceived for lower cost and higher performance.

VII. ACKNOWLEDGMENT

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