Hairpin Windings: Twists and Bends of a Technological Breakthrough [Scanning our Past]

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Hairpin Windings: Twists and Bends of a Technological Breakthrough

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Magnetic windings, in general, and small drives, in particular, are typically associated with thin round copper wires. This group of small drives includes electrical machines for automotive applications, ranging from ancillary units to traction machines for both hybrid–electric vehicle (HEV) and battery–electric vehicle (BEV) [1], [2]. Wire-wound machines can refer to well-established techniques for widely automatic manufacturing—except for traction machines with distributed windings, which still contain manual steps in most assembly lines, particularly after the insertion process [3]. Machines typically wind the loops of continuous wires on a bobbin with a linear or flyer-winding technique outside the stator and pull them from one side of the stator to the other into the slots. The overhang on both ends of the stator, the so-called end turns, forms automatically from the continuous loops.

This month's feature article explores the advancements in electrical machine windings, particularly the recent use of hairpin windings in automotive applications, which appeared to surface out of the blue.

The final position of each wire in the slots of such wire-wound machines has a stochastic nature and is typically not controlled, which can have advantages with respect to high-frequency effects and led to the alternative name of random wire wound [Fig. 1(a)] [4].

Since the first larger series use in a drive train, windings made of thick copper bars or strips with rectangular profiles have rapidly gained momentum

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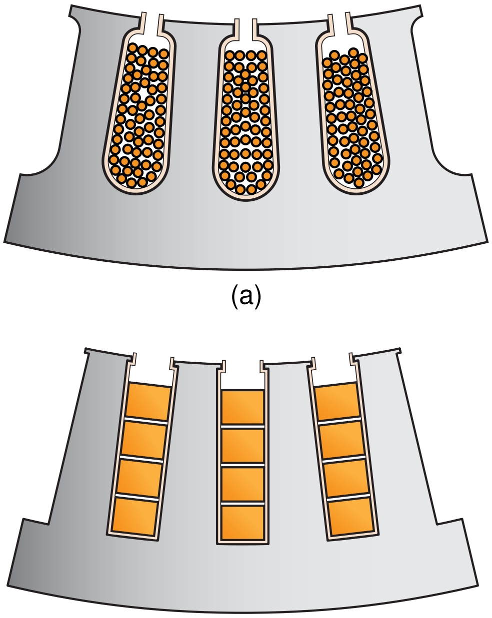


Fig. 1. ***Comparison of (a) wire-wound and (b) bar-wound machines illustrated with three stator slots. In the wire-wound case, the cross section of the teeth is determined by the available space near the air gap, which also determines the flux saturation. The cross section of the iron along the teeth typically stays the same in the radial direction, which leads to a rectangular tooth shape; the space between the teeth is more trapezoidal in turn and belongs to the slot and the winding. Bar-wound machines at present typically use rectangular slots and equal bar size in the radial direction. The remaining space is allotted to the teeth, which become trapezoidal. Saturation would set in near the air gap accordingly, whereas the footpoint has a higher magnetic cross section.***

in the automotive world [5], [6], [7]. Such bars with well-controlled positions in the slot enable larger cross sections for higher currents, in addition to a better fit to the likewise rectangular slots with clearly defined geometries [Fig. 1(b)]. The matched flat surfaces also increase the thermal contact area between conductors and slot walls. For easier insertion and due to the higher stiffness, the entire winding is split into smaller segments that are largely shaped beforehand. Most dominant are U-shaped segments, in which the community in accordance with their appearance widely calls hairpins.

This intermediate U shape typically already has the in-slot part of the arms aligned with the specific stator's slot walls (hence, the cross sections of the two legs are slightly twisted against each other to account for a different orientation of the two slots toward the stator axis into which they will be inserted) and matches not only the coil pitch but also the radius of the bar position to the shaft axis. Furthermore, the hairpins already form the overhang, i.e., the end turns on one side with their cusps. Thus, these conductor segments are close to the final shape in the machine and, on the other hand, can still be inserted easily into the slots either in the axial direction from the front side or alternatively in the radial direction from the bore in case the slots are entirely open and do not have overhanging teeth [8], [9]. After insertion into the slots, the individual segments must be mechanically brought in touch and electrically connected subsequently to form the final continuous winding.

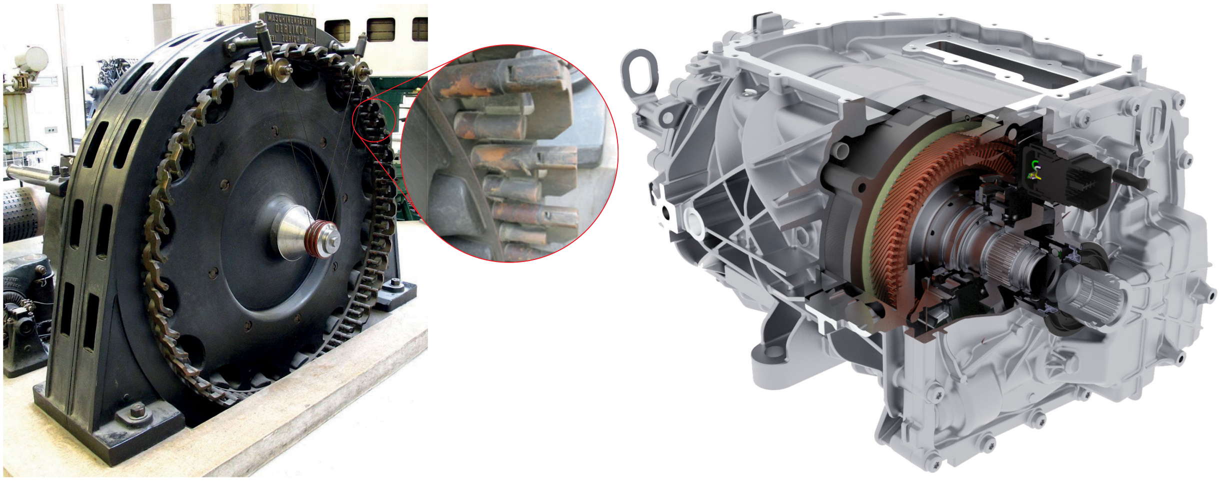
The sudden success of bar windings is credited to a number of advantages. Due to the growing quantities of EVs, full automation particularly of hairpin designs offers a clear substantial cost as well as quality advantage in mass production [10], [11], [12], [13]. Furthermore, a 50% reduction of end-turn length along a twofold increase in slot fill factor supports higher power densities [9]. The better defined and also larger interfaces between the rectangular conductors and the slot walls improve heat dissipation to further increase the achievable power density [8], [14]. Beyond the heat conduction to the slot walls, the large surface area and the clearance between the conductors at the end turns additionally allow highly effective direct cooling through liquid perfusion of this braid-like end-turn structure. The larger bars also substantially increase the possible insulation thickness as well as resistance, lifetime, and reproducibility [15], [16], [17]. Better reproducibility is a general feature of bar-wound machines and can extend to diagnosis, rework, and repair although the latter may be more relevant in small-series vehicles and/or during development.

At present, automotive traction motors aggressively increase the torque density and the voltage, resulting in power densities and temperature levels that conventional industrial drives are not able to achieve for reliability and cost reasons [18], [19]. Bar-winding technology, e.g., with hairpins, appears to be a good match and an enabler for these goals.

Interestingly, leading engineers have already demonstrated and promoted most of these features over the past century and even before. However, at that time, ac losses and rudimentary manufacturing automation limited bar windings, in general, and hairpin designs, in particular [20]. Since then, bar-wound machines ceased to be a dominant stream in motor technology and turned into a niche in low-voltage high-current applications. The electrification of cars generated needs for motors that are well met by bar windings. The recent expansion of electromobility has significantly boosted the development of electric motors with bar windings, built on the contributions of engineers and scientists from previous generations. While the technology seems new, it is deeply rooted in past advancements and highlights the importance of earlier work.

I. HISTORICAL DEVELOPMENT

The earliest electrical machines as well as transformers typically used round electrical wires in their structure [21], [22], [23], [24]. However, designers quickly recognized the potential of higher packing and slot fill through the use of conductor bars. Carl W. Siemens [25], for instance, discussed this topic in the 1880s as a means to reduce the electrical resistance for dynamo machines in one of his brother Werner's devices [26], [27]. Also, the



(a) (b)

Fig. 2. ***130 years of improvement of conductor bars in electrical machines. (a) Joint AEG–Oerlikon Project 240-kW 55-V three-phase generator in Lauffen in 1891. (Maschinenfabrik Oerlikon was later acquired by BBC and merged together into ABB, which is headquartered in Oerlikon, Zürich, Switzerland.) (b) BorgWarner (which acquired former Delco Remy) 400-kW 800-V high-voltage hairpin (HVH) 320 Electric Motor 2020 BorgWarner.***

contemporary patent literature appreciates the long known low resistance of bar conductors of copper or bronze [28].

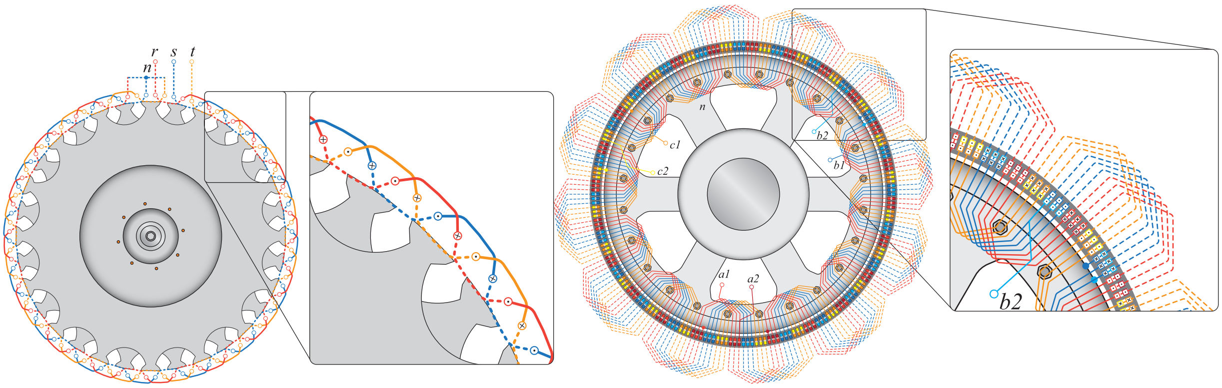
In 1891, Oskar von Miller fostered one of the first applications of three-phase bar-winding machines. A ground-breaking 15 000-V transmission system powered the International Electrotechnical Exhibition in Frankfurt (chaired by von Miller) from a hydro generator over 175 km away at the local cement works in Lauffen. With a maximum load of 240 kW and use for both lighting and propulsion power [29], [30], [31], this demonstration cleared many doubts related to the practicality and feasibility of long-distance ac electric power transmission, with 75% efficiency. It introduced the now dominant three-phase system and is one of the pivotal events that mark the end of the often cited War of the Currents between ac and dc power [32], [33], [34], [35], [36], [37], [38].

The involved claw-pole synchronous generator designed by Charles E. Brown[1] and Michael v. Dolivo-Dobrowolsky[2] (Fig. 2) is likely the very first three-phase ac machine. It featured 32 poles and was rated for 300 hp as well as 150 r/min. Similar to modern hydropower generators, the high number of poles was associated with a relatively low rotational speed, a high active diameter of 1752 mm, and a relatively short active length of just 380 mm, which also required short end turns. The combination of bars with connecting clamps guided the current from one slot to the next and not only reduced the end-turn length but also the leakage flux. With a terminal voltage of 50–55 V (stepped up to medium voltage through three-leg transformers [21], [36], [37]) and a 1400-A maximum current, the justified use of bar conductors enabled a spectacular 95.6% reported efficiency [36], [39].

The stator consisted of 96 solid round copper bars (29-mm diameter) each in a separate circular closed slots and insulated with asbestos sheets [Fig. 2(a)]. The bar arrangement resulted in a simple wave winding with one bar per pole per phase, which connected the bars in each phase in series [36]. The wave winding—also new at the time, today the standard winding for hairpin motors—turned out a cunning design to relay the stator current around the large active circumference and collect the phases at the terminals on top, right next to a clamp forming the neutral point. Accordingly, the design did not require jumper wires to bridge gaps or connect irregularities. Still, the three phases and their neutral point terminated right next to each other. They still only needed one type of identical radially c-shaped and axially s-shaped clamps with a pitch of three to form the continuous coils and particularly their end turns. This machine, which marked the commencement of three-phase systems, implemented the simplest possible winding scheme—single layer, full pitch, and integer slot [Fig. 3(a)]—which was already distributed but

[1]Charles E. Brown (1863–1924) was a British electrical engineer and inventor who co-founded the Swiss engineering company Brown, Boveri & Cie (BBC) in 1891, alongside German engineer Walter Boveri. Brown played a crucial role in advancing electrical engineering and power generation technologies during the early days of industrial electrification. His company, BBC (now part of ABB after a much later merger with Swedish ASEA in 1988), was known for innovations in power generation, electrical equipment, and rail transport systems, pioneering advancements in high-voltage and ac technology.

[2]Michael v. Dolivo-Dobrowolski (1862–1919) was a Russian-born engineer and inventor who made significant contributions to electrical engineering, particularly in the development of three-phase electrical systems. Working for Allgemeine Elektricitäts-Gesellschaft (AEG) in Germany, he invented three-phase induction motors in 1889. Dolivo-Dobrowolski also developed a three-phase transformer and other key components for ac power systems, which laid the groundwork for modern power distribution networks. His innovations were instrumental in establishing three-phase ac as the global standard for power generation and distribution.



(a) (b)

Fig. 3. ***Bar-winding scheme of early machines. (a) Stator of the Lauffen generator (1891). (b) Rotor of the Folsom Powerhouse generator (1895, the second set of windings in each phase is omitted for clarity). The dashed lines represent the connections on the back.***

not yet optimized for a smooth air-gap flux and perfect sinusoidal output. The end turns present a solution with two radial and two axial levels for guiding the bars around each other. In modern terminology, it might be called an I-pin design, where bars are interconnected on both sides through clamps, brazing, or welding [40]. Compared to a modern bar-wound machine [see Fig. 2(b)], the influence of this early example is still remarkable although hairpin motors currently feature about twice the power at a fraction of the size. Most gains stem from improved cooling and higher speed, in which bar-winding technology has improved over the years. The end turns have evolved due to developments in the form-winding domain discussed in Section II.

The 1891 exhibition presented various bar-wound machines, for instance, a three-phase ventilator motor with solid copper bars also developed by AEG [39, pp. 17f.]. These bars formed the windings, again by using c- and s-shaped pieces for connection in axial and radial directions and welded on both ends.

This machine achieved reported efficiencies of 83.0% at 60 hp and even 93.5% when generating 190 hp [36].

Many of the contemporary energy generation and transmission projects used some form of bar winding and further increased the voltage range compared to the Lauffen machine. In 1892, Westinghouse built the first three units of alternators for the two-phase system in Niagara Falls (12-pole generators rated at 2250 V and 250 r/min with two layers of bars per slot [44, p. 317], [45]).

In 1895, Charles Proteus Steinmetz[3] and E. Thomson had finished the design of the three-phase 800-V Folsom Powerhouse generator, which at the same time demonstrated the search for the ideal design of ac machines and the incremental developments on the way from dc.

Rather unusual today, the rotor of this in-runner incorporates the ac winding on the rotor and fixed poles on the stator—similar to the 1893 Mill Creek hydroelectric plant 2400-V generators from the same designers. The ac winding on the rotor indicates how ac technology to some degree evolved from dc motors, where the armature with the ac is likewise on the rotor. This design effectively took a dc generator almost as is and removed the mechanical commutator, which previously generated the terminal dc out of armature ac. Instead, slip rings without commutation fed the current to the armature winding on the rotor. On the other hand, the winding scheme was already improved compared to the Lauffen machine: it featured three slots per pole per phase as well as two bars per slot to form the rotating field [Fig. 3(b)]. The surrounding stator, on the other side of the air gap, incorporated 24 static excitation poles [51]. Since this early ac machine was practically a dc motor with slip rings instead of the commutator, it could reuse many of the existing dc components. The connections at the end turns were brazed according to the state of the art at the time. While the Lauffen generator featured only one bar per slot, the Folsom Powerhouse generator seems to have introduced the typical intertwined two-bar pattern of modern hairpin machines. The two wave-winding half layers are transposed and switch radial positions in each slot for lower ac loss; one of the two bars has its end-turn braiding on the front side moving radially inside, and the other one on the back moving the bar radially outside.

Another critical application where bar windings outperformed wire-wound designs was electroplating generators. The bars provided ample cross sections for the large currents, while the typical voltage was often in the single-digit range. Prominent manufacturers were Société des Machines Magnéto-Électriques Gramme (known for its machines with low ripple content, e.g., Gramme machines) and Siemens [25], [56], [57], [58], [59]. These dc

[3]Charles Proteus Steinmetz (1865–1923) was a German–American mathematician, engineer, and pioneering inventor in the field of electrical engineering. Known for his work with ac, Steinmetz developed essential theories on electrical phenomena, including hysteresis and complex algebra applications in ac circuits, which were critical to the widespread adoption of ac power systems. He worked at General Electric (GE), where he contributed to numerous innovations in power engineering, lightning arresters, and electric motor design. His work laid the foundation for modern electrical power distribution and earned him recognition as one of the leading electrical engineers of his time.

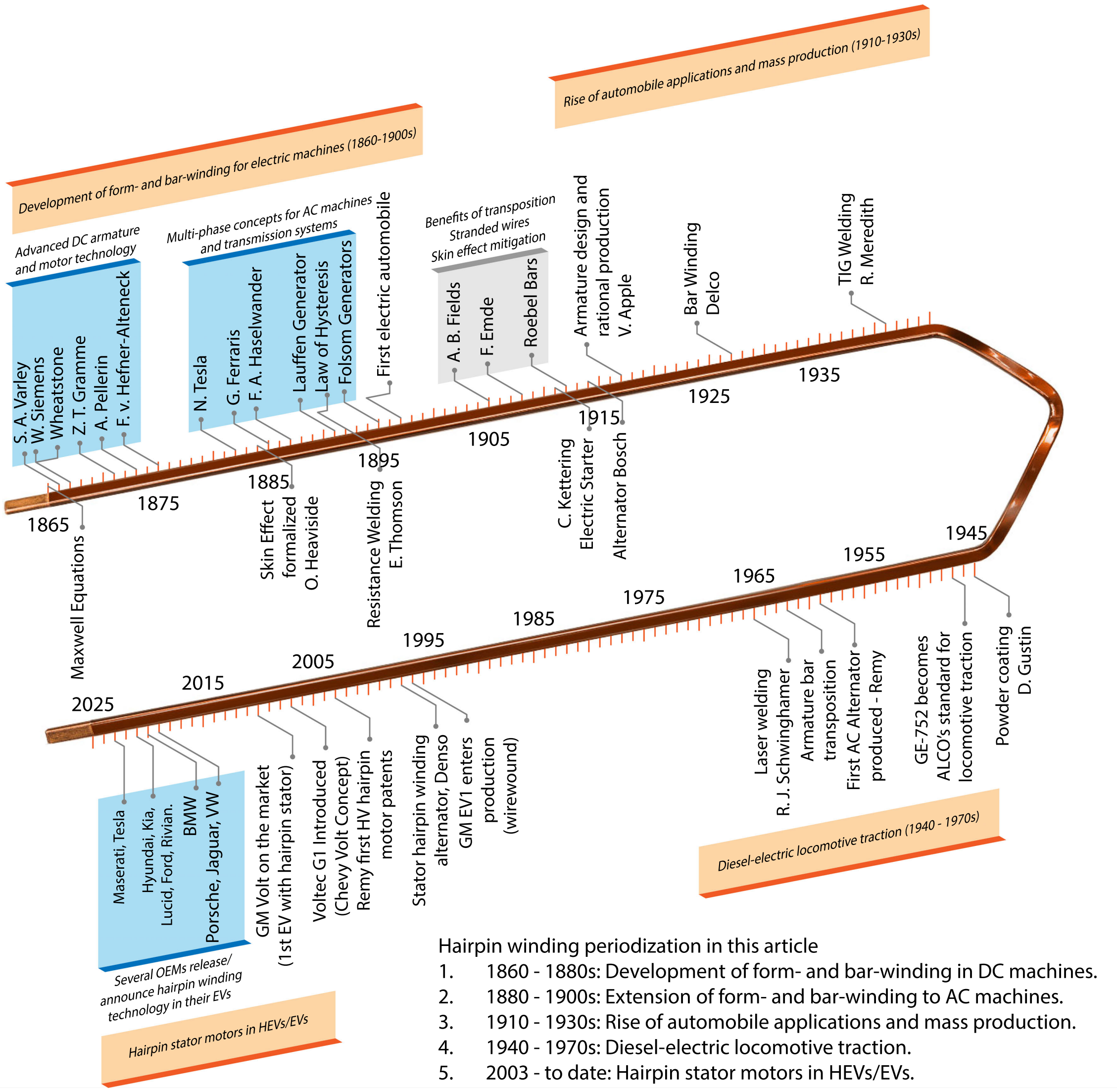


Fig. 4. ***Timeline showing the historical development of hairpin winding technology along with several other breakthroughs related to hairpin manufacturing, such as the key welding technologies that enabled reliable hairpins (resistance, tungsten-inert-gas, and laser welding) [39], [41], [42], [43].***

alternators were optimized for high current and heating tolerance, later also for a stable voltage. Asbestos sheets served to insulate the bars from the slot walls, which offers high-temperature stability if its hygroscopic trait can be managed [60], [61], [62]. Even the insulation of bars with surface coating, which is an essential component of modern hairpin windings, was already explored with shellac and hard rubber (Ebonite) [60].

Fig. 4 sorts and highlights some of the most relevant discoveries around bar and segmented windings throughout the years. Sections II–V will discuss the most prominent ones.

II. FORM-WOUND COILS AS KINDRED TO HAIRPINS AND MUTUAL INSPIRATION

Form-wound coils are compacted coil segments made of multiple wires, wire turns, or other conductors packed together to act as one and are well-established for large machines. They obviously create a link between hairpins or more generally bar-winding and wire-wound machines [83]. These windings have had substantial influence on the development of the dominant basic machine topologies, and techniques for cost-efficient manufacturing consolidated in the early twentieth century. Already in the nineteenth century, form-wound coils provided means for fast shaping of coils from round wires as well as copper bars or strands and electrically insulating them from the slots before their installation in the machine. In contrast to the closed slots of the Lauffen generator, half-open and open slots dominate form-wound machines as the windings are typically inserted from the bore. The openings are then often closed with slot wedges. The major challenges are the end turns and their shape in order to connect the active in-slot portions of different slots, i.e., how the winding is guided from one slot to another and how the various

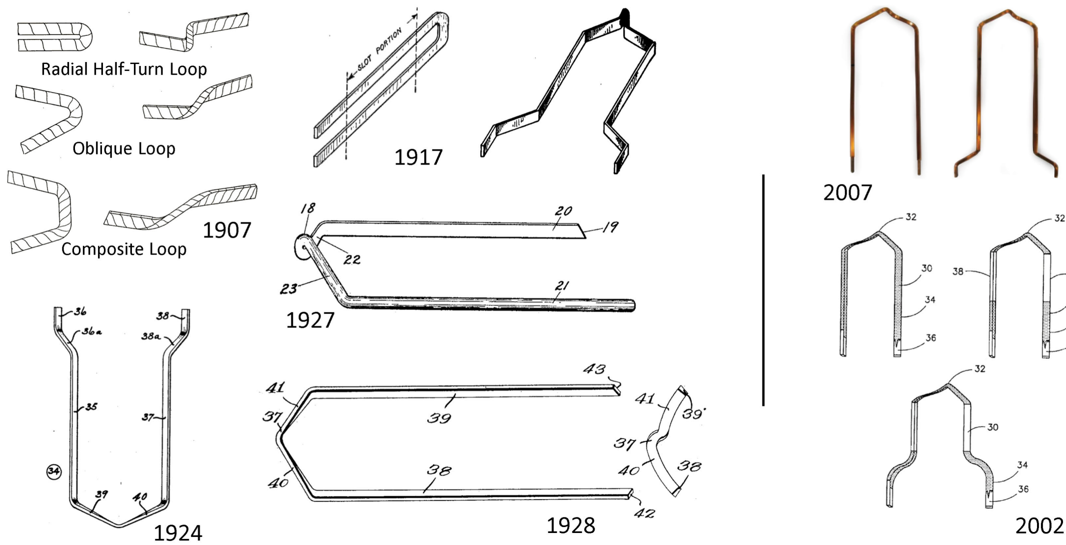


Fig. 5. ***Historical hairpins [49], [52], [53] versus modern ones [54], [55]. Although hairpins had been out of fashion for a long time before their rediscovery, several features survived in form windings for large machines. The technique is really called form winding.***

strands are interwoven to minimize size, copper use, and end-turn inductance. Various forms of such end-turn patterns have evolved; established shapes include rectangular, round, and diamond ends, while diamond end turns shaped as involutes either radially toward the shaft or nowadays more frequently in axial direction have become the dominant design [84], [85], [86]. Other still existing developments include half-turn loops at the end turns to form a wide variety of coil shapes without bulges [49], [83], [87]. Form and bar windings share large similarities and have inspired each other particularly with respect to end-turn patterns.

The end-turn patterns that dominate in modern hairpin machines follow the Lauffen approach for guiding bars around each other with typically two modifications (Figs. 5 and 6). First, the pattern is, in stark contrast to the one bar per slot in Lauffen but revisiting the idea of the Folsom Powerhouse generator design, extended to two bars, which alternate between two radial positions in the slots and have their slot-to-slot connections on opposite sides of the machine, generating advantageous clearance in the end turns for welding and direct cooling. The bar closer to the air gap leaves the slot on the front side to enter the next slot after the respective coil span at the radially outer bar position, i.e., farther away from the air gap. The two or more bars per slot (typically multiples of two, following the alternating pattern within each pair) allow short-pitched double-layer windings, which engineers of the time found to not only improve the air-gap flux smoothness at the cost of a marginally lower winding factor—the usual reason for short pitching—but also a potent way for reducing ac effects in the large-cross-section conductors [55]. For two such bar positions and a coil span of s, the pattern needs to guide $2s$ bars around each other and does that—following the Lauffen design—by forming several radial and axial layers in the end turns (Fig. 6). Most commonly, end turns reflect the two radial positions that nowadays already exist in the slots and establish s axial layers [5]. Second, the overhang follows a triangular or diamond shape, at the end of which the bar changes its radial position before it dives back down. This cusp is sometimes called a *knuckle* and can be on the bent as well as on the jointed side (see Fig. 5, Nos. 18, 32, and 37) [88].

Modern hairpin windings typically have a higher even number of rows (commonly 4, 6, 8, and 12) to adopt the fundamental interwoven pair design. Short pitching, e.g., through shifting the rows against each other, and overall more complicated winding schemes may not always work with just one type of pins and require so-called jumpers. Jumpers are pins that deviate from the typical pitch or pattern, jump from one row to another, or connect more distant pin ends. Concepts for simple jumpers that blend in well, however, have also been developed early (Fig. 7). Such jumpers form the phase terminals. The use of layered jumpers and terminals that remind of printed circuit boards and allow axial and radial bypassing appear smart and compact and are therefore used and promoted intensively.

Although both wave and lap windings are possible, hairpins nowadays predominantly use wave windings as the Lauffen generator did. Bar windings with longer segments than I-pins and hairpins are also available, typically as lap windings, and resemble what was once developed as so-called spread-diamond coils (Fig. 8) [20], [79], [88], [89], [90].

The change of the radial position of bars (e.g., within a pair) from slot to slot practically pairs two Lauffen windings, interweaves them, and generates a regular pairwise

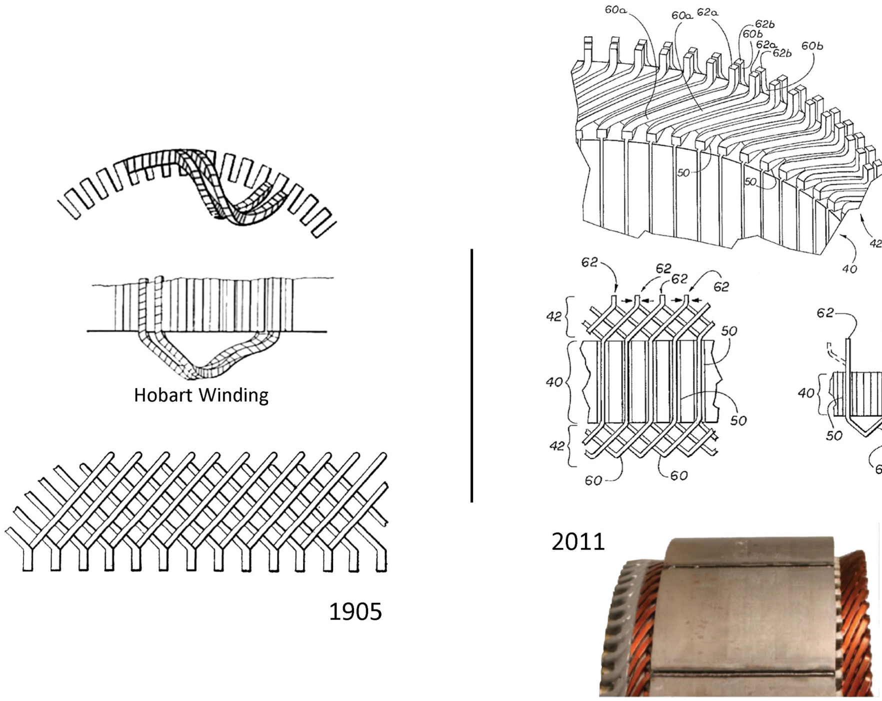


Fig. 6. ***Major art in hairpins is a smart pattern at the end turns to reduce the size of the overhang and guide the conductors around each other. While Dolivo-Dobrovolski had already found the fundamental braided three-phase pattern using two radial positions for ascending and descending bars, the more modern shape using bent wires evolved around the turn of the century [63], [64].***

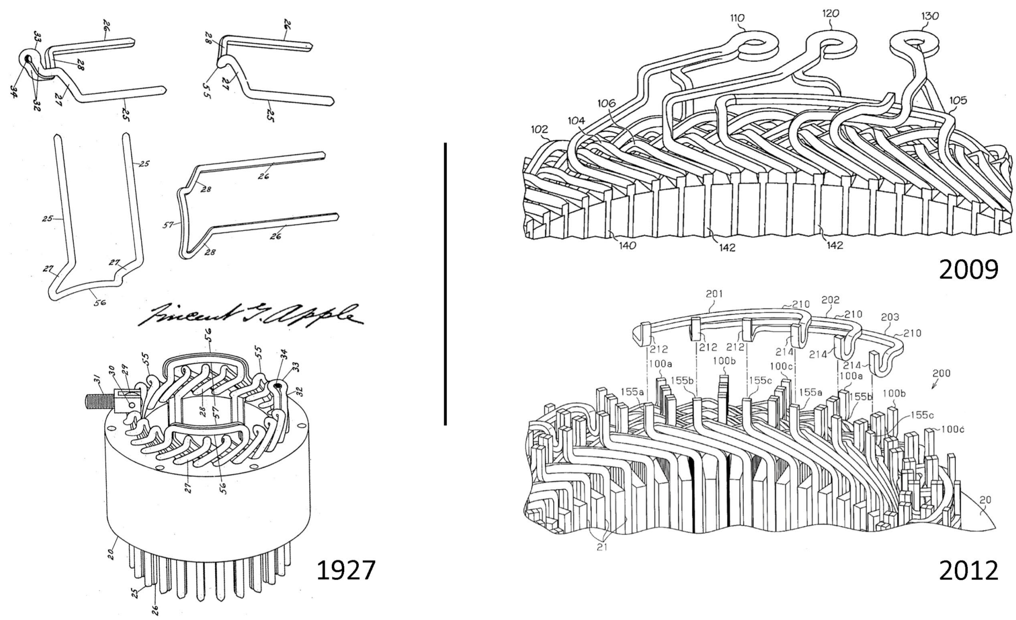


Fig. 7. ***Jumper wires and collectors with more complicated bending sections of various kinds can form terminals, neutral points, or delta connections, as well as wider bar transpositions [69], [70]. Earlier inventors during the first hairpin wave, among them Apple, suggested many such techniques [71].***

transposition, which alleviates high-frequency ac effects to some degree. This pattern has been well-established for more than 100 years [60]. Transposition patterns for more bars were devised early on and have been rediscovered or reinvented and advanced to guide a phase's current through ideally all possible positions inside the slots to

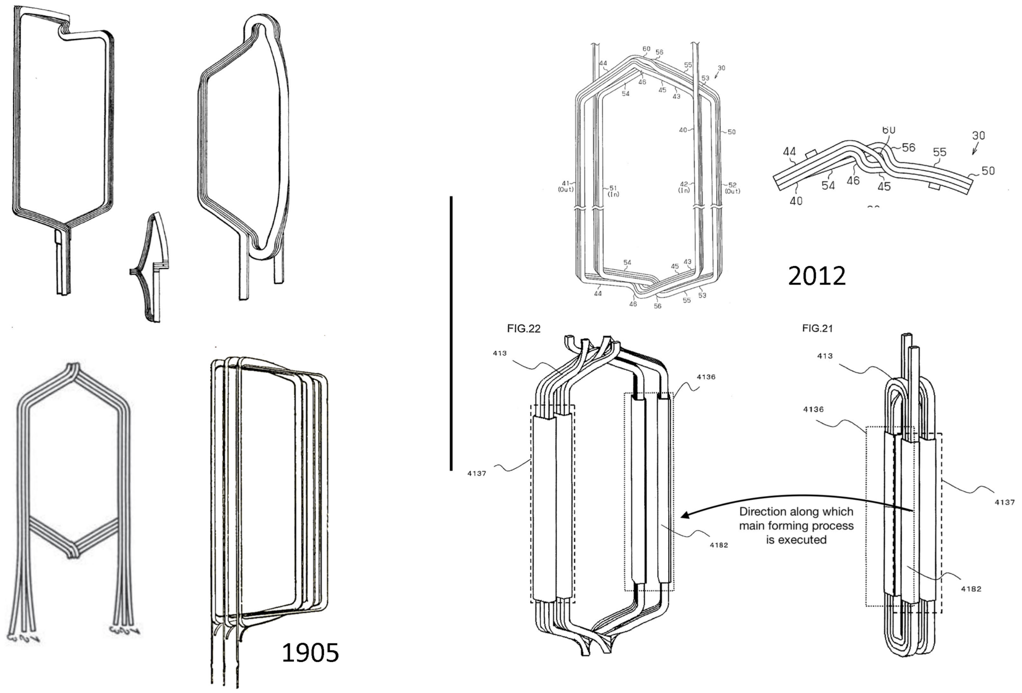


Fig. 8. ***Longer segments than U-shaped hairpins are used particularly in lap windings and sometimes called diamond coils [70], [79]. Those include winding elements that have turns in more than two slots, e.g., for higher winding factors and/or skewed windings [49], [63], [80].***

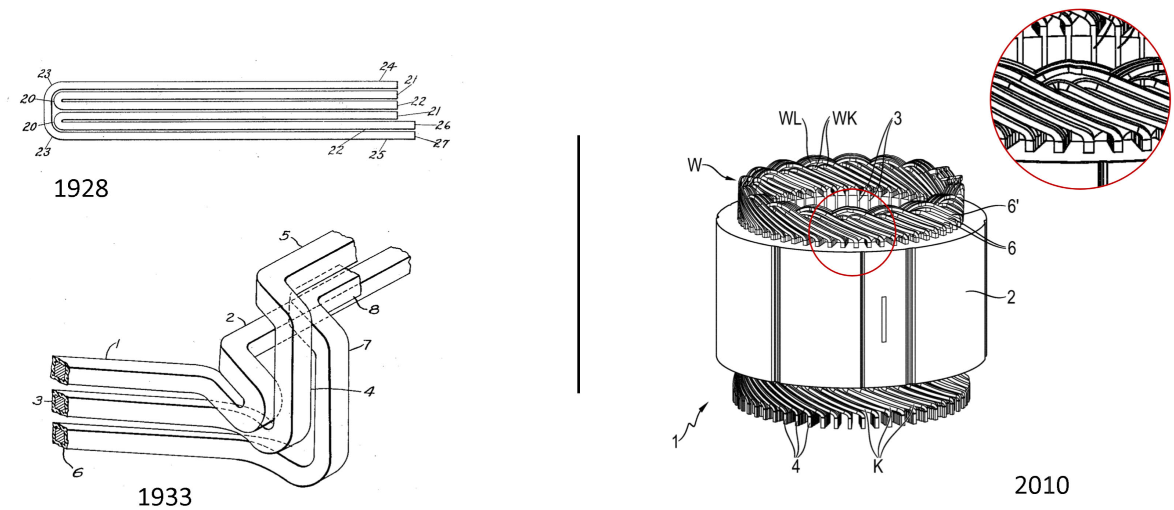


Fig. 9. ***Of major importance in hairpin and bar windings is the control and suppression of high-frequency losses. Recently, a number of transposition techniques have been proposed, which change the position of bars within slots [65], [66]. However, the importance of the problem as well as solutions to it were discovered long ago [67], [68]. The prior art provides a rich knowledge source for these subjects.***

balance different magnetic field conditions (Fig. 9). For that purpose, pins can, for example, reach over a pair forming a kind of arc. Even with more than two conductors per slot and potential transposition patterns, most modern hairpin machines still group their bars in pairs, each of which follows this long-established design.

By 1910, form- and bar-wound coils had become standard for dc machines [20], [60]. For ac machines, they were not gaining similar importance. The slower development had various reasons. First, the typically higher voltages and therefore lower currents of ac machines did not necessarily justify the higher slot fill; second, ac machines were still underdeveloped compared to dc machinery [36], [91]. By that time, also three-phase induction machines were tested with solid bars for the stator winding to increase the phase current. However, the increased complexity of the interconnection led to typically not more than one–four bars per slot in one or two layers with both lap windings for higher voltage and wave windings for lower voltage machines [91]. Insulation with closed tubes of oil paper, oil canvas, calico cloth, varnish, and mica already enabled phase voltages of several kilovolts [61], [91]. Early enamel coatings had thicknesses of approximately 0.1 mm and allowed denser packing than cloth or bandages [91].

III. DISCOVERY OF AC LOSSES AND ASSOCIATED RETREAT OF BAR WINDINGS TO NICHE APPLICATIONS

Considering that early bar-wound machines used conductor bars with relatively large cross sections, an important constraint was and still is additional loss due to the skin effect, proximity effect, and copper eddy currents. Although Maxwell and colleagues from the physics and engineering communities in the late nineteenth century had discovered these effects, they had not worked out completely their practical implications. The full appreciation as well as understanding of the involved tradeoffs appear to have taken decades as the following paragraphs illustrate [92, p. 487ff.].

Thus, despite the reported understanding of different ac effects, many motor designers probably underestimated the true level or accepted it for their applications, while the knowledge about them diffused gradually through the community.

Heaviside [93] and Rayleigh [94], [95] studied the skin effect analytically in the 1880s, whereas the detrimental consequences of the skin effect on bar conductors had been clearly communicated in 1889 [96], i.e., approximately the time of the design of the Lauffen generator. In 1897, Merritt [97] presented spatial distribution plots, which rendered the effect of current concentration on the surface obvious also to nontheoreticians.[4] Dolivo-Dobrowolsky, Brown, and others almost certainly knew about eddy currents—including those in iron parts and conductors—given the coverage in the literature of the time [21], [96], [98], [99]. At this time, inventors and scientists, respectively, exploited and discussed the skin or Thomson effect (after W. Thomson) on solid conductors as well as means such as stranding to suppress it in windings [100], [101].

With Russell's [92, pp. 487ff.] and Field's [102] work on skin and eddy-current phenomena, sufficient knowledge about the adverse effect of large cross sections became available in the literature [36]. However, even ten years later, Rogowski [103] concluded that despite good theoretical and experimental coverage, the skin effect was not widely understood and appreciated. Despite early phenomenological knowledge from at least part of the community, applicable models and measurement approaches for ac losses in various conductor types and shapes were not available before the early twentieth century [52], [104], [105], [106], [107], [108].

The additional losses due to skin and proximity effects, as well as due to circulating currents, constrained the use of large conductors in early bar-wound machines altogether. Their discovery revealed the tradeoff between ac loss and the cross section of individual bars or parallel strands, as well as the dilemma that in some cases, an increased cross section could reduce the efficiency. Significant advancements led to design rules, and recommendations from that time are still in place [109], [110]. Some authors recommended avoiding large cross sections of conductors and preventing the radial stray flux injected by the rotor poles into the slots (instead of the stator teeth) from reaching conductors, e.g., by increasing the distance of the first bar in a slot from the air gap (see Fig. 1) [91]. Also, given that the transverse magnetic field in the slot cannot be shielded, tooth saturation should be kept moderate, and large-cross-sectional copper bars should be divided into segments in radial direction. Such parallel strands of a conductor phase should not be shorted at the end turns after each segment to suppress circulating currents, but rather run through the entire stator to be paralleled at the overall ends only so that imbalances average out [111].

Considering ac losses, manufacturing techniques, and their high-frequency challenges, bars were recommended primarily for larger currents and cumulative cross sections above 20–25 mm^2 as part of segmented form windings. Their use became less common for small industrial ac drives [91], [112].

Despite the temporary retreat of bar windings into niche applications, the challenge with ac effects inspired important innovations. The experience with litz wire in radio engineering initiated the development of transposition concepts for conductors between two slots, i.e., systematically changing the radial conductor position from slot to slot, so that conductors are close to the air gap in one slot and adjacent to the slot ground in another. The position change averages out the flux experienced by each conductor [67], [109], [112], [113], [114], [115], [116], [117]. In addition to short-pitching, transposition of conductors from one slot to another by shuffling them beyond the fundamentally interwoven hairpin pair, as described above, is a key technique for mitigating high-speed ac losses in bar and hairpin windings to this day [66], [109], [118], [119], [120], [121].

IV. SMALL DRIVES IN THE TWENTIETH CENTURY

Hairpin and other bar windings for small drives in the modern sense experienced a major thrust from the 1910s on, because of rationalized production and growing power densities in the young automobile industry [52, p. 1230, Figs. 1519–1522]. Bar-wound dc armatures were, for example, a good match to provide the high torque density required for electrically started automobiles.

[4]Merritt co-founded *The Physical Review* in 1893 and the American Physical Society in 1898, where he served as the first secretary, about the same time as his work on high-frequency current distribution effects.

Several contributions by Charles F. Kettering[5] and Vincent G. Apple,[6] both from Ohio, USA, shaped the development of modern automobiles (including electric motors), given their numerous influential inventions [122], [123], [124], [125], [126], [127], [128].

Dayton Engineering Laboratories Company (Delco) along with Remy Electric Company jointly developed technology and manufacturing facilities that set the standard for today's production of starter armatures and triggered a massive incubation phase for novel solutions in the entire industry (see Fig. 10) [47], [73], [129], [130].[7]

From today's perspective, starter motors seem to have been the perfect opportunity for bar windings, at a time when they did not work well with the ac effects in more conventional motor drives. Starter motors have a relatively low speed and therefore mostly low-frequency armature current content but require massive torque density. Furthermore, manufacturing needs to be highly rationalized to limit cost. Finally, efficiency is secondary due to short usage. As a solution to the high injury risk of hand cranks, electric starters quickly became the industry standard (Fig. 10). Whereas the Ford Model T was initially without an electric starter, Delco soon offered a device for retrofitting it [Fig. 10(c)]. General Motors (GM)'s 1912 high-end Cadillac Model Thirty offered such starters as a standard configuration based on Kettering's [122] patent. In 1927, the release of the Model A, the second biggest success for the Ford Motor Company, included an electric starter in the basic version.

Some of the developments of Apple have lasting impact and may serve as examples for this rapid technology development. His one- and two-layer winding design for dc armatures with single-turn bars anticipated modern hairpins including the insulation concept using specifically folded paper lining for the slot walls and separating pins (Fig. 11) [50]; he contributed elegant transposition patterns for more than two bars supporting both lap and wave windings, as well as the combinations of both (such as frog-leg windings) in a single armature [67]; and Apple developed the I-pin concept of half hairpins further, for instance, for solder-free dual-commutator armatures [131]. In the aftermath of these developments, bar-wound technology became the dominant solution for automotive dc starter armatures. In fact, practically, all major equipment suppliers in that business used it [Fig. 10(e)]. The conductors of most modern starter armatures have the distinctive hairpin shape with two legs and use round or, less frequently, square or rectangular strip conductors with one or sometimes two conductors per slot.

Bar windings enabled high torque and moderate cost for self-starting cars. Through a reduction of the risk of injury and the inclusion of less muscular drivers, the technology's social impact contributed to the expansion of private transport, which shapes the design of global infrastructure and cities to the present.

The efforts made by the incipient automotive industry to reduce costs resulted in highly rationalized and professionalized manufacturing processes comparable to today's standards. The tools for early hairpin manufacturing introduced a wide variety of techniques and tricks still applied in modern machines (Fig. 12). Although classic books present manual tools and formers for prototyping or low-quantity or bespoke motors may look simpler (Fig. 13), the need for these automotive starters in large numbers led to the two fundamental ways to form hairpins: through either bending them with full control over the cusp shape in a widely automated tool with a bending mold (Fig. 12); or bending pins through rotating two disks with the cusp following passively (Figs. 12 and 14). Both techniques remain the dominant methods to manufacture hairpins today.

On the other hand, automotive ac machines with hairpin stator winding did not play a major role until the second half of the twentieth century for heavy-duty applications (particularly synchronous machines [90], [132]). A clear example is the Delco Remy 50 DN, a 215-A/12-V claw-pole alternator for buses introduced in the late 1950s [Fig. 10(f)]. It is also considered to be the first modern series-manufactured ac hairpin machine. Compared to wire-wound alternators, this oil-cooled machine had a high slot number of 72 for a two-layer wave winding and resembles modern traction machines in EVs. Delco Remy reported an efficiency below 50% for the original design due to severe ac losses in the thick conductors at high speed (6500 r/min) [133], [134]. Since then, their design has been improved, partly through relearning and rediscovering how to make efficient hairpins, e.g., short-pitching, clearing the space of the slot near the air gap of windings (as stray flux injected from the rotor enters the slot here, which induce circulating currents into bars), and forming the crowns of the teeth in partially closed slots. These improvements reduced ac loss and increased voltage capabilities, with the updated 50 DN version rated for 270 A/24 V with an efficiency of up to 78% [135], [136].

[5]Charles F. Kettering (1876–1958) was a prolific American inventor, engineer, and businessman, best known for developing the electric self-starter for automobiles, which replaced hand cranks and revolutionized car ownership. He co-founded Delco (Dayton Engineering Laboratories Company) and served as the Vice President for research at General Motors (GM) for nearly three decades, where he performed a wide range of developments in automotive technology, including leaded gasoline, ethanol fuel, diesel engines, and early air conditioning systems. Kettering held over 180 patents, and his innovations extended beyond automotive to areas like medicine, with contributions to cancer treatment research. His work significantly shaped modern engineering and industrial research practices.

[6]Vincent G. Apple (1874–1932) was an American inventor and electrical engineer known for his pioneering work in automotive ignition systems and early battery technology. He was a key figure in the development of magneto ignition systems, which were critical for the reliable operation of early automobiles. Apple held numerous patents, primarily in the fields of electrical engineering and motor technology. He also contributed to advancements in fuel efficiency and automotive electrical systems, making a lasting impact on the automotive industry. His work laid foundational technology that influenced modern ignition systems and electric power generation.

[7]Both companies were merged after their acquisition by GM in 1918.

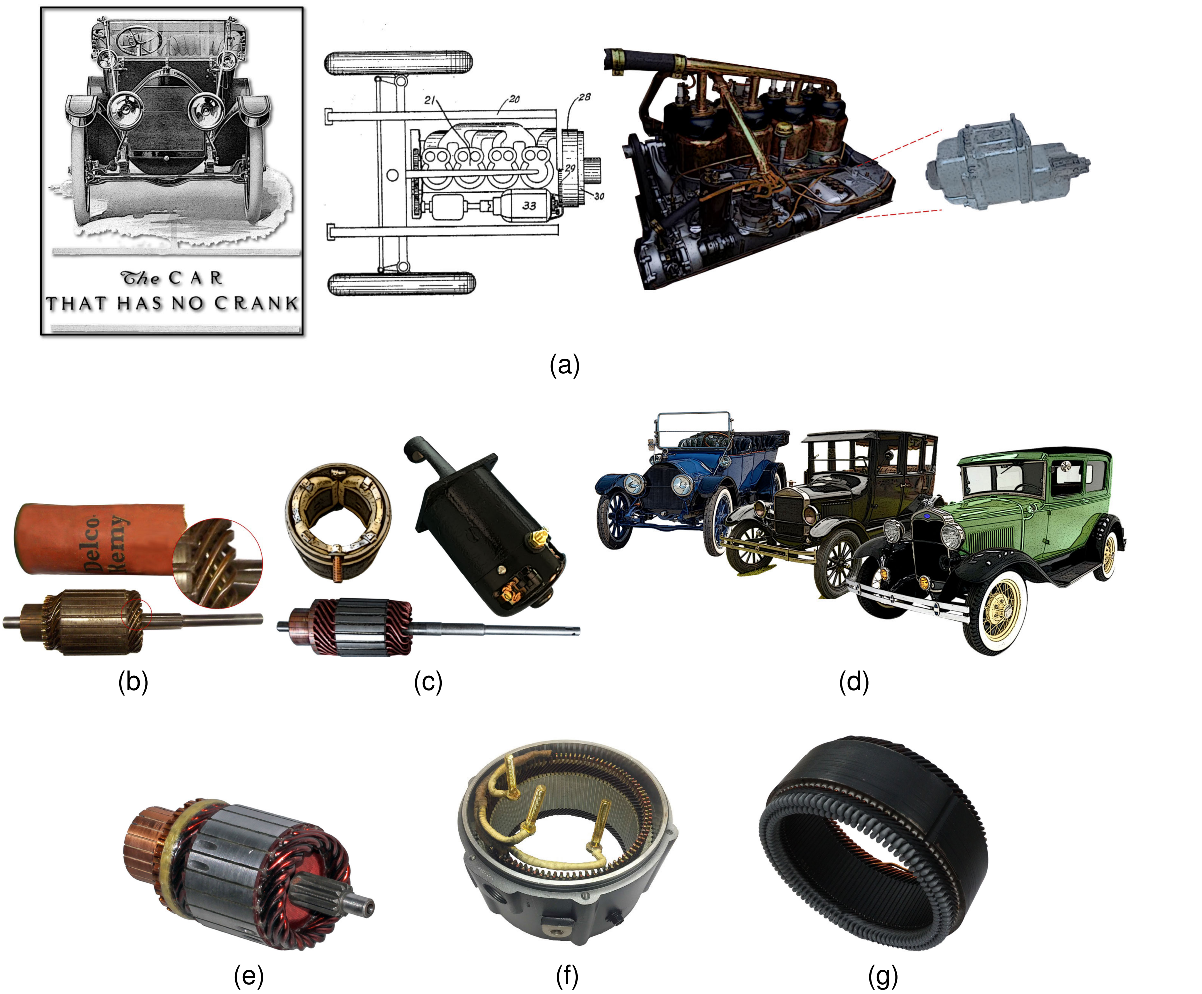


Fig. 10. *(a) Contemporary advertisement of the Cadillac Model Thirty as one of the first series vehicles with an electrical starter for the four-cylinder engine (the engine compartment patent drawing shown center left almost perfectly matches the Cadillac's [122]). (b) Bar-wound starter armature for Buick from the early days of electric starters. (c) Stator, armature, and casing for a Model T for retro-fitting. The bars have the characteristic hairpin shape where the bent side neatly guides the pins around each other using two radial levels (see magnification). (d) From left to right: Cadillac Model Thirty; the likely more widely known Ford Model T in the middle, which in its standard configuration was with hand-cranking but allowed already retro-fitting with an electrical starter (see the photograph and notice the absent hand crank), and the successor Ford Model A, which had an electrical starter installed in its standard configuration. (e) Delco Remy PG260M PMGR starter armature. The development of bar windings in dc armatures and ac motors was closer as is the case today. Early ac machines, such as GE's, had the ac winding on the rotor and therefore closely resembled dc armatures but with three-phase slip rings instead of a commutator. Accordingly, the windings could be practically the same. More familiar today, however, is the rotating field on the stator with the static poles on the rotor for synchronous machines as in the (f) Delco Remy 50 DN 270-A/24-V 72-claw-pole alternator, which was first introduced in the 1950s. (g) Denso DAN930 alternator.*

Nowadays, alternators with a hairpin stator (e.g., for 12 V) are available from various manufacturers. Among the pioneers were Denso [137], [138] and Valeo [139], [140], [141]; the Denso DAN930, for instance, has four bars per slot, a triangular shape on the welding side, and relatively round end turns on the other side, the one with the hairpin vertex or cusp [Fig. 10(g)]. Most interestingly, the two pairs of bars, each of which alternates between their two positions in the slot on the welding side as in most other hairpin wave windings, are interwoven by bending the outermost bar of each slot over all others to become the innermost on the vertex side; the next slot can alternate between neighboring bars again. Thus, a current is running through all four bar positions in the slots. This transposition scheme has similarities with Apple's design from approximately 100 years ago [67].

V. HIGH-VOLTAGE BAR-WOUND MOTORS FOR TRACTION

In the 1940s, when the automotive world used bar-wound machines for alternators and starters, General Electric (GE) explored this winding technology for higher power diesel–electric locomotive traction. The GE-752 motor series (Fig. 15), for instance, was a high-voltage, high-torque, and wide-speed-regulation-range dc traction motor. By 1950, it became GE's basic motor for large

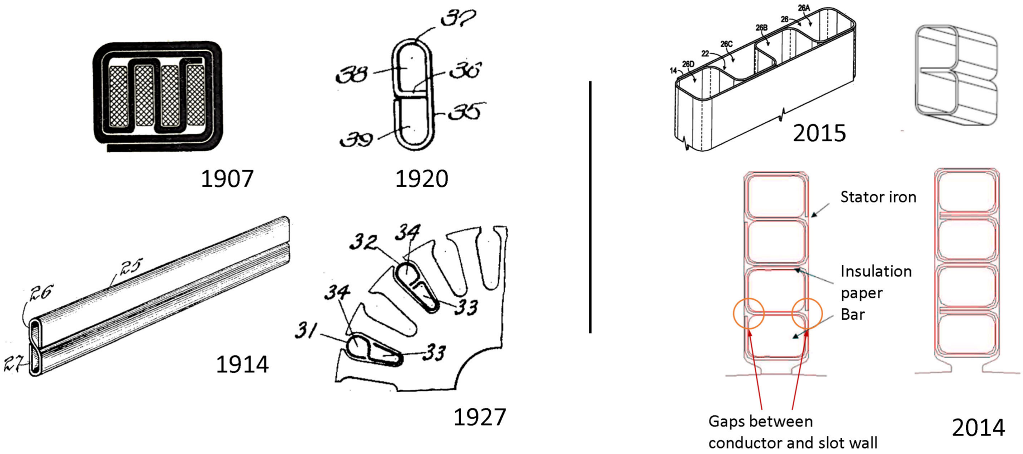


Fig. 11. ***Insulation paper is used for electric insulation, but should be as thin as possible for good thermal conductivity and leave no gaps for high voltages. Innovations presented in the ongoing wave of hairpin designs and the subject of patent applications [12], [13], [46], however, turn out to have substantially close historical, though likely earlier counterparts [47], [48], [49], [50]. B-shaped slot liners that meander around all conductors as recently promoted offer gap-free insulation with sufficient creepage and no larger overlaps but were suggested already by Apple and others about a century earlier with similar arguments and even drawings [48].***

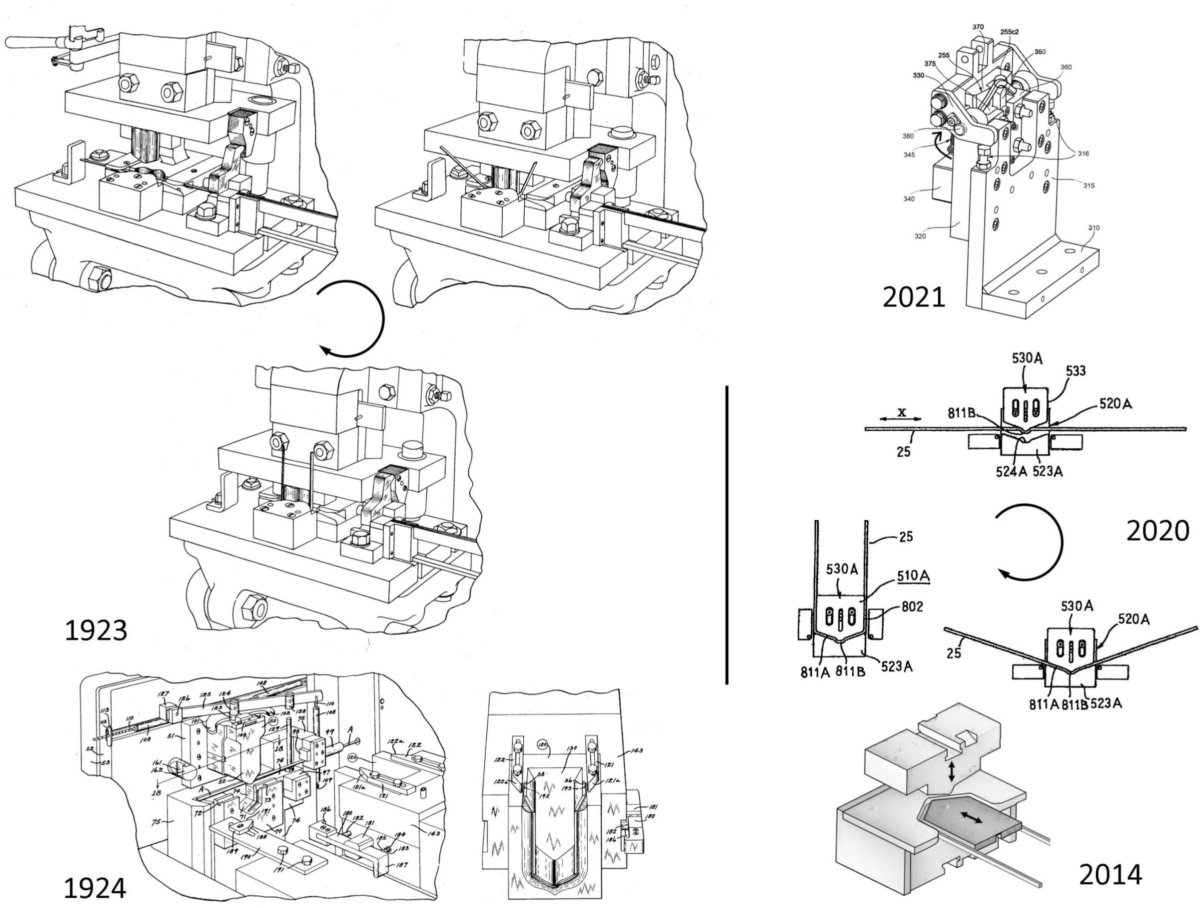


Fig. 12. ***Hairpin windings offer a highly economical, fully automated, manufacturing process with automated bending, insertion, and particularly interconnection process. The automotive industry exploited these features as early as the 1920s with machines that appear very modern even now [72], [73], and continues to use similar methods or rediscovers them [12], [74], [75].***

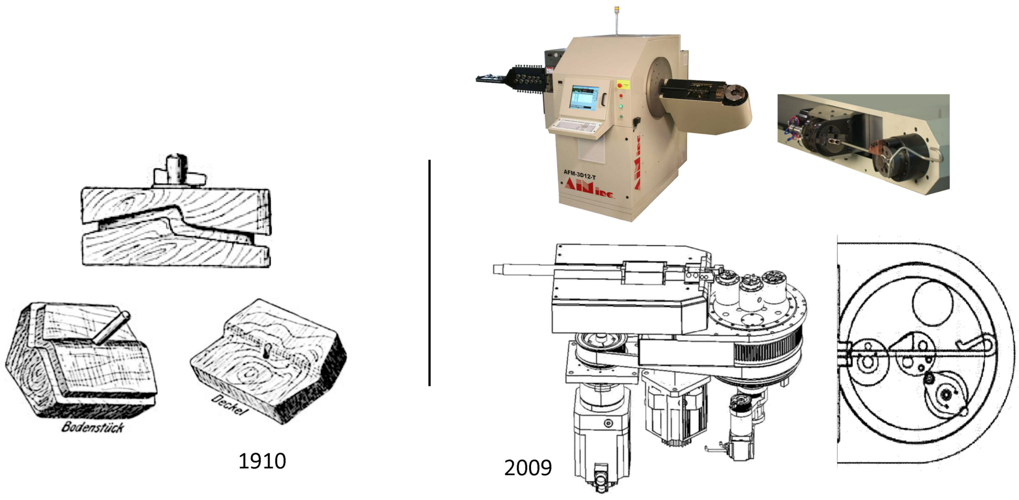


Fig. 13. ***Clear innovations appear to drive prototyping of hairpin and bar windings. Historically, formers for the pins included both the end-turn shape as well as the twisting of the legs' cross sections against each other [20]. Since the 1970s, computer numerical control (CNC) bending machines, such as those from AIM Machines, enable faster shaping, even for a larger number of parts or small-scale manufacturing [81], [82].***

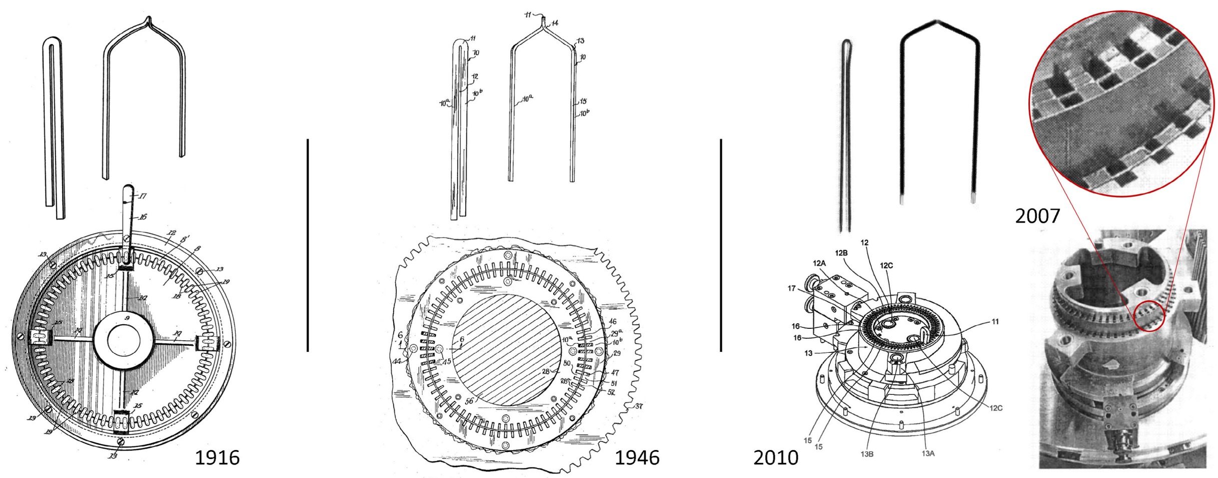


Fig. 14. ***As an alternative to hairpin forming with molds in presses (Fig. 12), hairpins are routinely formed by inserting closed hairpins into harnesses where the two legs are pulled apart when the respective disks that hold them rotate relative to each other [54], [76]. This technique may have less control over the end-turn shape but intrinsically adjusts the angle between the corresponding sides of the legs according to the slot walls when the radius of the disks is matched to the slots of the machine that should receive those pins. The idea is almost as old as hairpin windings and figures in patent applications appear strikingly similar [47], [77], [78].***

locomotives [American Locomotive Company's (Alco) passenger (PA) and freight families (FA)]. Improvements in insulating materials, especially for high-temperature environments, led to lighter and more powerful traction systems. The combination of solid insulators with synthetic varnish led to thinner and improved insulation of the conductors and improved the fill factor as well as the heat-transfer coefficient [142]. Consequently, these technological advances also enabled an increase in the voltage range of bar-winding machines. Early versions supported 900 A with a rated voltage of 750 V (max. 1300 V) [143]. These features put the GE-752 into a wide variety of locomotives in the 1950s–1970s. From the standard option for Alco diesel–electric trains, it eventually propelled all GE electric models built in that period. Moreover, it became the standard for GE's own line of diesel–electric locomotives built between the 1960s and the 1980s and was also available to diesel–electric locomotives of other builders upon request.

Though intensively modified and extended, the GE-752 series exists to this day, mainly used in high-torque drilling applications since better alternatives appeared for traction in the mid 1980s.

Delco Remy developed technology for stronger insulation and further increased the voltage ratings for ac

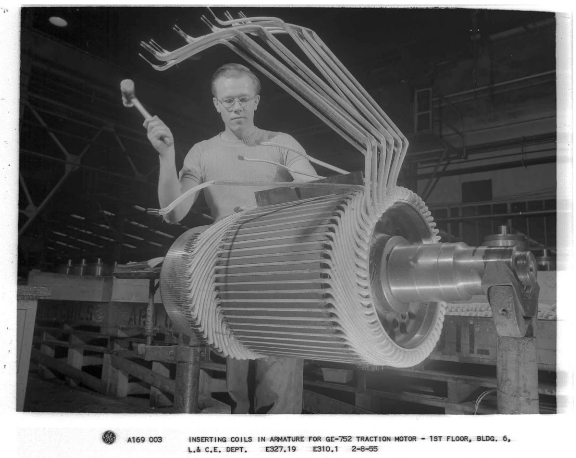


Fig. 15. ***Armature bar insertion for GE-752, which features the characteristic pairwise transposition at the end turns known from modern hairpin machines.***

machines to enable a rather new application for automotive traction machines. This initial development has subsequently resulted in distinctive hairpin designs arranged in wave or lap segments—some of which use open slots for insertion—from various manufacturers [134], [144], [145], [146], [147]. Today, several concepts and terms can be classified as bar-wound coils: hairpin, single and dual diamond coils, and bent as well as straight concentric coils [148], [149], in addition to coils that were built with substructured rods (such as the Roebel bar).

Around 2006, GM capitalized on Remy's advancements to lay the foundation for mass-producing bar-wound traction motors for HEVs. This initiative later expanded to BEVs, with a flexible, modular motor design that could power both permanent-magnet synchronous and induction machines. By 2010, the technology was ready for mass-market deployment.

The stator shown in Fig. 16(a) represents the first-generation Voltec electric drive system, featured in the 2011 Chevrolet Volt (branded as Opel/Vauxhall Ampera in Europe). GM significantly improved this technology in the Volt's second generation (2016–2019) and the fully electric Chevrolet Bolt (2016–2023). The Bolt's eight-pole stator increased the number of conductors per slot from four to six, with an optimized winding scheme that reduced ac losses [Fig. 16(b) and (c)]. GM further enhanced this technology with its latest Ultium drive and introduced it to heavy-duty vehicles, where the high-torque density is ideal for the 180- and 255-kW front and rear traction units. The BrightDrop Zevo, a commercial delivery vehicle, uses the same drive. Thanks to its proven performance and fully automated manufacturing processes, the hairpin motor design has been widely adopted by various automakers as listed in Tables 1 and 2.

Toyota, for instance, employs bar windings with longer segments than hairpins in recent models, e.g., the Aqua (Prius) or Yaris, and has turned it into their baseline technology [Fig. 16(e) and (f)]. Moreover, through Toyota's suppliers and subsidiaries, bar-winding technology also diffused to other brands, such as Subaru, so that it formed a seed and breeding ground in Asia. Honda has collected some experience with hairpin windings in their electrified vehicles, particularly the recent generations of the Accord Hybrid. Hyundai also developed a hairpin-based universal powertrain-denominated Electric Global Modular Platform (E-GMP). The platform displayed in Fig. 16(g) is the foundation for future Hyundai and Kia electric cars. The first vehicle equipped with E-GMP is the Ioniq 5, launched in 2022. In principle, this platform was designed as a rear-wheel-drive unit but now can also be equipped with a second electric motor at the front axle.

Meanwhile, Magneti Marelli and Tecnomatic served as pioneers and multipliers in Europe. Porsche, for instance, uses this technology almost entirely in BEVs (both series as well as motor sports) and achieves high torque densities at still relatively high speeds in the motors [Fig. 17(a)]. This feature may have also been the major motivator behind Ferrari's choice of hairpin motors as well as Jaguar's, e.g., in the I-Pace [150] and Maserati's in its GranTurismo Folgore [Fig. 17(b)]. The high automation level attracted BMW and Volkswagen as seen in the units presented in Fig. 17(c) and (d). After intensive research and development, Ford implemented hairpin windings in their motors, for example, in the Mustang Mach-E or the most recently released F-150 Lightning, as shown in Fig. 17(e). Some automotive start-up companies have embraced bar-winding technology from the beginning, such as Rivian in their R1T [Fig. 17(f)] or Lucid Motors in their Air model [Fig. 17(g)]. Tables 1 and 2 compare different hairpin drive units in the market.

Aside from original equipment manufacturers (OEMs), the hairpin expertise within the EV motor supply chain is becoming increasingly evident. Several Tier 1 motor manufacturers are already highly skilled in the art of bar windings, such as BorgWarner, Hitachi, LG, Denso, or Magneti Marelli, while others are quickly catching up. Tier 2 supplier companies that manufacture high-quality rectangular profile wire, insulation systems, and production equipment can be found in North America, Europe, and throughout Asia.

The major challenges for bar windings and particularly hairpins on the way to automotive traction were threefold: first, winding schemes were needed to achieve a sufficient inductance and thus flux linkage without a high number of bars from the same phase in each slot. That required short-pitching with ideally as few different pin sizes as possible to minimize the number of parts and tools. This aspect is closely linked to the second challenge, specifically the high-frequency losses had to decrease to such a degree that higher motor speeds could be achieved for higher power density. Third, manufacturing had to be rationalized to eliminate any manual steps and speed up the connection formation. The newest cars feature motors exceeding

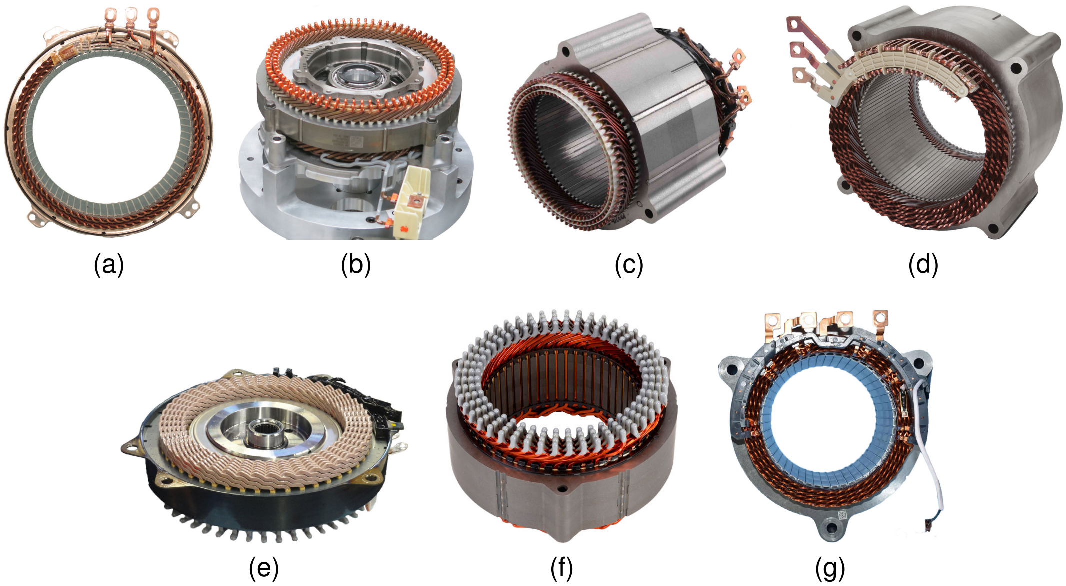


Fig. 16. ***Modern hairpin-wound machines. (a) Chevy Volt Gen 1 stator GM. (b) Chevy Volt Gen. 2 motor GM. (c) Chevy Bolt stator GM. (d) GM Ultium rear motor stator GM. (e) Toyota Prius C P510 Transaxle motor. (f) Toyota P910 Transaxle stator. (g) Hyundai E-GMP front-motor stator.***

Table 1 Modern Hairpin-Wound Motors for HEVs/EVs, Part I

	General Motors	Toyota	General Motors	General Motors	Porsche	Volkswagen AG	Toyota
Propulsion System	Voltec G1 Motor A/Motor B	P510 Transaxle MG1/MG2	Voltec G2 Motor A/Motor B	BEV2	Porsche Taycan Front Motor/Rear Motor	MEB APP 310	P910 Transaxle MG1/MG2
Input Voltage	360 V	144 V	360 V	344 V	800 V	400 V	177.6
Peak Power	55/110 kW	31/45 kW	48/87 kW	150 kW	190/335 kW	150 kW	59/59 kW
Peak Torque	200/370 Nm	140/169 Nm	118/280 Nm	360 Nm	400/550 Nm	310 Nm	141/141 Nm
Peak Rotor Speed	6000/9500 r/min	10000/13500 r/min	10000/11000 r/min	8810 r/min	16000 r/min	16000 r/min	17876 r/min
Conductor Depth	4	12	4	6	4	6	8
Number of Poles	12	8	12	8	8	8	8
Stator Slots	72	48	72	72	72	48	48
Production	2010 – 2015	2011 – 2017	2016 – 2019	2016 – 2021	2018 – present	2019 – present	2019 – to present
Picture	Fig. 16(a)	Fig. 16(e)	Fig. 16(b)	Fig. 16(c)	Fig. 17(a)	Fig. 17(d)	Fig. 16(f)
Models	Chevy Volt 2010-2015 Cadillac ELR Opel/Vauxhall Ampera	Toyota Aqua, Corolla Prius C, Yaris Hybrid	Chevy Volt 2015-2019 Chevy Malibu Hybrid Cadillac CT6 PHEV	Chevy Bolt, Bolt EUV Buick Velite 7 Opel Ampera-e	Taycan 4, 4s, Turbo, Cross Turismo, Cross Sport	ID.3, ID.4/5, ID.6 ID.Buzz, Audi Q4, Q5 Skoda Enyiaq IV	Yaris Hybrid 2020

800-V operating voltage and 20 000 r/min. Furthermore, manufacturing has even bypassed wire-wound motors with distributed windings, which typically still contain some manual wiring after the insertion process. With laser welding, also the previously time-consuming joining process of the many pins can be performed in the manufacturing cycle time without the need for batch steps. After solving the major obstacles, researchers now study methods to use the available degrees of freedom in the winding to mitigate the effects of the sharp voltage transients of latest wide-bandgap transistors; improve the thermal limits of the conductor varnish; and cool more directly [151], [152], [153], [154], [155], [156], [157].

The benefits of bar-wound motor designs are tangible, and solutions to mitigate the remaining drawbacks are developing rapidly. Hairpin technology may, furthermore, be a major technological driver of electromobility and, therefore, have a considerable impact on our daily life. Whereas society and policy makers push for a transition to EVs for ecological and climate reasons, the high torque and instant acceleration that hairpin windings can offer at lower cost over wire-wound machines appear

Table 2 Modern Hairpin-Wound Motors for HEVs/EVs, Part II

	BMW	Hyundai Motor Group	BorgWarner	Lucid Motors	General Motors	Bosch Mobility	Magneti Marelli
Propulsion System	xDrive 5th Gen.	E-GMP Front Motor/Rear Motor	Integrated Drive Module (iDM220)	Lucid Air Platform	Ultium Drive Front Motor/Rear Motor	eAxle	Maserati Rear Motor
Input Voltage	400 V	800 V	400/800 V	924 V	400/800 V	400/800 V	400/800 V
Peak Power	210 kW	160/270 kW	210 kW	358 kW	180/220 kW	240 kW	300 kW
Peak Torque	400 Nm	350 Nm	430 Nm	600 Nm	440 Nm	430 Nm	450 Nm
Peak Rotor Speed	17000 r/min	15000/20000 r/min	18000 – 20000 r/min	19500 r/min	14000/16000 r/min	14000 – 18500 r/min	17500 r/min
Conductor Depth	4	8	8	8	8	6	6
Number of Poles	6	8	8	6	8	8	8
Stator Slots	54	48	48	72	96	48	72
Production	2019 – to present	2020 – to present	2021 – to present	2020 – to present	2022 – to present	2021 – to present	TBD
Picture	Fig. 17(c)	Fig. 16(g)	Fig. 17(e)	Fig. 17(g)	Fig. 16(d)	Fig. 17(f)	Fig. 17(b)
Models	i4, iX, iX3, i7	Ioniq 5, Ioniq 6, Genesis GV60, Kia EV6, Kia EV9	Mustang Mach-E, Ford F-150 Lighting, Aiways SUV U5	Lucid Air, Lucid Gravity	Hummer EV, Cadillac Lyriq, Brightdrop Zevo 600	Rivian R1T, Rivian R1S, Rivian R2 series	Maserati GranTurismo Folgore

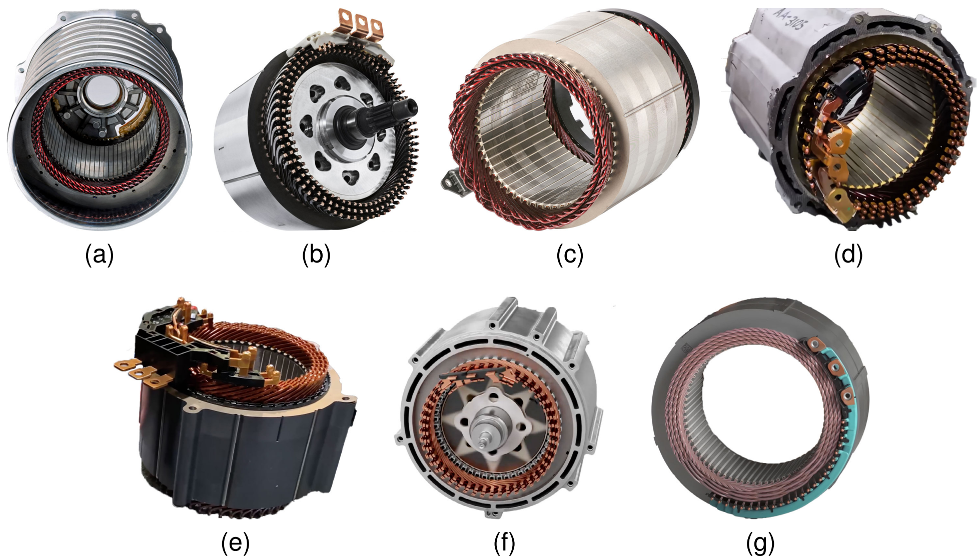


Fig. 17. ***Modern hairpin-wound machines. (a) Porsche Taycan stator. (b) Maseratti GranTurismo Folgore motor Marelli. (c) BMW xDrive fifth-geneneration stator BMW. (d) Volkswagen MEB APP 310 stator Volkswagen. (e) Ford Mustang Mach E stator BorgWarner. (f) Rivian R1T Motor Bosch. (g) Lucid air platform stator lucid motors.***

to have become a notable economic and cultural argument for some individuals to switch to electric. While EVs are coming to the fore in the top and mid-segment passenger vehicle market, commercial vehicles such as trucks are on the horizon. Bar windings offer both high performance and economical manufacturing. Wire-wound motors might well be relegated to lower performance and special applications.

VI. CONCLUSION

Bar windings, particularly hairpins, have rapidly gained dominance in traction drives of recent vehicles. On the one hand, significant advancements have led to highly rational manufacturing processes, which match the automotive production demands: fully automated, resource-efficient with short lead times. Furthermore, bar windings offer additional benefits that are essential in this challenging industry, most importantly larger slot fill factors (up to ≈80%) in addition to more compact winding overhang, which, in turn, enable improved power density, better heat dissipation, and longer insulation life.

While this technology might seem new in the field of car propulsion motors, a closer look at historical literature and engineering artifacts reveals that bar windings, including hairpins, were explored and exploited much earlier than most readers might expect. This technology was initiated and developed when the fundamental understanding of motors themselves was still evolving, with many open questions remaining. Today, however, we have the knowledge and tools to fully harness its potential. This article discusses ac effects as an example of how we can build upon this foundation. Additionally, the advantages of bar windings, such as fully automated assembly, improved thermal conditions, and superior cooling options, are more valuable than ever in modern applications.

The recent rapid advancements in this technology reflect a resurgence of ideas that were first envisioned many decades—if not over a century—ago. This rediscovery process has sparked fresh innovation and patent activity, which brings classic concepts back to the forefront. Bar windings, including segmented hairpin windings, exemplify an area where revisiting historical developments reveals that many current challenges already have effective solutions or provide inspiring directions for today's engineers and researchers. ■

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