History and Future of Exciterless Wound-Field Medium-Power Synchronous Machines

Abstract—**The excitation system of the wound field synchronous machine has remained largely unchanged over the past 50 years. Nonetheless there has been significant research into exciterless solutions which, through integration of the excitation system with the main machine, aim to offer improved power density, simplified manufacture, and better cooling opportunities. This work presents the history of exciterless solutions for wound-field synchronous machines focusing on the challenges for medium power generators. The very latest innovations are discussed, signposting the future for the exciterless machine along with new challenges and opportunities for engineers.**

I. Introduction

The wound-field synchronous machine (WFSM) has a long history of power generation applications, yet has had limited success in emerging applications due to low power density, despite other advantages [1]. This is largely due to the excitation system (ES) required to supply power to the rotating field winding, for which the typical AC exciter represents a significant additional volume [2]. Exciterless has long been suggested as the next step – improving power density by integrating the exciter and main machine magnetic circuits. Additional benefits including simplified manufacture are also a key driver as illustrated in Fig. 1.

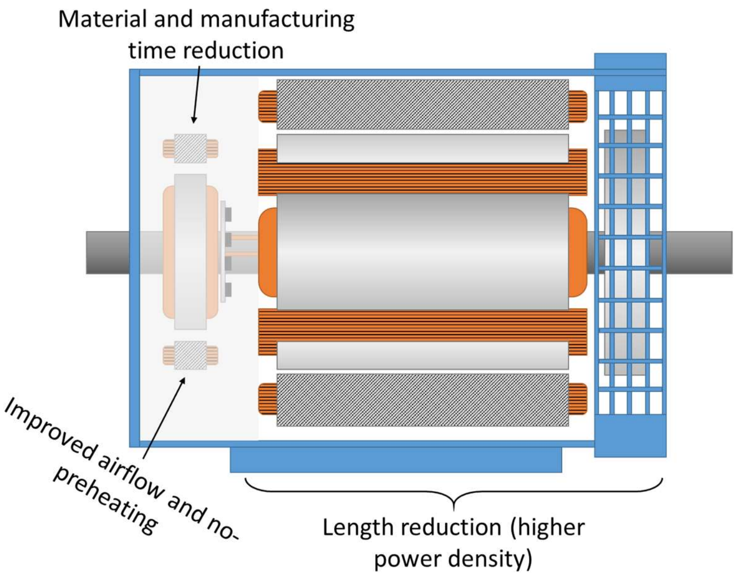

Fig. 1. Diagram of a typical synchronous generator with a rotational exciter showing the potential benefits of exciterless solutions.

This work begins with a brief discussion of the ESs in common use today before an in-depth look at exciterless topologies in which the excitation magnetic circuit is combined with that of the main machine. Modern ESs using wireless power transfer topologies are discussed and how these signpost the future of WFSM excitation.

II. Conventional Excitation Systems

Before the invention of the silicon rectifier a excitation was achieved using a complex DC ES, Fig. 2a, in which a controllable DC generator produces the excitation power and the commutator provides rectification [2]. The need for both commutator and slip rings posed a key failure point such that, with the development of robust silicon diodes, alternatives in the form of static slip ring excitation, Fig. 2b, and the AC exciter, Fig. 2c, were developed. A slip ring system is supplied by an external controlled DC source, typically from a power converter. It is prone to the same wear as the DC ES but allows for static excitation by decoupling the field current from the rotation of the machine, which results in faster transient response and startup. Whereas the ‘brushless’ AC exciter replaces the commutator/slip-ring arrangement with a shaft mounted diode rectifier, this provides a maintenance free solution whilst still leveraging the prime mover power, thereby minimizing converter requirements of the control system. These advantages make it the dominant choice for medium-plus power machines [3], [4]. Both these solutions are still in common use today despite a number of exciterless topologies having been proposed.

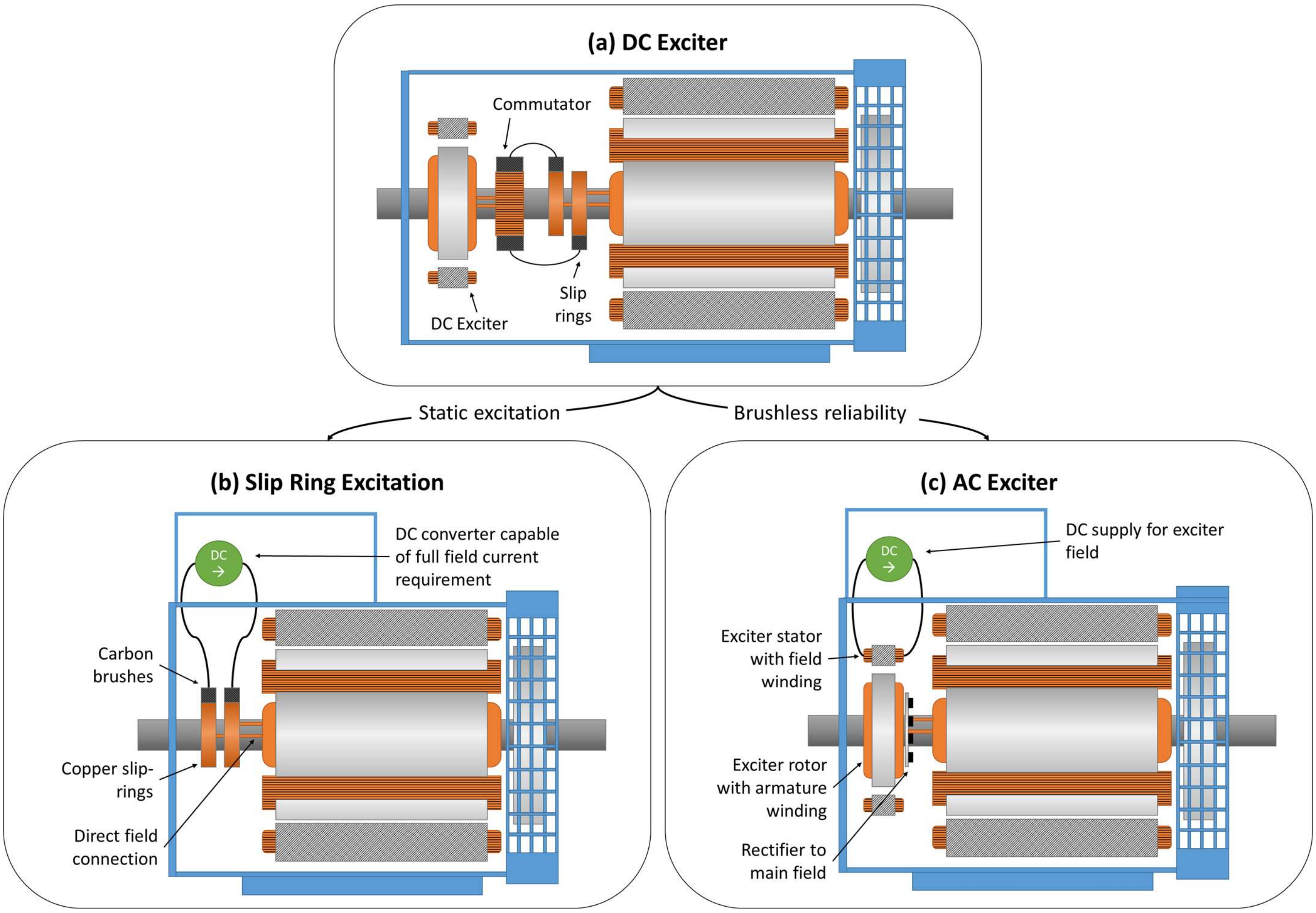

Fig. 2. Evolution of conventional excitation systems with main components of each, (a) direct coupled DC exciter, (b) static excitation through slip rings, and (c) the brushless AC exciter.

III. The Exciterless Synchronous Machine

The most apparent solution to exciterless is integration of the AC exciter windings within the main machine magnetic circuit; yet this presents limitations in the form of increased magnetic loading, lack of a damper winding (fitted to improve harmonic and transient performance [5]–[7]), and greater winding complexity. Exciterless development has mainly focused on winding complexity, producing topologies that allow for the excitation and main machine currents to flow in the same windings. These simplifications, shown in Fig. 3, have been 'mixed and matched' producing many unique topologies.

These combined magnetic circuit exciterless methods can be categorized by their excitation scheme into three types:

1. DC field excitation methods, in which the stationary excitation field winding produces fixed magnetic poles.
2. Fundamental AC excitation methods, in which the stationary excitation field winding is energized with AC at the same frequency as the machine output.
3. Harmonic AC excitation methods, in which the excitation is derived from harmonics of the main machine output.

It should be noted that all the methods discussed below are demonstrated on low power machines, with only two greater than 3kVA. This raises questions around the scalability of these methods to higher power machines and their suitability to medium power applications.

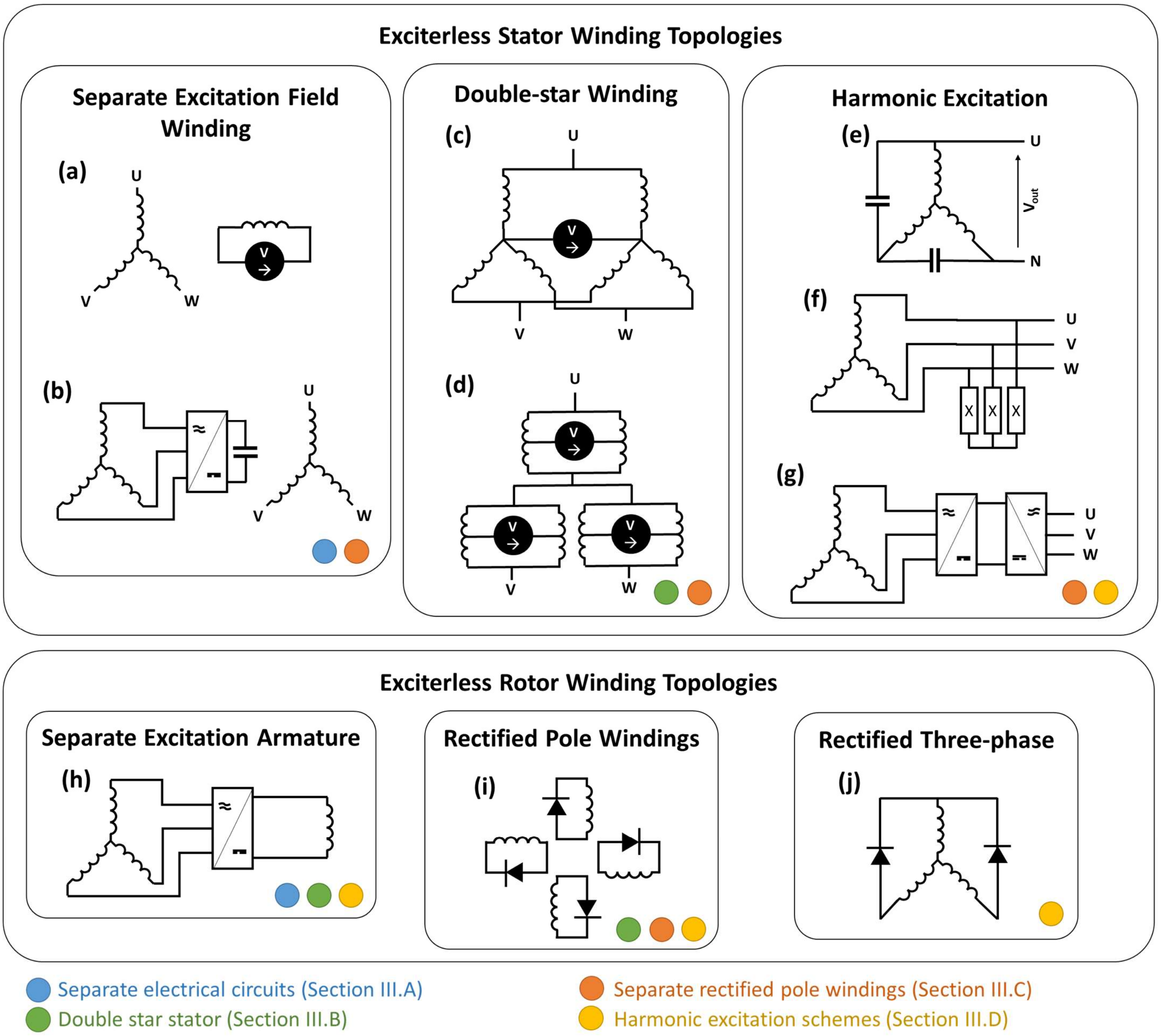

Fig. 3. Circuit diagrams of exciterless stator and rotor winding topologies. (a) additional stationary field winding [8], (b) converter controlled induction machine excitation [9], (c) double-star winding with excitation current injection between neutral points [10], (d) double-star winding with excitation current injection on phase center taps [11], (e) single phase harmonic excitation with capacitive loading for regulation [12], (f) harmonic excitation with reactive load for start-up and regulation [13], (g) harmonic excitation current injected using back-to-back converter [14], (h) round rotor method with additional armature winding [8], (i) salient pole method with pole windings individually rectified [15], (j) round rotor method with shorting diodes to produce DC field [14].

A. *Base method – separate electrical circuits*

Patents from the 1960s discuss replicating the AC exciter circuits within the main machine (see Fig. 3a and Fig. 3h), citing advantages in terms of reduced manufacturing cost and machine size [8], [16]. In general fitting additional rotor windings presents an issue for salient pole machines as they do not have the freedom of a slotted round rotor. Nonetheless a solution is presented in [17] for a single phase machine, in which the pole shoe contains a slot.

A recent take on this method is presented in [9], [18] in which the excitation magnetic circuit is an induction, rather than synchronous, machine. The rotor winding is that of Fig. 3h whereas the stator, shown in Fig. 3b, contains two separate 3-phase windings, one an induction machine armature connected to a converter, and the second the synchronous machine armature for the output. The converter control allows for self-excitation without the need for an external excitation power supply.

B. *Double-star stator – combined excitation and load circuit*

A double-star stator winding configuration was patented in the 1970s that allows both an AC excitation current and AC main output current to flow in a single winding [11]. This exciterless topology saw significant development by the patent author with publications throughout the 1980s, including an alternative structure in which the excitation current is supplied at the neutral point [10]. These topologies are shown in Fig. 3d and Fig. 3c respectively, and coupled with the rotor of Fig. 3h.

The winding is shown in [19], [20] to produce a higher output for a given excitation current when excited by a DC source. Additionally the configuration has been discussed as rotor winding simplification, though not implemented [20], although a single-phase rotor configuration is demonstrated in [21]. The method, with DC excitation between the neutral points as shown in Fig. 3c, is demonstrated on a salient pole machine utilizing the rotor winding topology of Section III.C, that of Fig. 3i, in [22]. This produces an exciterless machine with a very simple winding structure.

C. Separate Rectified Pole Windings

A rotor winding simplification for salient pole machines, is to fit a parallel rectifier diode to each pole, Fig. 3i. First shown in [15], followed by development through the 1980s and 1990s, this method relies on the significant mutual inductance between the pole windings to ensure that the pulsating pole current produces a constant air-gap flux. A single-phase machine is shown in [23] in which a freewheeling diode is placed in parallel with the stator field winding to reduce current ripple and improve excitation. The same concept is shown in [24] for a two-pole machine with both three- and single-phase configurations. The finite element analysis of the machine concept is detailed in [25]–[27]. The rotor topology is typically coupled with a DC excitation winding, Fig. 3a, but has been used with a harmonic excitation scheme in [28], similar to Fig. 3f but with the reactive load connected to an additional single-phase 6-pole winding. This demonstrates the versatility of this rotor winding method.

D. Harmonic Excitation Schemes

Harmonic excitation schemes were first shown on single-phase machines, Fig. 3e, where the negative sequence current produced by the load provides an excitation source, with capacitors to aid regulation [12]. Three-phase harmonic excitation schemes have been shown, typically using the dual rotor winding of Fig. 3h to allow the excitation pole number to match the harmonic frequency. The 5th harmonic has been utilized in [13], [29] with a reactive load (Fig. 3f), and DC excitation winding (Fig. 3a) respectively, both methods providing regulation. A form using the 2nd harmonic is first demonstrated in [30] using a capacitive load, this is moved to an additional winding in [31], and analytically modelled with core loss in [32]. Use of a converter to impose harmonics, Fig. 3g, is demonstrated in [14], [33] with a simplified round rotor structure, Fig. 3j. A similar ES for salient machines is proposed in [34] using the dual rotor winding of Fig. 3h with winding slots on the pole shoe to house the excitation armature.

E. Summary

Combined magnetic circuit methods demonstrate truly exciterless solutions for the WFSM. Many of the simplified winding structures are interchangeable, giving a range of unique topologies. Nonetheless, the machine designer faces many design challenges, particularly where established designs utilizing a conventional ES are the focus. Reduction of performance, due to removal of the damper cage, and potential drops in power density, due to magnetic loading, are hard to justify to existing customers. Restrictions in winding design place further constraints and require a significant development effort to implement across an existing portfolio. The methods presented are summarized in Table I, and whilst the construction complexity is minimized, this is at the expense of design flexibility and performance. To minimize business risk, and leverage current designs, an exciterless method is required that does not impact the main machine design.

TABLE I
KEY CHARACTERISTICS SUMMARY OF VARIOUS EXCITERLESS METHODS

Method → / Metric ↓	AC exciter machine (baseline)	Separate electrical circuits	Double-star stator, rectified pole rotor	Harmonic excitation with converter
Construction Complexity	0	+	+ + +	+ +
Design Flexibility	0	-	- - -	-
Cost	0	+	+	- -
Performance	0	- -	- -	-

IV. WIRELESS POWER TRANSFER EXCITATION

Wireless power transfer (WPT) has been a focus of recent research for many application areas and WFSM excitation is no exception [35]. Both inductive WPT and capacitive WPT have been demonstrated, most often applied to traction machines where reliability and power density are significant requirements, and conventional ESs are unsuitable. These basic topologies are shown in Fig. 4. A detailed review of both inductive and capacitive systems for small gap applications, i.e. those similar to a WFSM ES, has been presented in [36]. This work shows that systems requiring power greater than 1 kW, and those with a primary/secondary gap greater than 1mm favors inductive power transfer.

Not relying on a combined magnetic circuit, a WPT ES allows freedom in the main machine design, in contrast with the methods discussed in Section III, and importantly features such as the damper cage can remain. The implementations shown are more compact that the AC exciter and maintain the brushless benefits. However, these methods present new limitations that must be considered by the designer. Both WPT topologies require relatively high operating frequencies which influences both the materials used and the types of switching devices in the control system. These are key considerations for traditional applications where low cost must be maintained.

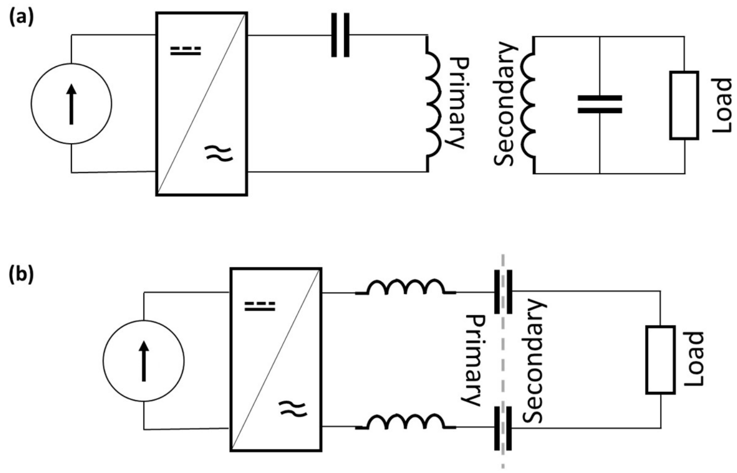

Fig. 4. WPT circuit topologies: (a) inductive with series-parallel compensation network, (b) capacitive.

A. Inductive WPT Excitation

An inductive WPT ES is, in essence, a rotating transformer, with reactive load compensation when operated at the resonant frequency. Non-compensated ESs have also been demonstrated such as a 50Hz slip ring replacement system in [37], a compact 20kHz design for traction machines in [38], and a similar 20kHz system proposed for a 75MW hydro-generator [39]. Compensated inductive WPT ESs include a 40kW traction machine, demonstrated in a series of papers [40]–[42], followed by a 60kW machine in [43]. At the higher power range a 12kW ES is proposed in [44]. These works have shown that not only is inductive WPT a viable method it also scales well up the power range.

B. Capacitive WPT Excitation

Capacitive WPT ESs have been developed over a series of papers starting with [45], in which a parallel disc capacitor arrangement is used to excite a 1.5kW machine. A similar stacked plate arrangement for an 80kW traction machine is shown in [46], followed by using printed circuit boards as the capacitive coupling in [47] for a 30kW generator. Alternative coupling arrangements using fluid bearings [48] and journal bearings [49] have also be demonstrated. Whilst successful, capacitive methods require tight tolerances and operate at high resonant frequencies.

C. Summary

Both WPT topologies have been shown as valid ESs for the WFSM, with traction machine applications of key interest, driven by demand for alternatives to permanent magnet machines. A summary of the key characteristics of each method, against the AC exciter, is provided in Table II. There remain viability challenges in traditional power generation applications. Most notable of which is ensuring low manufacturing cost both from the materials used, ancillary components (such as power converters), and manufacturing methods. In addition, there remains the opportunity of further integration to produce an ES with the desired exciterless benefits.

TABLE II
KEY CHARACTERISTICS SUMMARY OF WPT EXCITATION METHODS

Method → / Metric ↓	AC exciter machine (baseline)	Rotating Transformer	Inductive WPT	Capacitive WPT
Construction Complexity	0	+	+	+
Converter Requirements	0	++	++	+++
Design Tolerance	0	0	+	-
Power Range	0	0	-	- -

V. Future of WFSM Excitation

The WFSM exists over such a significant power range that there will never be a perfect singular solution for excitation. For classical medium power generator applications, the AC exciter is the only viable option, shown by its current and long-term dominance in this area.

A. The problem

Commercial development of the classical WFSM, as used in applications such as continuous islanded power generation, grid support, and backup generation, has stagnated with products only receiving minor design changes for decades. Manufacturers have instead maintained a competitive edge through cost-reduction rather than product development. This manufacturing optimization has led to a highly integrated product range where changes to a design can represent significant cost and business risk, including long recertification processes requiring multiple prototype machines [50]. Considering this, manufacturers are understandably reluctant to invest in development, particularly where market competition is tight. In short, a step advancement is needed to reinvigorate and kick-start development in this field at an industrial level.

Exciterless remains the 'Holy Grail' to provide this step improvement in product performance, but only if it can be achieved without modification of the existing main machine design, thus ensuring an acceptable development cost and meeting additional challenges arising from strict power quality and transient performance requirements. As this work has shown, existing exciterless solutions have yet been unable to achieve this.

B. The solution

WPT has been shown to be an effective ES that can be implemented without change to the machine design. The remaining challenges are to: 1) integrate the WPT system to produce an exciterless machine, and 2) reduce the manufacturing cost so that it is competitive against the brushless exciter. The classical air-cooled generator presents an opportunity to the designer to achieve an exciterless machine by integrating the WPT system within the fan and its housing. As the largest rotating component, the fan allows large coils to maximize coupling. This arrangement, shown by the rendering of Fig. 5, can be further reduced in manufacturing cost by utilizing an air-cored system, rather than ferrite. Economies of scale can also be maintained by sizing the ES against the largest machine in the product range, as the fan and housing is typically shared. Finally converter demands and cost can be reduced by targeting low resonant frequencies in the design.

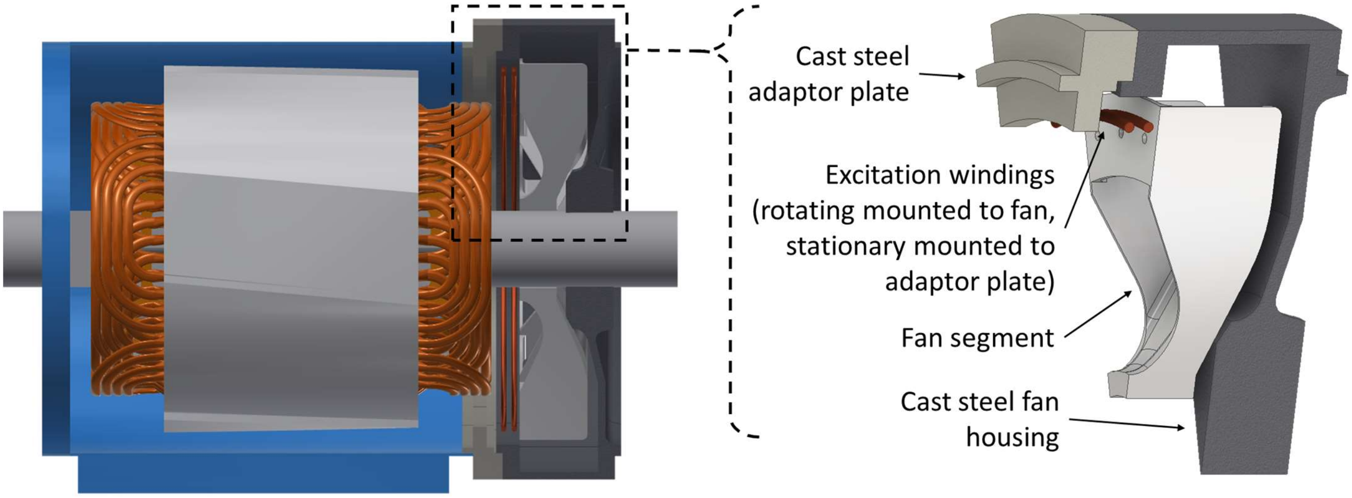

Fig. 5. Rendering of an inductive WPT ES that integrates with the existing fan and housing.

VI. Conclusion

The WFSM ES has had a long development yet only a handful of topologies are in use today, as shown in Fig. 6. Whilst many exciterless topologies have been developed over the past 60 years these have failed to gain wide-spread use against the AC exciter. Fortunately, new WPT ESs have been demonstrated which, through creative use of the existing machine components, could provide the promised benefits of exciterless without significant compromise or costly redesign of the main machine. There are still challenges to overcome, but for the medium power generator market, hope is on the horizon.

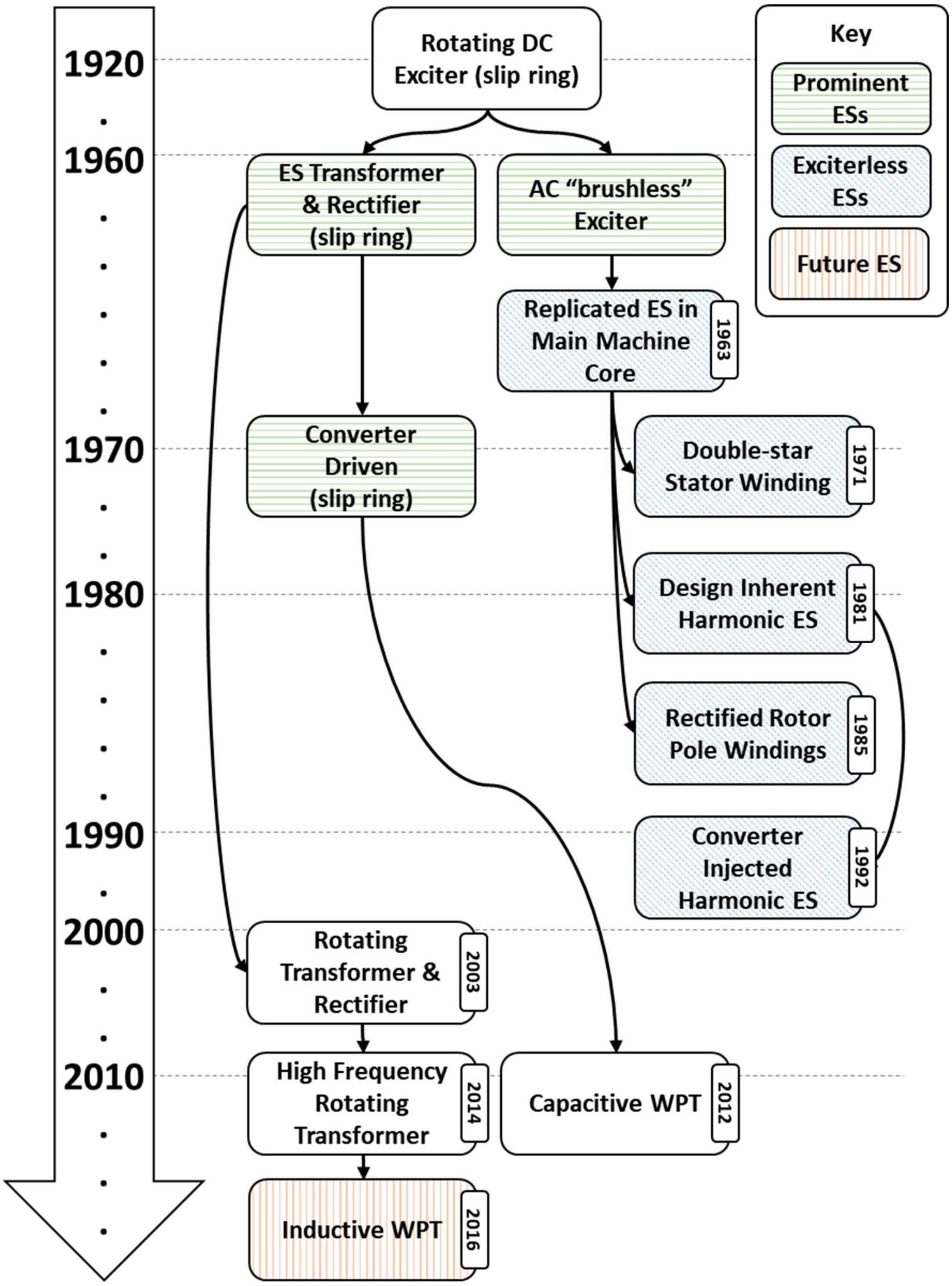

Fig. 6. Evolution of the synchronous generator ES over the past century, highlighting the prominent methods of today, the discussed exciterless methods (including the year first presented in the literature), and the future.

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