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TOPICAL REVIEW

Power Amplifiers and Their Feedback Mechanisms for AMB–A Comprehensive Review

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ABSTRACT Active magnetic bearings (AMB) have gained significant attention in recent years due to their superior performance in various industrial applications. One crucial component of an AMB system is the discrete power amplifier, which plays a vital role in driving the magnetic coils and controlling the position and stability of the rotor. This article provides a comprehensive review of power amplifier technologies in combination with the H bridge converter and feedback sensing circuits used in AMB. In addition, it discusses the design considerations, operational principles, and performance metrics of power amplifiers. Finally, challenges and potential future directions in power amplifier technology for AMB along with conclusions are highlighted.

INDEX TERMS Active magnetic bearings, power amplifiers, sensing circuits, H bridge, raspberry PI, simulink.

I. INTRODUCTION

This section introduces AMB and their fundamental principles, setting the stage for comprehending the following literature review.

A. WORKING PRINCIPLE OF AMB

AMB have seen more than three decades of research and application, with ongoing efforts to improve their control systems [1]. These are a promising alternative to traditional mechanical bearings, offering advantages such as reduced friction, enhanced stability, and improved controllability [2]. Unlike conventional mechanical bearings that rely on physical contact between components, AMB employs electromagnetic forces to suspend and control the position of a rotor. Applications include annular suspension and pointing systems [3], non-contact gyros, high-speed compressors [4], diary industries, high precision [4], machine tools, blood pumps [5], [6], artificial heart pumps [7], [8], turbomolecular pumps [9], jet engines, bearing less motors [10], [11] etc. Initially, the rotor, which remains non-rotating, is elevated into the air by the AMB, effectively functioning as a pure bearing. Subsequently, the driving mechanism impels the rotor to achieve the desired operational speed. During the acceleration phase, the AMB serve as controllers, effectively dampening undesirable vibrations, particularly those arising during resonant frequencies and unstable states. As the transient phase ensues and the rundown occurs, the rotor meets touchdown bearings [1].

It's important to note that AMB can exclusively generate attractive forces. Consequently, a closed-loop controller, equipped with supplementary hardware components, becomes imperative to sustain stable operation. The principal benefits attributed to AMB encompass a wide range of advantages, such as the ability to attain high rotational speeds, adjust the rotor's dynamic characteristics, eliminate wear and the need for lubrication systems, exhibit low energy losses, operate effectively across a broad temperature spectrum, consume less power compared to fluid film and rolling element bearings, and offer electronic control [2], [3].

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A schematic representation delineating the constituents of AMB, and their operational principle is shown in Fig. 1. The configuration of a magnetic bearing system revolves around four fundamental elements: the magnetic actuator, controller, power amplifier, and shaft position (proximity) sensor. The proximity sensor, devoid of physical contact, transmits measurement signals to the controller upon detecting alterations in the rotor's position.

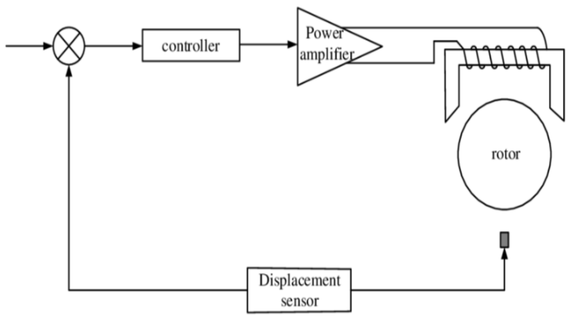

FIGURE 1. Working principle of AMB–rotor system.

Subsequently, the controller issues corrective signals to the power amplifier, which, in turn, delivers precise current adjustments to the coils within the electromagnets. The electromagnets generate a magnetic flux that draws the rotor back to its equilibrium position. This dynamic process transpires in real-time, thereby facilitating the levitation of the rotor during its operational phase.

B. AMB ACTUATORS

An AMB stator typically consists of two opposing electric coils, though four coils are common for radial bearings [4]. Load capacity equations can be found in a prior study [5]. Radial AMB can be categorized into homopolar and heteropolar configurations. Homopolar setups have stator poles with the same polarity, reducing eddy currents and eliminating the need for a laminated collar. Heteropolar configurations use varying stator pole polarities, necessitating laminated collars to mitigate losses [8]. Double-acting magnetic thrust bearings apply axial forces in both directions and are used in vertical centrifugal pumps. Combined radial and axial AMB provide comprehensive rotor control [11], [12].

C. HARDWARE CONTROLLER

The rotor's position signal undergoes analog-to-digital conversion before reaching the plant controller, then is transformed back to analog using a digital-to-analog converter. A high sample rate is used, and a low-pass filter counters electrical noise. Notch filters [18] suppress high-frequency resonances beyond the system's bandwidth. The final step involves sending the analog signal to power amplifiers.

D. AMB CONTROL LAW

AMB require feedback control to stabilize rotor levitation. This control employs position sensors to adjust the rotor's position by applying opposing currents to magnet poles, ensuring stability [1]. Various control laws are explored in the literature, with PID control commonly used but limited at high speeds and in the presence of gyroscopic effects. Complex Multi-input multi-output (MIMO) adaptive controllers like m-synthesis and H infinity controllers excel in high-speed AMB setups [7], [19], [20], [21].

E. POWER AMPLIFIERS

Power amplifiers play a crucial role in supplying current to the electromagnets, which generate the necessary magnetic field for controlling the rotor. They serve as key components in converting low-level control signals into high-power currents required to activate the magnetic coils effectively. In the context of AMB applications, each bearing axis typically employs a pair of power amplifiers. The primary function of these power amplifiers is to ensure precise control over the magnetic field generated by the AMB system. This precision control is achieved by modulating both the amplitude and frequency of the electrical current flowing through the magnetic coils. By doing so, the power amplifiers enable accurate positioning and stability control of the rotor. These amplifiers operate as high-voltage switches, utilizing transistors that rapidly switch on and off at high frequencies to convey positive and negative voltage levels. This switching action is guided by the pulse-width modulation (PWM) wave signal originating from the controller [34]. Notably, in recent times, switching power amplifiers have replaced traditional analog power amplifiers due to their enhanced performance [35].

F. SENSORS

Eddy current proximity probes, commonly used in AMB applications, induce eddy currents in the rotor's conductive material through an electromagnet's magnetic field. These currents create a counteractive magnetic field, altering the coil's impedance when the rotor-probe distance changes. Eddy current sensors offer a good frequency response, near-linear characteristics, minimal phase shift, and resistance to external interference over a wide frequency range (up to 2 mm displacement). Other non-contact displacement sensors include capacitive, inductive, magnetic, optical, and laser variants [7], [34]. Hall sensors, solid-state devices, produce voltage changes proportional to magnetic field density and measure magnetic flux on pole surfaces in AMB systems. In a study [37], hall sensors were integrated into pole structures for force estimation investigations. Authors in [12] examined the impact of solenoid actuator coils' magnetic fields on eddy-current sensors measuring shaft position, finding no significant influence from the support structure.

G. TOUCH-DOWN BEARINGS

In order to guarantee the protection of AMB components in situations like power failures or AMB load saturation, supplementary rolling element bearings are strategically placed at around half the AMB air gap. It is crucial to emphasize that these bearings remain unconnected to the rotor during standard operation to prevent any frictional issues at exceptionally high RPM.

II. RECENT PROGRESS ON POWER AMPLIFIERS

System faults [2] in AMB can be broadly classified as either internal or external to the magnetic bearing control system. External faults are rotor impact by hitting with foreign particles like solid matter, rotor mass loss (load unbalance), motion of system base (foundation looseness), rotor deformation, sudden changes in loading, bent rotor. Internal faults are mainly due to power amplifier failure or malfunction, sensor failure, loss of I/O board channel, controller failure, computer hardware failures [12], [13]. Thus, the power amplifier is a critical element that enables precise control of the electromagnetic forces in an AMB system [14]. Various research studies have been conducted to explore and improve their performance [15]. The nonlinear relationship between the input voltage and output current in an inductive load such as the electromagnetic actuators of AMB [16] is shown in Fig.2., Hence crucial design of SPA with feedback is necessary.

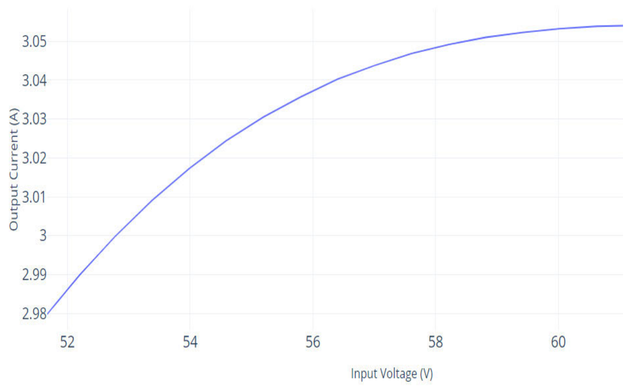

FIGURE 2. Nonlinear relationship between the input voltage and output current in electromagnetic coils of AMB [23].

Initially, linear power amplifiers were used in AMB [5]. However, they consumed a significant amount of power due to their operation in the linear region, leading to the adoption of switching power amplifiers (SPA) as replacements [15]. First digital implementation of magnetic levitation was by [17] focuses on a digitally based control system for magnetically suspended objects, requiring a fast microprocessor capable of rapid multiplication and addition. The Texas Instruments TMS32010 digital signal processor was chosen for its optimized instruction set.

Researchers in [18] investigated the factors influencing the inherent current ripple in SPA, while a dual-mode power drive hybrid power amplifier was designed in [4] to simultaneously reduce current ripple and enhance the current response rate, considering both transient and steady states in the AMB system. In [19], authors proposed a current predictive control method based on proportional-differential current-sensing resistor networks, which improved current tracking accuracy and reduced current ripple in SPA. The design of PWM circuit using a 555 timer and operational amplifier has been simulated in MULTISIM and PSIM. This PWM circuit is intended for controlling the power amplifier [20]. A SPA which utilized an integrated PWM known as SA60 was invented in [21]. The IC controlled the switching in a cost-effective way. SPA with bias voltage source was designed by [22]. It was used to power AMB coils of sensor less AMB. The bias voltage was provided simultaneously by a special internal circuitry.

Researchers in [23] used a digital signal processor (DSP)-controller for the digital control, with the power amplifier utilizing 3-phase IGBT modules. In [24], a 3-phase switching converter with IGBTs for radial AMB by recognizing the possible advantages such as 3-phase converters are extensively employed in large numbers for electrical drives, and their cost is exceptionally affordable. Consequently, the conversion of a 3-phase servo amplifier into a magnetic bearing controller is readily achievable by a straightforward software replacement and then the problem of cross coupling and non-linearity was addressed in this work. Dynamic performance limitations of space vector PWM were researched by [25]. The reference voltage is usually calculated by PID controller [26]. However, the PID parameters are difficult to adjust and need very complex control algorithm which tend to increase complexity of the SPA [27].

A reduced switch converter for AMB was designed by [14], reducing the number of components and analyzing the modulation method and control strategy. They proposed a shared-bridge drive with reversed direction, and designed a SPA with a redundant structure for multi-axis drive requirements. A 5-phase six-leg topology SPA for a five-degree-of-freedom (DOF) AMB system was designed by [28] and introduced the one-cycle current control algorithm, effectively reducing the output current ripple. In this approach, the duty cycle of the shared leg is optimized using finite control set model predictive control.

A 3 level SPA controlled by FPGA with low switching frequency on XC3S1000 was invented by [29], here 4-channel current and PWM modulation were carried out by the single chip to signal the H bridge. Current sensing for feedback was carried out by a hall effect based linear current sensor.

Evaluation of various topologies was carried out in [30] and guidance was offered on selecting the topologies based on different coil pair arrangements and bias current distributions. The work also compares both traditional and novel SPA topologies, providing a comprehensive comparison of three topologies: half bridge, 3-phase-half-bridge, and neutralized-sharing-bridge designs. This evaluation provides valuable theoretical guidance for selecting and designing SPA for AMB in various scenarios.

In [31], the authors proposed the design, and testing a 2-level PWM SPA for AMB with internal current control loop. The amplifier can operate in either voltage-controlled or current-controlled mode. The measured characteristics of the amplifier, including static input-output characteristic, frequency response, and current harmonic distortion.

In [32], the advantages of using standard industrial components for controlling AMB were discussed. These components offer several benefits, including robustness, availability, reliability, safety, security, traceability, certification, handling, universality, lower cost, and shorter down time of machinery [15].

A novel technique was implemented in [33], for powering the axial AMB in a bearing less permanent magnet synchronous motor, eliminating the need for a 4-quadrant chopper. An AMB system incorporating a low-cost chopper type SPA was utilized in [34] to actuate distinctive two-coil I-type structure that has been specially designed to ensure sufficient attractive force for rotor levitation while maintaining a stable position. To reduce costs, a single-switch power amplifier has been implemented. This I type coil is much more efficient than E or U type solenoid actuator since leakage flux is minimized.

The study in [35] addresses remote condition monitoring of AMB using off-the-shelf IoT hardware and custom software in SPA. Simplified wirings for internal circuitry in SPA have been patented by [36]. Research work in [37] performed a coupled simulation of buck amplifier with AMB coils by using Simplorer and ANSYS Maxwell. The effect of large separation between load and source for PWM transmission, then dynamic termination circuit [38] would be needed and transmission line theory needs to be studied. A method to encounter challenges related to total harmonic distortion (THD) limits was suggested by [16]. To address these issues, the remodified approach adopts a closed-loop PI controller with unipolar PWM and a LC filter in output, which reduces THD in the output, increasing stability, and minimizing mechanical vibrations. A 3-phase inverter for 3 stage winding supply to coils of AMB was suggested in [39] and [40]. The Spanish scholars used 3-phase matrix convertor to drive the 3-phase stator windings or electromagnets [41]. For three-pole magnetic bearings, authors in [42] and [43] used two full-bridge power amplifiers to drive bipolar windings. To solve the 3-phase asymmetry problems in 3-phase inverter, authors in [44] proposed 3-phase four-leg topology. Moreover, a five-leg inverter was employed to drive the multi-phase motor which is also an inductive load like solenoid actuators of AMB [45]. Servo amplifiers were used in [5] and [53] for active suspension control like that in AMB technology, which make use of SPA technology internally for controlling the system.

Flywheel electromagnetic suspension system was controlled by a single FPGA chip in SPACE environment by using Linux RTAI (Fig. 3) [46]. This control strategy used microcontroller based RTOS for control loop in SPA, like that of AMB technology.

RTOS was used for controlling the AMB in [47], yet more work is needed to make this technology more reliable. The experimental work had one motor to provide rotation to vertical shaft, of which the other end was supported through AMB. Fig. 4 shows the control process using RTOS on ATmega 338P.

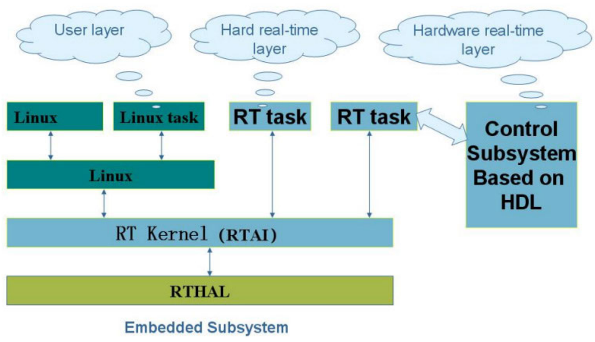

FIGURE 3. Linux RTAI for controlling SPA in flywheel electromagnetic suspension system.

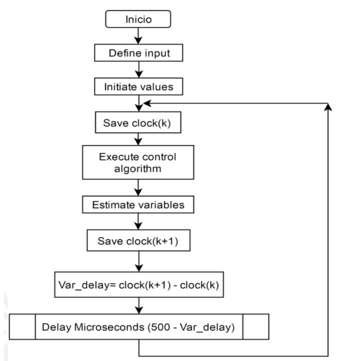

FIGURE 4. Control process using RTOS on ATmega 338P.

Recent development in internet of things (IoT) has led to widespread implementation of remote and intelligent data monitoring and control systems for using SPA in AMB industries [35], [48]. Therefore, looking into the capabilities of system on chip (SoC) systems, the Raspberry Pi may be used for control of AMB, hence making the AMB technology affordable and open source, like work done by [49]. Authors in [50] and [51] used open-source Arduino as I/O board to send signals to servo amplifier cards with LabVIEW to successfully control AMB. It involves taking feedback for current from the servo SPA for close loop feedback control and outer position feedback using eddy current position sensors. The outer loop controller used computational resources from the PC that was running LabVIEW in real time. Even real time MATLAB/Simulink [52] interfaced with Arduino can be a convenient option.

III. OPERATIONAL PRINCIPLES OF POWER AMPLIFIERS

The operational principles of power amplifiers used in AMB are explored in this section. Different amplifier topologies, such as linear, switching, and hybrid configurations, are discussed. Switching amplifiers, also known as Class D amplifiers, have gained popularity in recent years due to their high efficiency and improved power handling capabilities compared to linear amplifiers. These amplifiers function by swiftly toggling the power supply voltage, creating a PWM output waveform. The amplified signal is reconstructed through low pass filtering of the PWM waveform. PWM signals are boosted via power amplifiers and are utilized in electronic control systems requiring high-power signals for motor or actuator operation. They take input from micro-controller systems, controllers, or sensors, amplify it, and transmit the enhanced signal to electromagnetic actuators. The advantages and limitations of each topology are examined in terms of linearity, efficiency, distortion, and power dissipation [53]. It explores various amplifier topologies, their advantages, limitations, and their impact on the overall performance of AMB system.

A. LINEAR AMPLIFIERS

Linear amplifiers as shown in Fig. 5, are a common choice for power amplification in AMB due to their excellent linearity and low harmonic distortion characteristics [54]. These amplifiers operate in the linear region of their transfer characteristics, where the output voltage is a linear function of the input voltage. They provide precise control over the magnetic forces and allow for accurate positioning of the rotor. They usually use two electronic OPA544 chips allows for push-pull power amplifier which is suitable for control of superimposed magnetic field model, and large amplitude for load current output can be achieved [55].

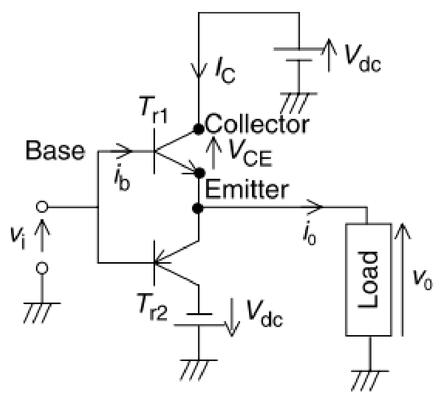

FIGURE 5. Schematic representation of linear power amplifier [10].

In a linear amplifier, active components like bipolar junction transistors (BJTs) or metal-oxide-semiconductor field-effect transistors (MOSFETs) are employed to enhance the amplitude of the input signal [56]. The key advantage of linear amplifiers is their ability to reproduce the input signal faithfully, minimizing distortion and allowing for precise control of the magnetic forces in AMB. However, they suffer from low efficiency and high-power dissipation, resulting in the generation of significant heat. Other categories of linear power amplifiers that amplify signals by acting as active resistors and dissipating power as heat to give output in line with the base input signal given to the active components are by using field effect transistors, JUGFET, IGFET [57]. These limitations faced by linear amplifiers have made industries like Waukesha, Calnetix Technologies, Keba etc. and researchers to move on to SPA. Since the development of power electronic switches with capabilities of high switching frequencies and DSP, FPGA which have high computational power [29], [58].

B. SWITCHING AMPLIFIERS

Initial comparisons of switching topologies were conducted by researcher in [59]. Later the different topologies were analyzed and simulated by authors in [30]. The basic concept of SPA relies on switching signal at very high frequency (up to 100kHz or more) called PWM. The average output voltage is linearly related to the percentage of duty cycle as shown in Fig. 6.

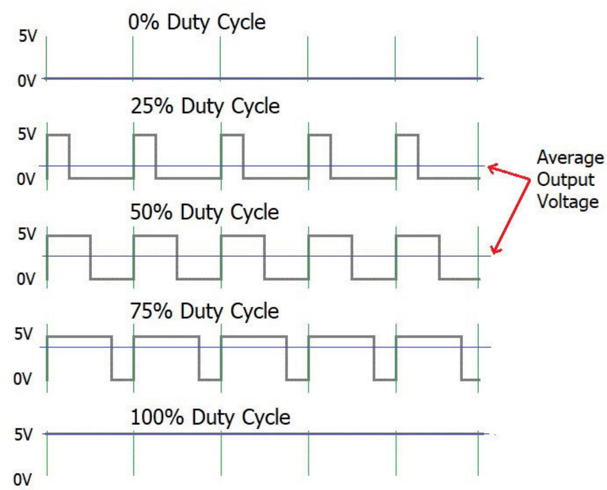

FIGURE 6. Relationship between average output voltage and percentage of duty cycle.

PWM is the best suited modulation technique for SPA of AMB. Here, a carrier signal is modulated by a reference triangular signal, resulting in the generation of pulses [60] [61]. Three level space vector PWM modulation techniques were also used in IGBT based SPA of Radial AMB [25]. The drive circuit is of utmost importance within the SPA system, with a special emphasis on the PWM modulator. Varied PWM modulation schemes, such as the two-level or three-level approaches, introduce alterations in the amplifier's traits. Implementing the PWM modulator can be achieved through two distinct methods namely, the hardware approach and the software approach. The hardware method employs a specialized PWM module like TL494 to generate the PWM wave. It can be integrated with the inner controller, inner feedback loop, and power main circuit as an independent SPA. This type of SPA does not require a computer and finds broader applications, but adjusting the PWM scheme is challenging. On the other hand, the software method relies on PWM outputs from devices like DSP. The PWM wave is generated using numerical methods by control loop. This approach allows for easy adjustment of the PWM scheme and simplifies the power amplifier's structure. Nonetheless, achieving this goal necessitates the meticulous design of internal feedback data, inner controllers, and position controllers within the computer system. This augmentation significantly enhances the intricacy of the AMB control system. As the software approach consumes computational CPU resources, it typically relies on high-speed DSP [38].

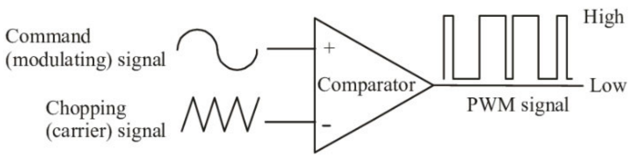

FIGURE 7. **PWM modulation using triangular wave and analogue input signal.**

A triangular wave serves as the carrier signal, while a sinusoidal wave acts as the reference signal in a modulation process that produces pulses of varying widths in each half cycle. These signals are combined in a comparator to achieve modulation. When the magnitude of the carrier signal exceeds that of the reference signal, the comparator generates a high output, resulting in the generation of output pulses. By adjusting the frequency of the carrier and reference signals, the number of pulses in each half cycle can be controlled, as illustrated in Fig. 7 [20]. There are 2 level and 3 level PWM switching techniques of which 3 level has lesser current ripple and hence more accurate, but the circuit is more complicated and expensive. Fig. 8 shows comparison of current ripple in output signals of 2 level and 3 level PWM modulation [62].

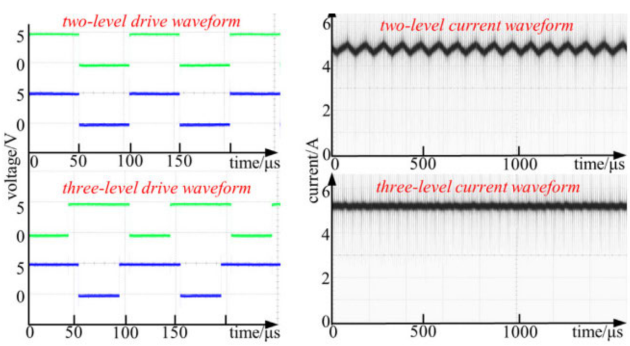

FIGURE 8. **Comparison of current ripple in output signals of 2 level and 3 level PWM modulation.**

C. SWITCHING TOPOLOGIES

1) MATRIX TYPE CONVERTER (MC)

Matrix type converter (Fig. 9) is modulated by selecting appropriate switching functions to achieve user or reference-defined output voltages and input currents [63], [64], [65], [66]. Various methods have been studied, including venturini (optimized), indirect, and scalar approaches. The foremost issue is the voltage transfer ratio constraint, which can reach a maximum of 86%. Directly connecting output

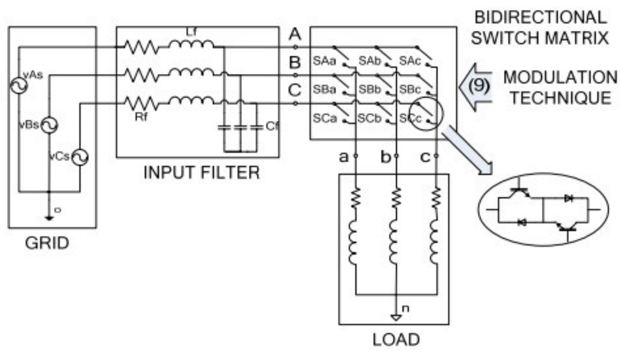

FIGURE 9. **Schematic of matrix type converter.**

to input amplifies sensitivity to grid distortions. Overcoming this, along with challenges like numerous semiconductor devices, complex modulation algorithms, and bidirectional switch commutation has seen significant advancements [41]. This study focuses on the direct space vector modulation (DSVM) technique. But even then, converters listed below in subsequent sections are simpler and cost effective than matrix type.

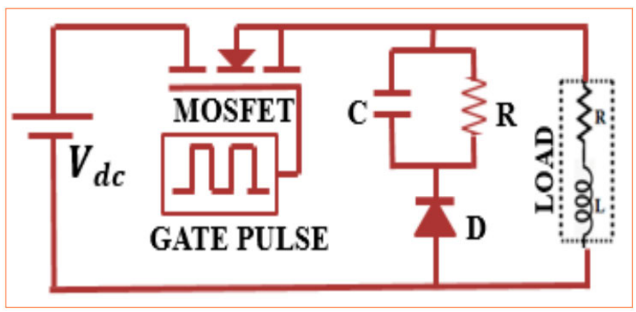

FIGURE 10. **Schematic of chopper type amplifier with charge dump circuit [34].**

2) CHOPPER TYPE AMPLIFIER WITH CHARGE DUMP CIRCUIT

The circuit diagram for a chopper type SPA is shown in Fig. 10. This circuit employs a MOSFET switch in conjunction with the fast-recovery power diode MUR460 for the chopping process. To enable the energy dumping function, a DC capacitor and a variable resistor are incorporated. Upon activation of the input, both voltage and current in the coil rise. The current passing through the coil during each switching cycle is directly proportional to the duration of the signal pulse being ON. Consequently, the energy dump capacitor undergoes a partial discharge through the rheostat while the signal is ON. When the switch is turned OFF, the fast-recovery power diode offers a path for the coil current to combine with the resistor and capacitor. This leads to an effective increase in voltage across the coil with a negative polarity.

Subsequently as shown in Fig. 11, when the coil voltage reverses, the coil current decreases, following a slope determined by the coil inductance and capacitor voltage.

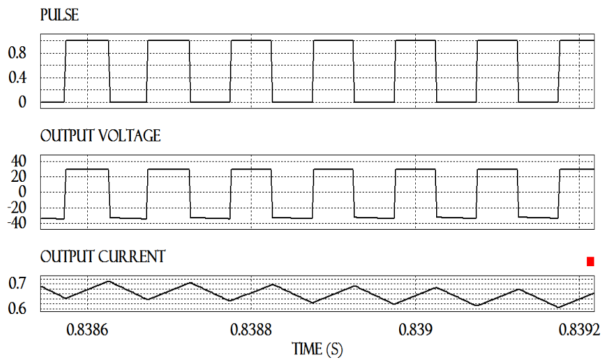

FIGURE 11. **PSIM simulation results of output characteristics of chopper type amplifier with charge dump circuit [67].**

3) FULL H-BRIDGE

It is a type of electronic circuit (Fig. 12) that allows the direction of current flow to be controlled and reversed through a load, typically solenoid coils or other actuators. The H-bridge consists of four switches labeled as S1, S2, S3, and S4. It also has solenoid coils connected between the outputs of S1/S2 and S3/S4 [19].

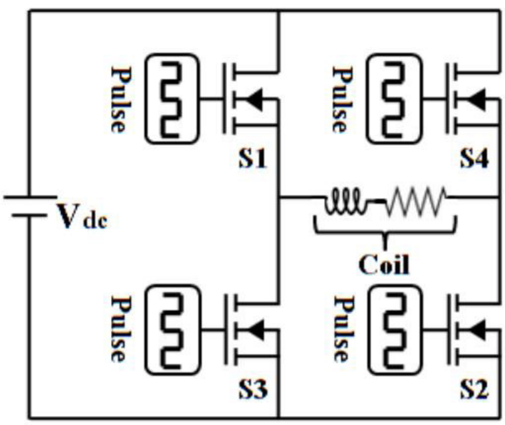

FIGURE 12. **Schematic of H Bridge converter [68].**

The axial DOF in the system can be limited in two ways. First, coupling can transmit motor torque, resulting in a four DOF AMB. Alternatively, axial DOF can be restricted using an axial thrust AMB, forming a five DOF AMB configuration. In a four DOF AMB, limiting four motion DOF requires an amplifier with a minimum of eight full-bridge circuits (Fig. 12.), necessitating 32 switches and their corresponding isolation drive circuits [30].

Properly modeling stray inductances in connecting wires is crucial for practical results closely matching simulations [59]. Switching power amplifiers typically employ two main power circuits i.e., semi-bridge type and full-bridge type. In AMB systems, the semi-bridge type is more commonly used due to its economic and straightforward design. Then there is 3-phase-half-bridge topology, neutralized-sharing-bridge topology.

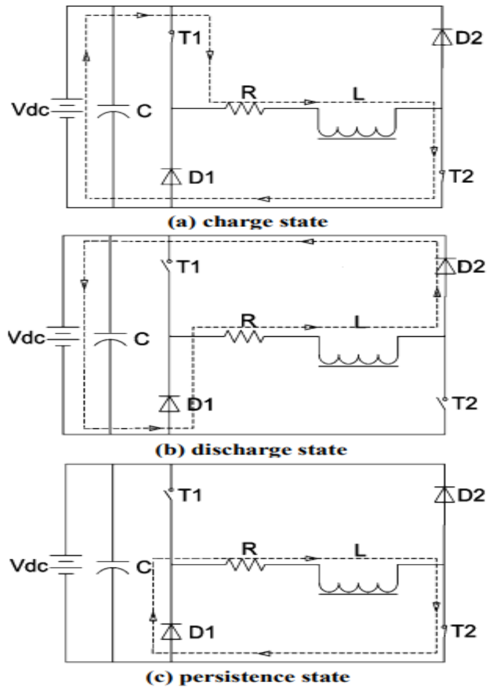

FIGURE 13. **Working states of H Bridge converter [31].**

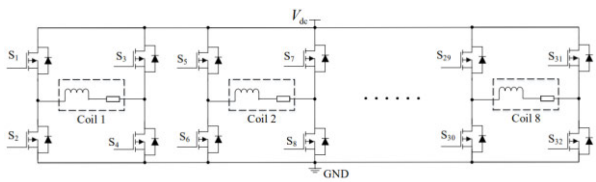

FIGURE 14. **Full H Bridge converter for 8 coils.**

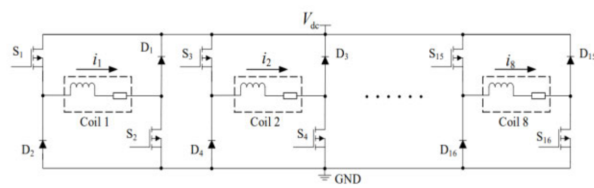

FIGURE 15. **Asymmetrical H Bridge for 8 coils.**

As per Fig. 13, the command voltage (Vc) is greater than 50% then charging of solenoid takes place (in state (a) and if Vc is less than 50% then discharging of solenoid happens (in state (b)). When Vc is zero then sustaining of energy in solenoid happens, the energy slowly dies out due to forward voltage drops in freewheeling diode and resistance of coil and on state resistance (Ron) of switching device (in state (c)). Minimum requirement of power amplifier for AMB in case of Full H Bridge with 32 Switches and 8 coils (Fig. 14) [30].

4) ASYMMETRICAL H BRIDGE

Minimum requirement of power amplifier for AMB in case of asymmetrical H Bridge with 16 Switches and 8 coils (Fig. 15) [30], suggesting that cost, simplicity, and size is halved [60].

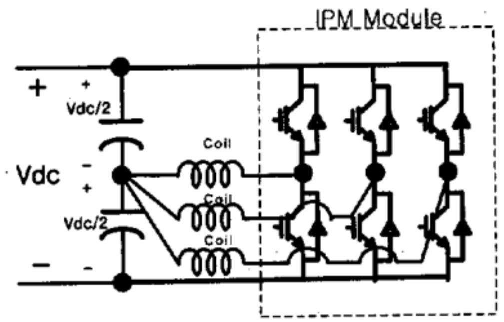

FIGURE 16. Schematic of asymmetrical H bridge with capacitors for 3 phase converters using IGBT [25].

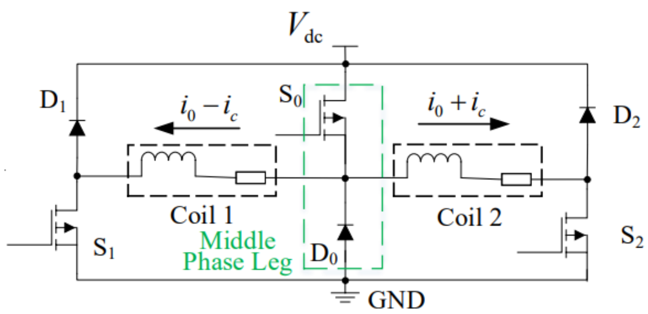

FIGURE 17. Schematic of 3-phase half bridge converter.

5) ASYMMETRICAL H BRIDGE WITH CAPACITORS

The variant amongst half bridge converter that can produce negative voltage, requiring 2 capacitors to provide stable currents when switching takes place due to PWM [20].

The two DC sources are constructed by dividing the DC link voltage using a pair of capacitors, as depicted in Fig. 16. The magnet coils are segregated into two distinct clusters, corresponding to these two DC sources. However, a notable challenge is to meticulously uphold the equilibrium between the two segments of the circuit. This equilibrium necessitates that the total currents in both halves of the circuits remain identical. In the configuration involving an AMB system with five axes, a total of four IGBT power modules (or seven power modules for a complete bridge setup) prove adequate. The two remaining half-bridge modules can be effectively utilized for maintaining equilibrium between the two circuit halves. It is important to note that utilization of a three-level PWM results in the emergence of substantial current harmonics.

6) THREE PHASE HALF BRIDGE CONVERTERS

Only 3 switches are required to effectively control the movement of a single DOF system as shown in Fig. 17. On the other hand, in a four-DOF AMB system, the number of switches increases to 12, resulting in a reduced component count. The upper switch located at the bridge's upper end is designed as a floating ground. Consequently, it necessitates a dedicated power supply. In contrast, the lower switches can share a common power supply. Theoretically, the positions of power diode and power switches can be exchanged. Specifically, switches S1 and S2 of the phase legs, located on both sides, are positioned at the lower end. Meanwhile, switch S0 of the middle phase leg is placed at the upper end to minimize the need for isolated power supply units. Furthermore, the middle phase leg serves both coils, thereby affecting its operational behavior due to its dual-coil association [30].

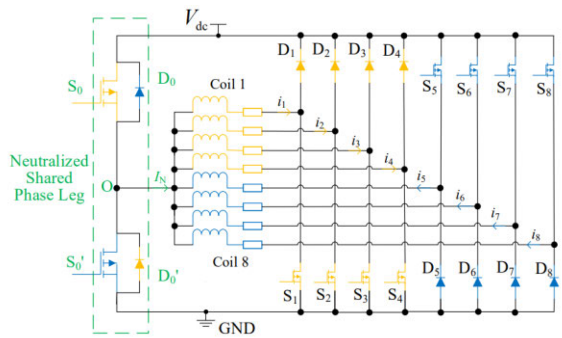

FIGURE 18. Schematic of neutralized sharing bridge converter for 8 coils of AMB.

There are two methods to control this circuit, coupling method and decoupling method of which coupling method increases computation and complexity. Hence, decoupling methods are industrially resorted [69]. The output performance of SPA is influenced by the continuous variation of average voltages on the coils within the range of -0.5Vdc to +0.5Vdc.

7) NEUTRALIZED SHARING BRIDGE CONVERTER

The coils can be categorized into two distinct groups: the initial set of coils (coil 1 to 4) carries current outward from point O, while the subsequent set (coil 5 to 8) channels current inward towards point O (Fig. 18). The current within the balanced shared phase leg is established as the discrepancy between the two group currents, as opposed to their summation, according to Kirchoffs law. For a comprehensive reduction of the current in the neutralized shared phase leg, a configuration is adopted where two coils governing a single axis are included within the same group [30]. This coil group entails two pairs of coils managing two DOF, and the resulting current, denoted as IN, within the neutralized shared phase leg is derived by deducting the bias current linked to the two coil groups. Furthermore, by ensuring that the bias current for each axis coil is uniformly designed, the IN current in the neutralized shared leg remains below the coil current and approaches near-zero values.

There is one more variant in this named Integrated sharing bridge, which suffers from heating problem that leads to lesser reliability of the SPA and loading is quite heavy on the components hence, neutralized sharing bridge is a good option. Detailed performance comparison is given by [30].

D. HYBRID AMPLIFIERS

Traditionally, analog drive circuits have held sway in the realm of AMB due to their inherent virtues of high linearity and minimal electromagnetic interference [54], [70]. However, a notable trade-off of analog drive circuits is their

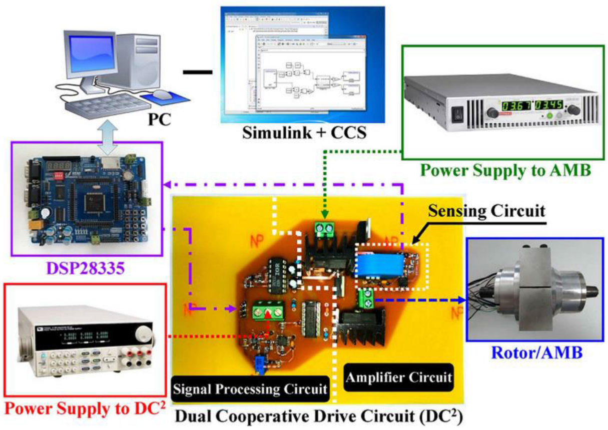

FIGURE 19. Overall schematic of hybrid spa with AMB [4].

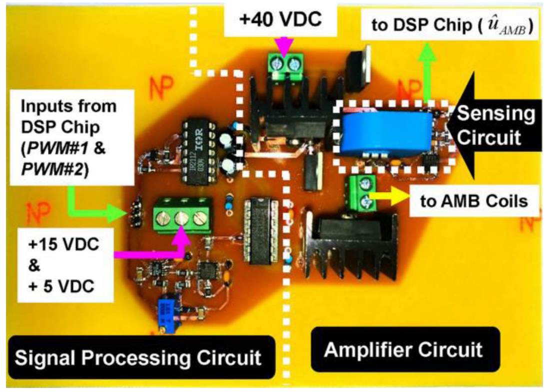

FIGURE 20. Hardware setup of hybrid amplifiers [4].

inherent energy inefficiency, resulting in a significant dissipation of energy as heat within the driver integrated circuits. Conversely, digital drive circuits exhibit comparatively lower power losses, which has spurred extensive research over decades to enhance their efficiency and performance [26], [29], [38], [67], [78], [79], [80]. A recurring challenge in digital drive circuits for AMB is the presence of pronounced current ripple [71], [72]. To mitigate this issue, the widely adopted recourse involves the implementation of a 3-level PWM scheme. Yet, the problem of current ripple remains more pronounced in digital drive circuits compared to their analogue counterparts. Recent times have witnessed the emergence of Switch-Linear Hybrid (SLH) power amplifiers (Fig. 19), which capitalize on the strengths of both analog and digital drive circuits [73], [74].

Hybrid SPA was run using PC and MATLAB/Simulink using a DSP chip with I/O by [4]. The circuit uses MOSFET in the saturation region as well as in linear region for switching amplification and linear amplification respectively. The 2-level PWM signal is passed through a Digital to Analog Converter (DAC) and then fed into the gate pin for use in linear region. If the circuit needs to be run in switching mode, then the PWM signals are fed directly into the gate of the MOSFET. Schmitt Trigger is used to detect timing change between switching and linear amplification. After conducting the experiments, it is shown that when compared to a conventional 2-level PWM modulator, the reduction in peak-to-peak current ripples amplitudes is notably enhanced, with an improvement of up to 62%.

These SLH power amplifiers typically amalgamate a linear power amplifier with a 2-level switching power supply. However, a critical consideration arises from the need for the switching frequency of the 2-level switching power supply to vastly surpass the tracking bandwidth of the SLH amplifier [75]. This prerequisite, while addressing high-frequency switching losses, introduces a conundrum due to the resulting switch-related losses [75]. In response, a proposal advocates the replacement of the 2-level switching power supply with a multilevel converter to augment the overall power efficiency of SLH power amplifiers.

Hybrid amplifiers (Fig. 20) combine the advantages of both linear and switching amplifiers to achieve a balance between linearity and efficiency [60], [70]. This approach effectively minimizes the number of switching components compared to the full bridge type, while simultaneously achieving superior current regulation performance. These amplifiers employ a linear amplifier for small signal amplification and a switching amplifier for large signal amplification. This approach allows for improved efficiency while maintaining good linearity and low distortion.

A novel concept that combines the benefits of a traditional analog power amplifier and a switching amplifier was introduced by [56]. The advantages of this new approach are demonstrated through numerical simulations and experimental measurements, highlighting its superiority over a standard switching amplifier.

In hybrid amplifiers, the input signal is split into two paths: a small-signal path and a large-signal path. The small-signal path is amplified using a linear amplifier, which provides accurate control of the rotor position and small perturbations. The large-signal path, responsible for generating significant driving forces, employs a switching amplifier for higher efficiency and power handling capabilities [4].

Hybrid amplifiers offer a compromise between the linearity of linear amplifiers and the efficiency of switching amplifiers [76]. They are well-suited for AMB where a wide dynamic range of forces is required, allowing for accurate control at low amplitudes and high efficiency at high amplitudes. Regrettably, the 'multilevel' approach demands a greater number of electronic components, potentially compromising the circuit's overall reliability. Furthermore, the heightened circuit complexity exacerbates challenges associated with time delays, thereby impacting the quality of rotor dynamic control.

More computational power is necessary and complexity of the power amplifier, cost is higher, size and weight of the PCB is bigger than SPA [60], [76]. Due to the combination of different amplifier types, hybrid amplifiers can generate

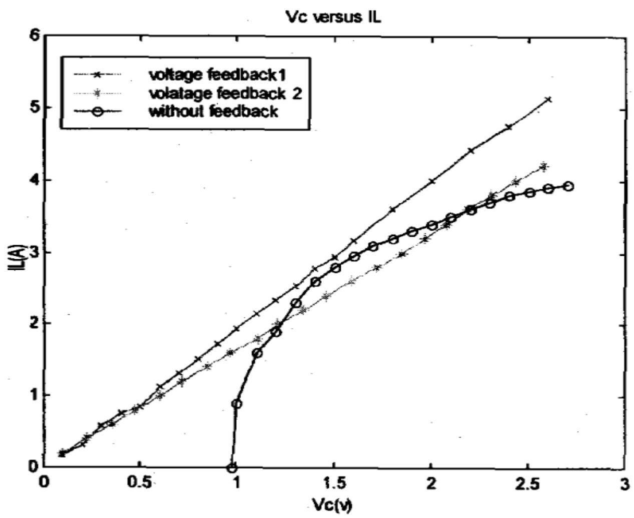

FIGURE 21. Graph of output characteristics comparison of high frequency isolation transformer vs optocoupler isolation gate driver with voltage feedback control in SPA.

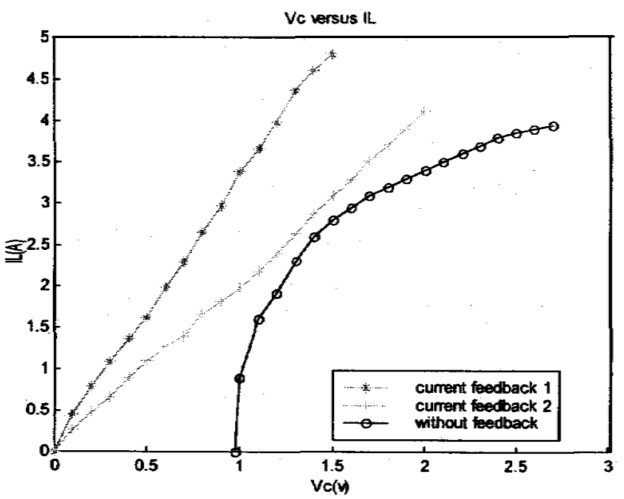

FIGURE 22. Graph of output characteristics comparison of high frequency isolation transformer vs optocoupler isolation gate driver with current feedback control in SPA.

more heat than single-type amplifiers. Effective heat dissipation becomes crucial to avoid overheating issues and ensure system reliability. The integration of different amplifier technologies introduces more components and points of failure, potentially reducing the overall reliability of the AMB. Limited standardization in hybrid amplifier configurations can vary significantly depending on the specific application and requirements, standardization might be challenging, making it more difficult to interchange or upgrade components in the system.

E. GATE DRIVE CIRCUITRY

There are few types for isolation in gate drivers like optocoupler driven and high frequency isolation transformer driven [77].

Here voltage feedback 1 is current response of SPA by using high frequency isolation transformer and voltage feedback 2 is by using optocoupler isolation gate driver in voltage negative feedback testing of Half H Bridge topology SPA (Fig. 21) [77].

In Fig. 22 current feedback 1 is current response of SPA by using high frequency isolation transformer and current feedback 2 is by using optocoupler isolation gate driver in voltage negative feedback testing of half H Bridge topology SPA [77]. Thus, we can see that high frequency isolation transformer has better response compared to optocoupler isolation gate driver, but the design is complex since magnetics are involved. Fault tolerant gate drive circuitry had been designed in [78] for SPA. Researchers employed Texas Instruments DRV8412 PWM H-bridge driver with a capacity to provide up to 3 A of continuous current and a peak current surge of 6 A, the DRV8412 driver facilitates the amplification of low-level PWM signals from a Piccolo controller up to 24 V [79]. Usually, Infineon IR2112 series are used which have in built bootstrap for driving high side MOSFETs in the H bridge of SPA.

F. LOGIC LEVELS AND OUTPUT VOLTAGE LEVELS

In flywheel energy storage a 48 V and 60 V logic level was used [80]. Few others have used 100 V and maximum up to 200 V for small and medium size AMB. For large scale applications 1000 V AMB is also used with specialized switching components and gate drives [10].

In the early development of AMB [31], linear analog power amplifiers were used due to their ease of implementation and control. Although they offered advantages such as less current ripple and noise, as well as greater bandwidth, they suffered from significant power losses and inefficiency, particularly at higher power ratings. To address these limitations, SPA was introduced, offering reduced power losses by operating at high voltage and high current levels only during short periodic intervals. 2-level and 3-level SPA are commonly used in AMB systems. The current ripple of the 2-level SPA depends on the DC supply voltage. While boosting the DC supply voltage can improve dynamic characteristics, it also increases the current ripple. In contrast, the 3-level PWM switching power amplifier proposed exhibits current ripple independence from the supply voltage and maintains smaller ripple levels compared to the 2-level PWM SPA. This feature allows for the enhancement of power amplifier dynamic characteristics through boosted DC supply voltage without sacrificing the benefits of reduced current ripple. The results are measured and compared with those of a standard 2-level PWM SPA. The findings support the superiority of the 3-level PWM SPA in terms of reduced current ripple, which can contribute to improved dynamic characteristics of the AMB system.

G. FEEDBACK MECHANISMS

The electrical signal obtained from the current sensor might require some conditioning before being fed into the

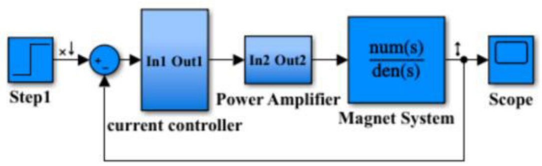

FIGURE 23. Overall schematic of feedback control in SPA [34].

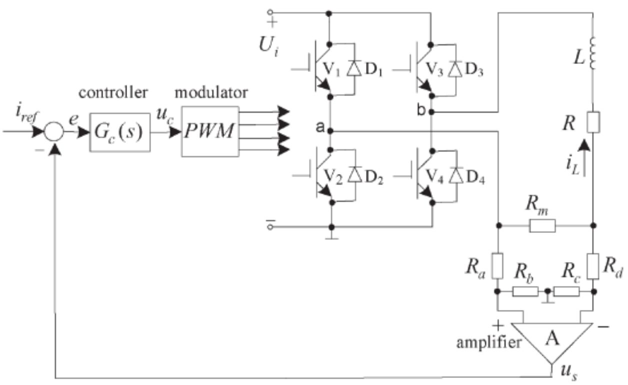

FIGURE 24. Current-sensing resistor method proposed by [19].

control circuitry. Signal conditioning ensures that the current measurement is accurate, stable, and compatible with the requirements of the control system and amplifier. Signal conditioning can involve several steps, such as amplification, filtering, analog to digital conversion. Once the current is measured and converted into a suitable form, it is fed back to the control circuitry of the SPA (Fig. 23). The control system uses this feedback information to adjust the duty cycle and frequency of the switching pulses to maintain the desired current and magnetic field strength for precise control of the shaft's position.

Ensuring precise current measurement is crucial for achieving the desired closed-loop performance of the current amplifier. The utilization of digital control in SPA for current tracking introduces inherent time delays, occurring simultaneously [21]. These delays primarily originate from the processes of AD conversion, DSP computation, and PWM generation. Each of these time delays introduces a phase shift in the control loop, leading to an inevitable degradation of the system's performance, resulting in slower response and reduced ability to reject current ripple and handle load disturbances or parameter variations [81]. This issue is particularly critical for magnetic bearings with high rotor speeds, large inductance, and strong gyro effects, where an excessively large phase shift can even jeopardize the stability of the closed-loop system [82], [83].

The existing approach for measuring the PWM carrier component was introduced in [84], while a model-based estimator with linearization was presented in [85]. To implement the system in real-time, it was necessary to calculate the relationship between harmonic current and the duty ratio of the modulator, as discussed in [84].

The current sensor design consisting of a current mirror and differential amplifier was used in [86] which was similar to applications of current sensing that was used in PWM drives for SRM motors which also use sample and hold techniques [87], it requires complex circuitry and all of them to work in proper sync [80].

A novel current-sensing resistor network was designed for incorporating current derivatives in PWM Half H-bridge unipolar SPA was introduced in [19] as shown in Fig. 24.

Researchers in [88] attempted to perform system order reduction by utilizing a controlled current source to excite the magnet coil. Many researchers have utilized voltage as the stimulating input for the magnet coil, leading to a third-order unstable system. In contrast [88], controlled current source is used to excite the magnet coil, resulting in a simpler second-order transfer function, albeit still unstable for the system.

Experimental validations in [18] showed deviations while taking current feedback from the circuit. Gain errors in detection circuit and quantization errors in ADC, noise and drift in analogue circuit was emphasized.

Simple Hall-effect current sensors are susceptible to drift [18]. In [89], presented a transformer-based current sensing circuit, and further developed it to ensure compatibility with digital control operations. While this method offers the advantage of isolation, enabling direct measurement of the actuator's DC current, it necessitates additional timing and control circuitry. Both aforementioned solutions have drawbacks in the context of AMB. Notably, they lack the ability to measure both positive and negative currents using the same setup or fixture. In [52] an equation (Eq. (1)) was used to find current from the pulsating voltages hence directly allowing it to be coupled to ADC of the microcontroller controlling the SPA.

$$i_{ADC} = \left[V_{ADC} - \left(\frac{R1 + R2}{R1} \right) V_O \right] \frac{R1}{R2} \frac{N}{R_S} \frac{1}{D} \qquad (1)$$

Research work in [80] utilized an instantaneous current measurement at specific intervals through a shunt resistor. During this process, an analog-to-digital converter is employed to convert the measurement signal into digital data, which is then fed back to the control device (Fig. 25). This method allows for a bipolar measurement, but it necessitates a differential amplifier with a high common-mode rejection ratio (CMRR) to accurately gauge the voltage drop.

The ABS stands for absolute value function because the ABS part of the demodulator [3] is nonlinear, it is difficult to precisely model how current is processed within the envelope detector. In this sensor less AMB setup the high-frequency current can be obtained from the sensed currents using a band pass filter (BPF). Additionally, the magnitude of the cosine term can be determined by filtering the product of the current and -2sinωt through a low pass filter (LPF) [90]. Moreover, it is essential to extract the fundamental current and employ it as feedback for the current controller. The resulting signal

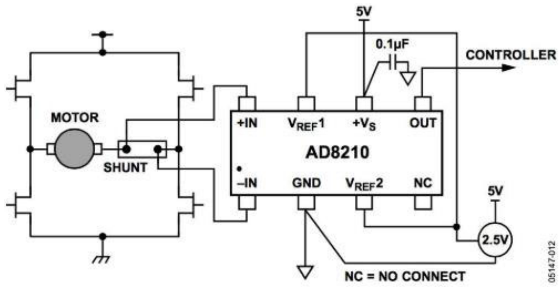

FIGURE 25. Current sensing op-amp with high CMRR used in SPA [80].

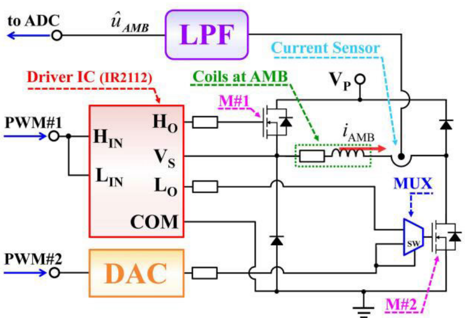

FIGURE 26. Current sensing after signal conditioning using LPF [4].

can be sent as control signal into the controller for controlling the output current of the SPA [90].

LPF filtering of output from half bridge or full H bridge is a common practice in Class D audio amplifiers. This technique was extended into AMB SPA like the filters used in pure sine wave inverters. The value of inductance kept in series with the load and capacitor in parallel with the load have some calculations to achieve smooth output. This output can be easily detected by current sensors and can be fed into the ADC for PI current control. Usually, they are used with sine wave inverters [91].

Recently a non-intrusive type of sensor was used to measure the current in the AMB coils, by passing the signal from the sensor through a LPF and then measuring it suitably after converting it from analog to digital in [4]. The signal voltage drops after passing from the LPF hence voltage level needs to be properly conditioned before sampling it in the ADC (Fig. 26). This work finally simplified the current sensing technique and is also utilized by inverters with feedback since it is simple to use and reliable.

Several types of current sensors can be employed, depending on the specific application and requirements. They are hall-effect sensors [92], current transformers [52], integrated circuit-based current monitors, shunt resistors [80]. Of these hall-effect sensors are widely used due to their non-intrusive design. Three types of current sensing techniques were used in PWM drives namely, low side sensing [93], high side sensing [94] and inline sensing [94]. Schematic in Fig. 27 shows the various current sensing techniques in SPA. Of these, inline

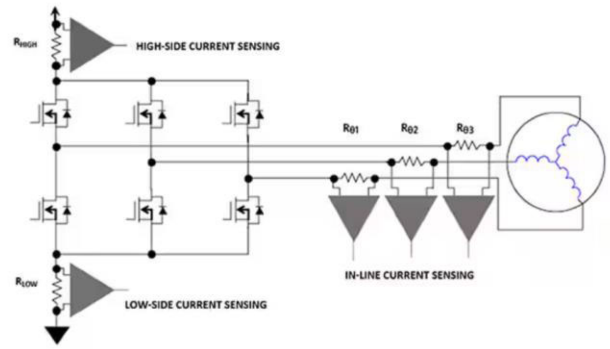

FIGURE 27. Different Sensing techniques in feedback [94].

sensing is a highly effective technique and frequently used in drives requiring high accuracy.

In SPA for AMB, current sensing is typically achieved using shunt resistors and current sensors. Current sensors are used to measure the voltage drop across the shunt resistors and convert it into an electrical signal that represents the current magnitude. Hall-effect sensors are commonly used in AMB due to their non-intrusive nature and isolation from the high-voltage switching circuitry. These sensors are usually built up from opams with high CMRR [57]. The current feedback usually consists of PWM noise called ripple hence, current cannot be directly measured [95], therefore demodulation [96] techniques are used to remove all the harmonics in the signal by using a BPF (8th order) firstly then superimposing another wave like sine or cosine after which its passed through a LPF (3rd order) [95].

In [4], a LPF was used to condition the signal from a hall effect sensor placed in-line sensing mode with the electromagnetic coil of AMB, then it was directly sent to controller via ADC. This simplified the technique used by [96] and also reduced the load on the LPF which was kept in- line with the load as in [91], hence reducing the cost and size of the SPA.

H. CONTROL TECHNIQUES

Three types of control strategies were used in SPA of AMB namely, voltage control, current control, flux control. In the voltage control mode, the voltage is the output variable, while in the current control mode output current from SPA is variable, and in the flux-controlled mode magnetic flux density is controlled. Of the these, flux control is very complicated hence voltage control and current control are usually used in SPA. The voltage-controlled mode provides accurate modeling, higher robustness, but the current control is even simpler and less complex.

Current negative feedback requires a lower driving voltage compared to voltage negative feedback, when considering the same conditions [77]. The optimal choice for a digital current control AMB is the synchronous three-level PWM scheme. By adopting this scheme, the benefits of voltage control AMB can be fully utilized in a digital current control setup, enhancing disturbance response, and reducing switching

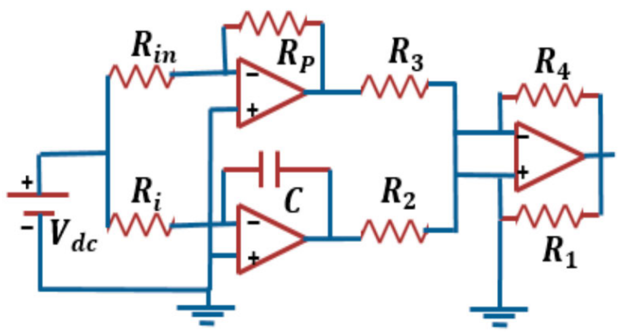

FIGURE 28. Analogue PID controller for current regulation in SPA [34].

frequency by about twenty times compared to asynchronous modes. This eliminates the need for specialized high-speed components and reduces current harmonics and eddy current losses for improved AMB performance [76]. Thus, combination of current and voltage control is superior, but circuit is more complex and can be used in very large plants [31]. The voltage-controlled mode provides accurate modeling, higher robustness, and ease of implementation. Accurately controlling the current needs accurate sensing of current in the coil. Thus, current sensor as suggested in [52] must be carefully selected. The current-controlled mode has a simpler setup as depicted in [88]. Typically, AMB systems use the current-controlled mode with high stiffness, neglecting the inner current loop dynamics. The proposed inner feedback loop for the SPA relies on current feedback. Sensors measure the coil current on the output side, compared with the reference current from the current controller. The resulting control signal is applied to power the AMB coils [97].

1) ANALOG CONTROLLER

The existing controller processes the signal by comparing the outputs of the position controller and the current sensor. It then generates feedback signals based on the controller's tuned parameters. The output of this controller dictates the current flowing through the electromagnet, which, in turn, generates magnetic force proportional to the current intensity. Typically, the PI controller (as shown in Fig. 28) is chosen for the role of the current controller. PI controllers are preferred by control system engineers due to their reputation for simplicity and robustness [88].

2) DIGITAL CURRENT FEEDBACK AND CONTROLLER

There are two types of digital control, which are linear control and nonlinear control. In linear control the output current is measured and then compared with the desired current reference [10], [62]. The resulting current error is then amplified using a controller block, which generates a corresponding voltage command. To ensure that the voltage command remains within the bounds of the PWM triangular carrier waveforms, a limiter block is employed. This controller amplifies the current error, limiting the output between −1 and 1, which corresponds to the amplitude of a PWM triangular waveform. This avoids operation at overmodulation [33]. The limiter output, or feedback voltage, is then compared with a PWM carrier triangular waveform operating usually at a frequency of 10 kHz. The resulting comparator output logic is used to control the main power-switching devices. The current error is amplified, and a voltage command is generated, which is limited by a limiter block. The current response is good for small step changes in the current command. However, for large step changes, the response can be improved by increasing the proportional gain and using a high-cut filter to remove high-frequency oscillations [20]. By employing PWM, it becomes feasible to eliminate a portion of the lower-order harmonics effectively, while also facilitating the straightforward filtration of higher-order harmonics. This process significantly enhances the quality of the output. With significantly increased proportional gain, the system approaches the nonlinear current control method. Overall, the linear current feedback method performs well with appropriate adjustments.

Nonlinear control in SPA is usually realized with a hysteresis controller as suggested by [10]. This is simpler than other controllers like delta modulation controller, sliding mode current controller, adaptive current controller, fuzzy logic current controller, neural network-based current controller, predictive current controller, resonant current controller etc.

The identified current is compared with the desired current setpoint to calculate the current deviation. This deviation is subsequently input into a hysteresis module, responsible for generating a binary control signal for the primary power-switching components. These components work in conjunction with a phase-locked loop to determine the optimal switching actions [98].

IV. PERFORMANCE CONSIDERATIONS

A. RESPONSE CHARACTERISTICS

After the simulations of all the different blocks of SPA, performance considerations [111] such as step, sinusoidal current and mutation have to be looked into.

The step response simulation demonstrates the system's rapid and stable reaction to sudden changes, indicating a well-designed control strategy and efficient dynamic performance. The sinusoidal current response analysis reveals the system's ability to accurately track and maintain a smooth sinusoidal waveform, showcasing its robustness in handling cyclic variations and maintaining desired currents. The mutation response simulation provides insight into the system's adaptability and resilience against unexpected perturbations, highlighting its potential to effectively handle dynamic mutations and ensure reliable operation in varying conditions. Techniques for calibration of SPA was used in [99], hence better performance of SPA can be achieved.

While selecting a power amplifier for an AMB system, it is essential to consider the desired linearity, efficiency, harmonic distortion, bandwidth, and transient response characteristics. The specific requirements of the AMB application and the trade-offs between different performance metrics will determine the most suitable power amplifier topology. Advances in power amplifier design, control algorithms, and filtering techniques continue to improve the performance of power amplifiers for AMB, enabling enhanced control, stability, and efficiency in these systems.

B. LINEARITY

Linearity refers to the ability of the power amplifier to accurately reproduce the input signal without introducing distortion or non-linearities. In AMB, precise control of the magnetic forces is crucial for accurate positioning of the rotor. A linear amplifier offers excellent linearity, faithfully reproducing the input signal and minimizing any deviations or distortions. This ensures precise control and stability of the rotor position. However, it should be noted that linear amplifiers may have limited efficiency compared to other amplifier topologies. Nonlinearities in the amplifier's response can result in harmonic distortion and affect the control performance of the AMB system.

C. POWER RATING REQUIREMENTS

The power rating of a power amplifier is a critical consideration in AMB systems. It depends on factors such as the size and weight of the rotor, the required magnetic forces, and the system's dynamic response. The power amplifier should be capable of delivering sufficient power to generate the required magnetic field strength while ensuring stability and control of the rotor [30].

D. SIZE AND INTEGRATION

The physical size and integration of the power amplifier should be considered, especially in applications with limited space or weight restrictions. Compact and lightweight amplifier designs facilitate easy integration into the overall AMB system without compromising performance or reliability [30].

E. EFFICIENCY

Two types of losses such as static (forward voltage drop) and dynamic (switching devices don't start or stop conducting instantaneously when turned on or off [77]) determines the efficiency in SPA. Efficiency is a measure of how effectively the power amplifier converts the electrical input power into output power. Efficiency is a vital performance metric for power amplifiers in AMB, as it directly affects the overall energy consumption and thermal management of the system. Efficient amplifiers minimize power dissipation and convert a higher percentage of the input power into useful output power. Switching amplifiers, such as Class D amplifiers, are known for their high efficiency due to their on/off switching operation. They can achieve efficiency levels above 90%, significantly reducing power losses and heat generation. Hybrid amplifiers also offer a good compromise between linearity and efficiency by combining linear and switching amplifier topologies. High-efficiency power amplifiers minimize power losses and reduce the need for extensive cooling mechanisms.

F. THERMAL MANAGEMENT

Power amplifiers generate heat during operation, and efficient thermal management is essential to ensure their reliability and longevity. Working of PCBs are usually limited −40°C to 125°C [80]. Effective cooling techniques, such as heatsinks, fans, or liquid cooling, should be employed to dissipate the heat generated by the power amplifier. It is very clear that the eddy current loss by control current is very small and switching ripple current plays the most important role [100]. Temperature sensors and control mechanisms can be integrated to monitor and regulate the amplifier's temperature, preventing overheating and potential damage.

G. THERMAL EFFICIENCY

The reliability of SPA is positively influenced by operating at lower temperatures. Conversely, higher temperatures enable more effective thermal utilization by enhancing the amplifier's electromagnetic excitation capability, leading to improved efficiency. Moreover, it has been observed that the strategic integration of thermal management and advanced integration technologies within the design process can substantially augment power densities of amplifiers, consequently leading to a notable reduction in cost per kilowatt [58].

H. HARMONIC DISTORTION

Harmonic distortion is characterized by the existence of undesirable frequency components occurring at multiples of the frequency of the input control signal. These harmonics can result from non-linearities in the amplification process and can have adverse effects on the performance of AMB. Power amplifiers in AMB should produce minimal harmonic distortion, as it can adversely affect the control performance and stability of the system. The level of harmonic distortion is typically quantified using metrics such as THD and intermodulation distortion. The THD can be made as less as 0.133% in voltage and 0.008% in current by using LPF a power filter in the load line to convert PWM signal into a continuous signal. Linear amplifiers generally exhibit lower harmonic distortion compared to switching amplifiers [16]. However, with proper design and filtering techniques, switching amplifiers can also achieve acceptable levels of harmonic distortion in AMB systems.

I. BANDWIDTH

The bandwidth of a power amplifier is the range of frequencies over which it can effectively operate. In AMB, a wide bandwidth is desirable to accurately control the position and stability of the rotor across various operating conditions. The amplifier should be capable of amplifying the desired signal frequencies without significant attenuation or phase shift. Linear amplifiers typically offer a wider bandwidth and better frequency response compared to switching amplifiers, making them suitable for high-frequency applications. However, advancements in switching amplifier design have led to improved bandwidth capabilities, allowing them to meet the requirements of many AMB applications. To achieve effective high-bandwidth current control with the ability to produce the desired orthogonal forces, a predictive control strategy has been introduced. This method presents several benefits, such as quick dynamic response, elimination of modulation prerequisites, smooth incorporation of nonlinearities and system limitations, the possibility of integrating nested control loops into a single loop, and adaptability to include other system necessities within the controller [97].

AMB systems often require high bandwidth amplifiers to achieve fast response times and accurate control. The bandwidth of the power amplifier should be sufficient to accommodate the changes in external circumstances, reaction to control signals, and the system's capacity to adapt to different operating demands, which include rotor oscillations i.e., the periodic or repeated motion of a rotor around its axis of rotation. Additionally, the amplifier's bandwidth should be well-matched with the bandwidth of the control system to ensure stability and avoid phase delays.

J. ELECTROMAGNETIC COMPATIBILITY (EMC)

Problems such as harsh sound and unexpected vibrations created by current fluctuations in LC circuit which are the source of EMI [101]. Power amplifiers in AMB systems should comply with electromagnetic compatibility standards to prevent interference with other electronic components or systems. Proper shielding, grounding, and filtering techniques should be employed to minimize electromagnetic emissions and susceptibility.

In conclusion, the design considerations provide a foundation for developing power amplifiers tailored for AMB systems. For example, a 20kHz switching frequency in SPA can cause an EMI in the range of 0.3 MHz to 2 MHz [101].

K. TRANSIENT RESPONSE

Transient response refers to the ability of the power amplifier to quickly and accurately respond to changes in the input signal or disturbances. In AMB, rapid changes in the magnetic forces may be required to counteract external disturbances or position the rotor accurately. Power amplifiers with good transient response characteristics enable precise and responsive control. Linear amplifiers generally exhibit better transient response due to their accurate signal reproduction capabilities. However, advanced control algorithms and feedback systems can compensate for the slower transient response of switching amplifiers, making them suitable for many AMB applications, reducing the chances of instabilities or vibrations.

L. FAULT TOLERANCE

Fault tolerance is an important consideration for power amplifiers in AMB [102]. It refers to the ability of the amplifier to operate reliably and maintain system stability even in the presence of faults or failures. Power amplifiers should be designed to detect and handle fault conditions like voltage saturation using anti windup controller [103], other problems such as short circuits or open circuits [78], without causing catastrophic effects on the AMB system. Redundancy and fault detection mechanisms can be implemented to enhance the fault tolerance of power amplifiers [14].

M. PROTECTION MECHANISMS

Power amplifiers in AMB systems should incorporate protection mechanisms to safeguard against faults and failures, because the size of the AMB increases depending on the load carrying capacity. The coil size also increases so does the inductance value, giving rise to higher back emf or voltage spikes while switching off the coils during PWM control. Overcurrent protection, overvoltage protection, and short-circuit protection are essential features that prevent damage to the power amplifier and the AMB system. Since levitation system is mechanical and not electrical failure, switches can take over whenever there is fault, and it can be made fail safe. Additionally, fault detection and diagnostic capabilities enable early detection and identification of potential issues, allowing for timely maintenance and system integrity [14].

V. HARDWARE REALIZATION OF SPA

The comparison between the triangular wave of the current controller and its output is conducted using a comparator, which is implemented using an op-amp TL084 [104]. Inverter ICs can be configured for H bridge like FSAM10SH60A with 500 W output with input gate drivers were used in [105]. To enable accurate duty ratio regulation of the MOSFET switch, a 28 kHz triangular wave is generated. This triangular waveform is then compared with the output of the PI controller from the current loop. The hardware realization of SPA is shown in Fig. 29.

The comparator's output does not provide adequate signal strength to control the MOSFET switch's gate. To address this, the output is directed into an inverting buffer circuit employing a 555-IC. The resulting inverted output from the 555 buffer is then linked to the MOSFET gate through 100 Ω resistors [104].

In order maintain a balance between device temperature and favorable track temperature the track width needs to be determined by using IPC 2221 [58]. The selection of copper weight needs a balance between accommodating high current flow and ensuring an optimal temperature rise, crucial for the dependable performance of the amplifier. Static Induction transistors were used for switching in very high-power SPA used in nuclear power turbine AMB. These switch loads up

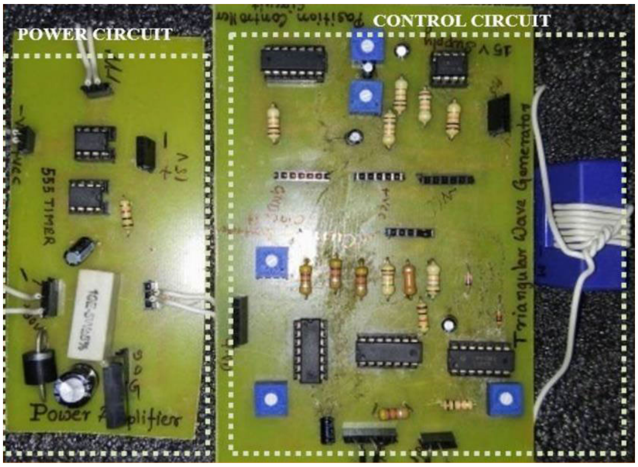

FIGURE 29. Hardware of SPA [106].

to 1000 V [107]. By implementing increased copper weights, designers can access various benefits including [58], [79]:

- Enhanced resilience against thermal strains, leading to heightened mechanical strength at connector locations.
- Expanded capacity for carrying higher amperage.
- Compact amplifier designs achieved by integrating multiple copper weights within the same circuitry layer.
- Streamlined cable routing processes.

The production of PCB with elevated copper weights allows the integration of high-current circuits with thicker copper plating in vias. The use of plated through holes negates the necessity of adding duplicate parallel layers, effectively eliminating concerns related to load distribution across multiple layers. This approach simplifies the measurement of temperature rise on boards and mitigates failures caused by thermal stresses, ultimately resulting in a PCB that runs cooler and exhibits enhanced reliability [108]. EMI filters play a crucial role in minimizing ringing on output lines, with a key emphasis on preventing any potential issues related to overheating. 'Gate turn-off resistor' is needed to reduce turn off transients. Common mode filters and differential mode filters are used to increase current rating and to reduce EMI effects.

The basic parameters of the SPA for small AMB in general have a DC bus voltage 150 V, the switching frequency fs equals 20 kHz [3], and the coil resistance (R) and inductance (L) are 2.1 Ω and 5.3 mH respectively. Two MOSFETS (IRFP450) or Intersil HIP408 and two fast recovery diodes (MUR1560) can be used for any of the above H bridge topology depending on the working conditions. Arduino GPIO can be used to interface LabVIEW with the SPA of AMB [49]. The gate driver IC can be IR2112 [4] depending on the working voltage and slew rate as indicated by equations in [109] of the particular end application different variants can be used. Some researchers suggest human machine interfacing can also be used along with UART communication [79]. The actual current of the coil can be sensed by a Hall effect current sensor of LEM make. PCB can be made by sharing the Gerber files designed in CadSoft Eagle to vendors

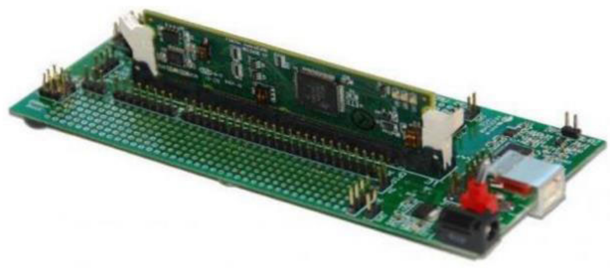

FIGURE 30. TMS320F28035 control card for Realtime control [79].

like JLCPCB, PCBWay etc [110]. Complete guidance on common grounding to avoid voltage spikes from damaging the PCB is mentioned in [110]. Authors in [111] provide complete design aspects of SPA to interface with Arduino and MATLAB.

VI. RECENT ADVANCMENETS IN SPA OF AMB

This section highlights recent advancements in power amplifier technology for AMB. It discusses emerging techniques, such as digital control, advanced modulation schemes, and adaptive control algorithms, which aim to improve the efficiency, accuracy, and robustness of power amplifiers in AMB systems. In addition, various intelligent controllers, including Fuzzy Logic controllers, Artificial Neural Networks, Genetic Algorithms, Particle Swarm Optimization, H infinity, Feedback, PIDD, and LFT [2], are highlighted.

A. RTOS IN MICROCONTROLLER IMPLEMENTATION FOR AMB CONTROL

FreeRTOS and OpenRTOS was run on ATmega 338P microcontroller in [47]. This approach reduces the footprint of the device as whole and can perform the task in restricted resources. Realtime embedded microcontroller for control of AMB was used in [79] (Fig. 30). The difficulty in implementation is the open-source licensing and the technology has not been standardized yet, hence industrial implementation is not realizable yet.

B. SENSOR LESS AMB

The working principle of sensor less AMB involves using advanced algorithms and signal processing techniques to monitor and control the position and motion of a rotating shaft [112]. Instead of relying on external sensors to directly measure the shaft's position, these bearings utilize the electromagnetic properties of the system itself. By analyzing the electrical currents and voltages applied to the magnetic coils, the system can infer the shaft's position and adjust the magnetic forces accordingly. They detect the shaft position through ripple current feedback [96]. In [84], [85], and [113] use an innovative approach which eliminates the need for physical position sensors, reducing complexity and potential failure points while enabling precise and stable levitation and rotation control.

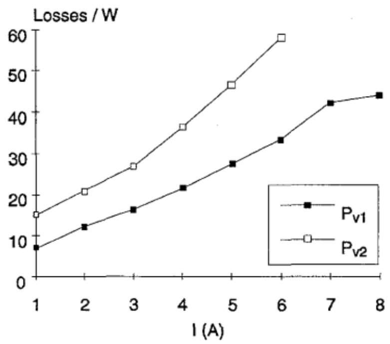

FIGURE 31. Experimental validation of normal PWM modulation vs delta modulation.

C. DIGITAL CONTROL

Digital control techniques have gained popularity in power amplifier design for AMB. Digital control offers advantages such as improved precision, flexibility, and the ability to implement advanced control algorithms. One approach involves using high-speed DACs to generate the control signals for the power amplifier. These DACs offer high resolution and accuracy, enabling precise control of the electromagnetic forces in the AMB system.

Furthermore, digital control allows for the implementation of DSP algorithms to enhance the performance of the power amplifier. These algorithms can compensate for nonlinearities, improve transient response, and provide fault detection and fault-tolerant capabilities. Additionally, digital control facilitates the integration of power amplifier control with other system components, enabling more comprehensive system-level optimization.

D. ADVANCED MODULATION SCHEMES

Advanced modulation schemes have been explored to improve the efficiency and performance of power amplifiers in AMB. Traditional modulation techniques, such as PWM, suffer from switching losses and harmonic distortion. To address these issues, advanced modulation schemes like sigma-delta modulation (SDM) and space vector modulation (SVM) have been investigated. Sigma-delta modulation is a technique that converts high-resolution digital signals into low-resolution, high-frequency bitstreams. It reduces quantization noise and provides high linearity and accuracy. SDM-based power amplifiers have shown improved efficiency and reduced harmonic distortion, making them suitable for high-performance AMB systems. Their efficiency is more compared to normal PWM modulation techniques. Pv1 in Fig. 31 is normal PWM modulation and Pv2 is by delta modulation [114].

Space vector modulation is another advanced modulation scheme that optimizes the switching pattern of the power amplifier to minimize losses and harmonic distortion. By considering the magnetic field vectors generated by the AMB coils, space vector modulation achieves more efficient utilization of power semiconductor devices. This results in improved efficiency and reduced torque ripple in AMB systems.

E. ADAPTIVE CONTROL ALGORITHMS

Adaptive control algorithms have been applied to power amplifiers in AMB to enhance their performance in dynamic operating conditions. These algorithms adaptively adjust the control parameters based on the real-time system response, compensating for variations in the rotor dynamics, environmental conditions, and other factors that may affect the AMB system. One example is adaptive feedback linearization control, which uses a mathematical model of the AMB system to estimate and compensate for nonlinearities. By continuously updating the model parameters based on the system's response, adaptive feedback linearization control improves the tracking accuracy and stability of the AMB system. Another adaptive control approach is model predictive control (MPC), which utilizes a dynamic model of the AMB system to predict the future behavior of the rotor and optimize the control actions accordingly. MPC considers constraints, such as current and voltage limits, and system dynamics, enabling precise control and stability even in the presence of disturbances or variations [97], [102], [115], [116], [117], [118].

Recent advancements in power amplifier technology for AMB have focused on digital control, advanced modulation schemes, and adaptive control algorithms. These advancements have demonstrated improvements in efficiency, accuracy, and robustness of power amplifiers in AMB systems. By leveraging digital control techniques, advanced modulation schemes, and adaptive control algorithms, researchers and engineers are pushing the boundaries of power amplifier design to achieve higher performance and reliability in AMB applications. These advancements pave the way for the development of more efficient, compact, and intelligent AMB systems with enhanced control capabilities.

VII. CHALLENGES AND FUTURE DIRECTIONS

The challenges and potential future directions in power amplifier technology for AMB are addressed in this section. Key challenges, including cost, size, and complexity, are discussed along with potential solutions. Additionally, the integration of power electronics with other components of the AMB system and the development of intelligent control strategies are explored as areas for future research.

A. COST CONSIDERATIONS

One significant challenge is the cost associated with power amplifiers for AMB. The high precision and high-power requirements of these amplifiers often result in expensive components and complex manufacturing processes. Future research should focus on developing cost-effective solutions, such as exploring alternative semiconductor materials, optimizing circuit topologies, and leveraging advancements in manufacturing techniques to reduce production costs.

B. SIZE AND WEIGHT CONSTRAINTS

The size and weight of power amplifiers can pose challenges in AMB applications where space is limited, such as in small-scale machinery or portable systems. Miniaturization techniques, integration of components, and efficient thermal management strategies are potential approaches to reduce the size and weight of power amplifiers without compromising performance. Additionally, exploring advanced packaging technologies, such as three-dimensional integration, could lead to more compact and lightweight amplifier designs.

C. COMPLEXITY AND CONTROL

Power amplifiers in AMB require sophisticated control algorithms to ensure accurate and stable positioning of the rotor. The complexity of these control systems can make them challenging to implement and maintain. Future research should focus on developing intelligent control strategies like that in [122] simplify the system architecture, enhance the ease of integration, and improve overall system robustness. Additionally, advancements in digital control techniques and signal processing algorithms can facilitate the implementation of complex control schemes with reduced complexity.

D. EFFICIENCY AND ENERGY CONSUMPTION

Efficiency is a critical consideration for power amplifiers, as inefficient designs can lead to excessive power dissipation and increased energy consumption. Improving the efficiency of power amplifiers in AMB can have significant implications for energy savings, reduced heat generation, and enhanced system reliability. Researchers should explore novel power amplifier topologies, advanced switching techniques, and optimized power management strategies to achieve higher efficiency without compromising other performance parameters.

E. FAULT TOLERANCE AND RELIABILITY

Ensuring fault tolerance and high reliability is crucial for AMB systems as suggested by [119], any failure in the power amplifier like failures in PWM modulation [35] can lead to catastrophic consequences. Future research should aim to enhance the fault tolerance and reliability of power amplifiers by incorporating redundancy, fault detection and diagnosis algorithms, and robust protection mechanisms. The development of self-monitoring capabilities can contribute to the overall system reliability and minimize downtime. Some researchers used switches in parallel in case of failure of switches.

F. ADVANCED MATERIALS AND TECHNOLOGIES

Advancements in materials and technologies can also drive improvements in power amplifier design for AMB. Exploring new semiconductor materials with superior performance characteristics, such as wide-bandgap devices (e.g., silicon carbide), to achieve higher power density, better thermal properties, and improved switching speeds. Furthermore, advancements in packaging technologies, such as chip-scale packaging and power module integration, can enhance the performance and reliability of power amplifiers in AMB.

Several potential future research directions exist for power amplifiers in AMB. These include investigating advanced modulation techniques to improve the dynamic response and reduce harmonic distortion, exploring digital control algorithms for enhanced precision and flexibility, and integrating power amplifiers with emerging technologies such as artificial intelligence.

G. ADVANCED MODULATION TECHNIQUES

Exploring advanced modulation techniques can significantly improve the dynamic response and reduce harmonic distortion in power amplifiers for AMB. Techniques such as PWM, sigma-delta modulation, or advanced modulation schemes like space vector modulation can be investigated. These techniques enable precise control of the magnetic forces while minimizing undesirable harmonics and improving the efficiency of power amplifiers. Resonant switching techniques can also be combined [16] as suggested by [15]. Managing the current of an inductive load with low damping can be challenging due to its inherent instability. To address this issue, voltage-mode control is implemented in a front-end buck converter, which adjusts the load current envelope through a downstream resonant boost inverter, effectively stabilizing the system. The resonant boost inverter is represented by a low-frequency equivalent circuit, and a control loop is designed to prevent any unwanted interaction between the buck converter and the resonant boost inverter.

H. DIGITAL CONTROL ALGORITHMS

The integration of digital control algorithms can offer enhanced precision and flexibility in power amplifiers for AMB. Digital control techniques provide the ability to implement complex control schemes, adaptive algorithms, and advanced signal processing methods. Research in this area can focus on developing efficient digital control algorithms that optimize performance, robustness, and energy efficiency of power amplifiers in AMB.

I. INTEGRATION WITH ARTIFICIAL INTELLIGENCE (AI)

The integration of power amplifiers with emerging technologies such as artificial intelligence (AI) holds significant potential for improving the performance and efficiency of AMB systems. AI algorithms can be employed for real-time control optimization, fault detection, and predictive maintenance of power amplifiers. Exploring AI-based control strategies, machine learning algorithms, and neural networks to enhance the intelligence and autonomy of power amplifiers in AMBs.

J. HIGH-FREQUENCY OPERATION

Investigating high-frequency operation of power amplifiers can lead to improved performance and reduced system size in AMB. Higher switching frequencies enable smaller magnetic components, such as inductors and transformers, and can result in higher power density and increased system bandwidth. Focusing on developing power amplifiers that can operate at higher frequencies while maintaining high efficiency and low distortion.

K. MULTI-OBJECTIVE OPTIMIZATION

Multi-objective optimization techniques can be employed to simultaneously optimize different performance metrics of power amplifiers in AMB. These metrics may include efficiency, linearity, bandwidth, harmonic distortion, and transient response. By considering multiple objectives, developing power amplifier designs that strike a balance between conflicting requirements and improve overall system performance.

L. INTEGRATED POWER ELECTRONICS SYSTEMS

Integrating power amplifiers with other power electronics systems in the AMB setup can lead to more compact and efficient designs. Exploring the integration of power amplifiers with power management modules, voltage regulators, and energy storage systems to enhance system performance, reduce power losses, and improve overall system reliability.

M. ADVANCED PACKAGING AND THERMAL MANAGEMENT

Advancements in packaging technologies and thermal management techniques can help to address the size, weight, and thermal challenges associated with power amplifiers in AMB [58]. Research can focus on developing advanced packaging solutions such as three-dimensional integration, chip-scale packaging, and enhanced thermal dissipation methods to improve the reliability and performance of power amplifiers in AMB. Utilizing energy from coils of AMB to cool the PCB boards during de-energizing cycles of the H Bridge, can improve the energy efficiency of the system.

N. CONDITION MONITORING

Remote condition monitoring of AMB was addressed in [41] and [49] using off-the-shelf IoT hardware and custom software. The proposed solution allows OEM technicians to observe AMB signals remotely, reducing the need for on-site service calls and minimizing downtime. VNC server and VNC client was used with Secure Shell (SSH) to plot FFT of magnetic levitation system. The successful demonstration on an AMB test rig proves the economic and effective nature of this approach to be extended for controlling AMB by controlling the coil currents using SPA. Future developments could focus on cybersecurity measures, a mobile application for remote monitoring, and real-time capabilities to create a cyber-physical system. This advancement would enable technicians to diagnose and potentially fix AMB issues remotely, some researchers have used ultra-high speed cameras to monitor vibrations like in [123] which can also be applied in the field of AMB. The ADS1115 4-channel 16-bit ADC was used, which was purchased from Adafruit Industries, LLC breakout board. The communication between the Raspberry Pi and the ADC was established using the standard I2C digital communication protocol. This protocol necessitates two wires: one for data transfer and the other for a timing trigger to measure the shaft displacement from eddy sensor probes. PID loop can be run on the Raspberry Pi and the command signals for current control to actuate the electromagnets can be sent as PWM signals or as analog signal by using an intermediate DAC, into the SPA which uses an internal PI controller to regulate the current thus, reducing the computational load on the Raspberry Pi. This technique can reduce AMB cost [120] and can make AMB an open-source setup and compact.

O. COUPLED SIMULATIONS

In research work of [37], coupled analysis of electronic circuit of SPA with electromagnets of AMB was presented. Yet there is lot of scope for further studies that include coupled simulation between Simplorer and ANSYS Maxwell featuring different converter topologies with different types of controllers for feedback.

VIII. CONCLUSION

A comprehensive overview of power amplifier technologies for AMB has been presented. It highlights the importance of power amplifiers in achieving high-performance control and stability in AMB systems and provides complete information on design of electronics related to SPA. The following conclusions are drawn related to the design and selection of SPA for AMB systems.

Switching signal circuit: Multiple modulation techniques are employed in power electronics, such as PWM, current hysteresis, sample-hold, and minimum pulse width modulation. Yet, practical use has shown limitations in hysteresis and sample-hold methods. Hysteresis is vulnerable to short pulses, impacting efficiency or causing device failure. Sample-hold resists short pulses but introduces harmonic distortion and dead band, especially at low signal amplitudes. To address these issues, minimum pulse width modulation combines the strengths of both hysteresis and sample-hold but requires more complex control signals. Among these techniques, PWM is the most widely adopted and researched, successfully applied in numerous power electronic systems [31]. PWM technique is best suited because in the realm of SPA, Due to the challenges posed by control signals crossing the high current wires, the switches needed to be organized in a linear configuration instead of the conventional H-bridge formation. If applications involve large distances between amplifier and the load, then dynamic termination circuits are needed [38].

Selection of converter as per requirement:

- Unidirectional current is sufficient for the working of AMB hence Half bridge topologies are best suited [30]. Asymmetrical H Bridge is best suited amongst all the topologies, since it has the least number of switches, less usage of capacitors and other passive components on the switching side, reduced cost, size and complexity. The half-bridge topology offers fast response and broad

bandwidth control, suitable for high-speed magnetically levitated rotors. It exhibits remarkable benefits in maintaining stability control for magnetically levitated rotors operating at ultra-high speeds.
- The 3-phase-half-bridge topology reduces components and allows easy substitution with an industrial inverter, promising industrial AMB production.
- The neutralized-sharing-bridge topology enhances integration but increases isolated drive circuits, showing promise for weight-sensitive applications like aerospace [30].
- In the Half bridge converter, it is possible to generate the bearing coil voltage (Vdc, 0, -Vdc) with superior precision in contrast to the 3-phase-half-bridge or neutralized-sharing-bridge topology (Vdc/2, -Vdc/2). Furthermore, achieving negative voltage amplification at elevated operating frequencies becomes feasible through the utilization of a full H bridge [121]. So, the 3-phase-half-bridge or neutralized-sharing-bridge topology current response rate is only half of that of the half-bridge topology SPA. The capacitive half bridge type has the drawback of requiring careful maintenance of the voltage balance between the two capacitors in the circuit [25]. The cost of neutralized and 3-phase Half bridge is lesser than half bridge type SPA.

Line Sensing Technique: Methodology implemented by [4] is cost effective and reliable since using a LPF in series with the load has to always undergo high voltage and high current during regular operation of the AMB coil, but using a non-intrusive type of sensor like hall effect and then passing the signal from it through a LPF guarantees a smooth average in line current which is suitable for feedback.

Control techniques: Using a LPF as suggested by [4] and [16], would not need to demodulate the PWM and signal can be directly measured by attenuating it and feeding it into a A/D converter with standard sampling rate of 20 kHz [14] or at same frequency as that of PWM signal if response desired is very fast. Usually, the control loop processing initializes from internal PI control and then proceeds to the outer position control loop, hence internal loop must be computationally efficient and fast to achieve excellent position control of the shaft in AMB. Therefore, a linear controller would be good choice for current control in SPA of AMB.

In short, PWM, hysteresis, and sample-hold are modulation techniques used in power electronics, however hysteresis and sample-hold have disadvantages such as sensitivity to short pulses and harmonic distortion. Due to high-current wire crossing issues, linear designs outperform H-bridge forms for switching signal circuits in systems such as Active Magnetic Bearings (AMB). The selection of a converter is influenced by aspects such as unidirectional current sufficiency, where the half-bridge topology, particularly the asymmetrical H Bridge, shines because to its efficiency and decreased complexity. These converters, which are critical for generating exact voltages in bearing coils, have a considerable influence on response rates and vary in price, favoring alternatives such as neutralized and 3-phase half bridge versions. Line sensing techniques use non-intrusive sensors such as hall effect and low pass filters to provide smooth feedback, as opposed to series LPFs, which survive high temperatures.

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