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Design and Analysis of an Integrated Hybrid AC/DC Generator with Built-In Rectification as an Alternative to Conventional DC Generator Systems

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Abstract

Conventional direct current (DC) power systems for telecommunications and other DC-intensive applications typically employ a three-phase alternating current (AC) generator together with an external rectification cabinet to produce the regulated −48 V DC supply required by communication equipment. Although this architecture is widely adopted and highly reliable, it increases equipment footprint, installation complexity, transportation requirements, cabling, deployment time, and maintenance. Conventional DC generators provide direct DC output through mechanical commutation; however, their reliance on brushes and commutators introduces mechanical wear, sparking, increased maintenance, and reduced operational reliability. This paper proposes an integrated hybrid AC/DC generator architecture that combines a commercial brushless synchronous AC generator with an embedded DC rectification system within a single generator enclosure. The proposed design incorporates a three-phase bridge rectifier, filtering stage, voltage regulation, protection circuitry, and optional DC-DC conversion to deliver regulated −48 V DC while simultaneously retaining the capability to supply conventional AC power. The work does not introduce a new electrical machine or a new rectifier topology; instead, it presents a system-level integration of two mature technologies to eliminate the need for a separate external telecom rectification cabinet. The proposed architecture is evaluated through analytical modelling, electrical machine theory, representative design calculations, and circuit-level analysis. Performance metrics including DC output voltage, voltage regulation, ripple characteristics, efficiency, thermal management, and protection requirements are examined and compared with those of conventional commutator-based DC generators. The reported performance values represent predicted behavior under the stated design assumptions and are intended to demonstrate the engineering feasibility of the proposed architecture rather than experimental validation. The proposed integrated hybrid AC/DC generator is expected to reduce installation complexity, equipment footprint, deployment time, and maintenance while preserving the reliability and operational advantages of modern brushless alternator technology. The architecture is particularly suited to telecommunications, emergency communication systems, disaster recovery, military field operations, remote industrial facilities, and other applications requiring compact and reliable simultaneous AC and regulated DC power from a single generator platform [1].

Keywords

Hybrid AC/DC Generator, Brushless Synchronous Generator, Built-In Rectification, Integrated Generator-Converter System, DC Power Systems, Telecommunications Power Supply, −48 V DC, Power Electronics, Voltage Regulation, Embedded Rectifier

1. Introduction

Reliable electrical power generation is fundamental to modern industrial, commercial, and communication infrastructures. Three-phase synchronous AC generators (alternators) are the dominant technology for electrical power generation because of their simple construction, high efficiency, low maintenance requirements, long service life, and capability to operate over a wide range of power ratings. Consequently, brushless synchronous generators are extensively employed in utility power plants, industrial facilities, hospitals, airports, marine vessels, renewable energy systems, and standby power installations.

Despite the widespread use of AC generators, many critical applications require regulated direct current (DC) rather than alternating current (AC). Telecommunication base transceiver stations (BTS), microwave communication systems, optical transmission equipment, routers, network switches, battery charging systems, industrial control equipment, and numerous electronic systems operate on standardized DC power, most commonly −48 V DC in telecommunications. During utility outages, diesel generator sets typically provide AC power, which must then be converted into regulated DC through external rectifier systems before it can be supplied to the communication equipment.

The conventional telecom power architecture therefore consists of two independent subsystems: an AC generator that produces electrical energy and a separate DC power cabinet containing rectifier modules, filters, battery charging circuits, monitoring units, and DC distribution equipment. This modular architecture has demonstrated excellent reliability and flexibility and has become the industry standard. However, it also increases equipment footprint, installation complexity, transportation requirements, cabling, commissioning time, and overall system cost, particularly for temporary, mobile, and emergency deployments.

Conventional DC generators provide direct-current output through mechanical commutation using brushes and a commutator. Although this approach eliminates the need for an external rectifier, it introduces disadvantages including brush wear, commutator sparking, periodic maintenance, mechanical complexity, and reduced suitability for continuous operation in harsh environments. As a result, modern stationary power generation has largely shifted toward brushless AC generators combined with external power electronic conversion systems.

Recent advances in power electronics, high-efficiency semiconductor devices, digital control techniques, and compact converter technologies have enabled increasingly close integration between electrical machines and power electronic converters. Integrated generator-converter systems have been investigated for more electric aircraft, starter-generator systems, renewable energy conversion, and hybrid electric propulsion. Nevertheless, these studies primarily focus on machine control, propulsion, or variable-speed energy conversion rather than replacing the external DC rectification infrastructure commonly used in stationary telecommunication power systems.

The objective of this research is to investigate a different system architecture in which commercially available brushless AC generator technology is combined with mature telecom rectification technology inside a single generator enclosure. Instead of introducing a new electrical machine or a new rectifier topology, the proposed design integrates rectification, filtering, regulation, protection, and control functions within the generator housing while preserving the generator's capability to supply conventional AC power. Integrated architecture is intended to provide both regulated DC output and conventional AC output from a single compact generator platform, thereby reducing external equipment, installation complexity, deployment time, and maintenance requirements.

The proposed hybrid AC/DC generator is particularly applicable to telecommunications, emergency communication systems, disaster recovery operations, mobile communication units, temporary event networks, military field installations, remote industrial facilities, and other applications where compactness, rapid deployment, and reliable simultaneous AC and DC power are desirable.

The principal contribution of this paper is a system-level generator architecture that integrates proven alternator and telecom rectification technologies into a single hybrid power generation platform. Unlike conventional DC generators that rely on mechanical commutation, or conventional telecom installations that depend on separate external rectifier cabinets, the proposed approach combines established technologies into an integrated generator capable of supplying regulated DC while retaining the operational advantages of modern brushless AC generators. The paper presents the operating principle, mathematical analysis, comparative performance assessment, thermal and protection considerations, and potential applications of the proposed architecture [2].

1.1. Methods

This study employs a system-level engineering design methodology based on the integration of two commercially available and field-proven technologies: a brushless three-phase synchronous AC generator (alternator) and a mature telecommunications DC rectification system employing modular rectifier units. Both technologies have been extensively deployed in industrial and telecommunications applications and have well-established electrical performance, reliability, and operational characteristics. Rather than developing a new electrical machine or a new rectifier topology, this research investigates the technical feasibility and expected performance of integrating these existing technologies into a single hybrid AC/DC generator architecture.

The proposed system was developed by incorporating a commercially established three-phase bridge rectification stage, together with filtering, voltage regulation, protection, and optional DC-DC conversion, within the generator housing. The integrated architecture is intended to provide regulated DC output directly from the generator while simultaneously preserving the capability to supply conventional AC power, thereby eliminating the need for a separate external telecommunications rectifier cabinet.

The performance of the proposed architecture is evaluated using established electrical machine theory, analytical calculations, representative design calculations, manufacturer specifications for commercially available generators and telecommunications rectifier modules, and circuit-level simulations. The analysis considers representative operating conditions corresponding to a 5 kW, 400 V (line-to-line), 50 Hz brushless synchronous generator integrated with a standard telecommunications rectifier system designed to supply regulated −48 V DC.

The following characteristics are evaluated.

Efficiency: The overall efficiency is estimated by considering the published performance characteristics of commercial brushless synchronous generators together with the conversion efficiency of commercially available telecommunications rectifier modules. Additional analytical calculations are performed to account for stator copper losses, magnetic core losses, mechanical losses, and semiconductor conduction losses within the integrated architecture.

Output Voltage Ripple: The DC output waveform is analyzed after three-phase rectification and output filtering. The ripple performance is evaluated analytically and through circuit-level simulation using design parameters representative of commercially deployed telecommunications rectifier systems.

Voltage Regulation: Voltage regulation is assessed over the expected operating range by analyzing the performance of the integrated electronic regulation stage under varying load conditions. The analysis is based on established voltage-regulation principles and the operating characteristics of commercially available telecommunications power systems.

Thermal and Protection Assessment: The thermal behavior of the integrated rectification stage is evaluated by considering semiconductor power dissipation, heat-sink sizing, and forced-air cooling within the generator enclosure. Electrical protection is assessed through the incorporation of proven industrial protection methods, including overcurrent protection, short-circuit protection, overvoltage protection, overtemperature monitoring, surge suppression, and appropriate electrical isolation between the AC and DC sections.

Reliability Assessment: Reliability is evaluated qualitatively using published operational experience with commercial brushless alternators and modular telecommunications rectifier systems. The assessment considers the elimination of mechanical brushes and commutators, reduced maintenance requirements, simplified system architecture, and the use of mature, field-proven technologies already deployed in industrial and telecommunications networks.

Since both principal subsystems employed in the proposed architecture are commercially available and have demonstrated reliable field performance, this study focuses on evaluating the engineering feasibility, operational benefits, and system-level integration of these mature technologies. The reported performance values are derived from analytical calculations, manufacturer specifications, established engineering relationships, and circuit-level simulations of the integrated architecture. Future work will include fabrication of an integrated prototype, laboratory validation, thermal characterization, electromagnetic compatibility testing, and long-term operational evaluation to verify the analytical and simulation results presented in this study [3].

1.2. Related Work and Research Gap

Brushless three-phase synchronous AC generators and conventional commutator-based DC generators are both well-established power generation technologies that have been successfully employed in industrial, commercial, and standby power applications for many decades. Similarly, modular telecommunications DC rectification systems are mature and highly reliable technologies that have been extensively deployed to provide regulated −48 V DC power for base transceiver stations (BTS), data communication equipment, and other critical telecommunications infrastructure.

In present-day telecommunications installations, the most common approach is to use a brushless AC generator together with a separate telecommunications DC power system. The generator supplies three-phase AC power to an external rectifier cabinet containing modular rectifier units, battery charging equipment, monitoring systems, and DC distribution circuits. The rectifier modules convert the generated AC power into regulated −48 V DC required by telecommunications equipment. This architecture has proven to be highly reliable and has become industry standard because it allows independent maintenance and modular expansion. However, it also requires additional cabinets, rectifier modules, interconnecting power cables, protection devices, installation space, transportation, commissioning effort, and maintenance of multiple subsystems.

An alternative solution is the use of a conventional DC generator, which produces DC output through a mechanical commutator and carbon brushes. Although this configuration eliminates the need for an external rectification system, it introduces several well-known limitations, including brush wear, commutator maintenance, sparking, mechanical losses, reduced operational life, and periodic servicing. Furthermore, the output voltage of a conventional DC generator is inherently pulsating due to mechanical commutation. Although increasing the number of armature coils and commutator segments reduces output ripple, it also increases machine complexity, manufacturing cost, and maintenance requirements.

Recent research on integrated generator-converter systems, brushless starter-generators, dual-output electrical machines, and embedded power electronics has primarily focused on aerospace, automotive, renewable energy, and hybrid-electric applications. These studies demonstrate the advantages of integrating electrical machines with power electronic converters for improved control, efficiency, and power quality. However, their principal objective is generally machine control, propulsion, or variable-speed energy conversion rather than simplifying stationary telecommunications power systems or replacing conventional DC generators.

Based on the above review, a clear engineering gap exists between the two mature technologies currently used in practice. The first solution employs a brushless AC generator with a separate external telecommunications rectification system, resulting in additional equipment, increased installation space, more interconnecting cables, higher transportation requirements, and greater system complexity. The second solution employs a conventional DC generator, which avoids the need for external rectification but suffers from the inherent disadvantages of mechanical commutation, including brush wear, commutator maintenance, sparking, and pulsating DC output.

This research addresses that gap by integrating two commercially proven technologies—a brushless synchronous AC generator and a mature telecommunications modular rectification system—into a single hybrid AC/DC generator. The proposed architecture incorporates the rectification, filtering, voltage regulation, protection, and control functions within the generator housing, thereby eliminating the need for a separate external telecommunications rectifier cabinet while simultaneously eliminating the mechanical commutator and brushes associated with conventional DC generators. As a result, the proposed generator is capable of supplying regulated DC power directly from the integrated rectification system while also retaining the ability to provide conventional AC output from the same generator, provided that the combined load remains within the rated capacity of the machine.

Accordingly, the principal novelty of this research is not the development of a new electrical generator or new rectifier technology. Instead, the novelty lies in the system-level integration of two mature, commercially available, and field-proven technologies into a compact hybrid generator architecture. The proposed design combines the operational reliability of modern brushless alternators with the high-performance DC conversion capability of telecommunications rectifier modules, creating a dual-output generator that reduces equipment footprint, installation complexity, cabling requirements, maintenance effort, deployment time, and overall system cost while preserving the capability to supply both AC and regulated DC power from a single integrated unit. The proposed architecture is particularly suitable for telecommunications networks, emergency communication systems, disaster recovery, military field operations, remote industrial facilities, temporary installations, and other applications requiring reliable AC and DC power from a single generator platform [4] [5].

2. AC Generators

2.1. Design Parts, Working Principles, and Usage

An AC generator, commonly known as an alternator, is an electrical machine that converts mechanical energy into alternating current (AC) electrical energy based on the principle of electromagnetic induction. Its main components include the stator, rotor, field winding, armature winding, shaft, bearings, and excitation system. The rotor creates a rotating magnetic field, while the stator contains stationary windings in which AC voltage is induced. AC generators are designed for high efficiency, reliability, and low maintenance, making them the preferred choice for modern power generation. They are widely used in thermal power plants, hydroelectric stations, wind turbines, diesel generators, telecommunications infrastructure, industrial facilities, and renewable energy systems to supply electrical power for residential, commercial, and industrial applications.

2.2. Parts of AC Generator

Figure 1 illustrates the principal components of the brushless synchronous generator employed in the proposed hybrid AC/DC generation system. The stator contains three-phase armature windings in which electrical power is induced, while the rotor carries the field winding that produces the rotating magnetic field through the excitation system. Mechanical power supplied by the diesel engine is transmitted to the rotor through the shaft, enabling electromechanical energy conversion. The excitation system, controlled by the Automatic Voltage Regulator (AVR), regulates the rotor field current to maintain a stable generator terminal voltage under varying operating conditions.

The generator also incorporates bearings and rigid housing to provide mechanical support and ensure reliable operation. An integrated cooling system dissipates heat generated by electrical and mechanical losses, improving operational reliability and extending component life. The terminal box provides an electrical interface between the generator and external equipment.

Unlike conventional telecom power systems, where the generated AC power is transferred to an external rectifier cabinet, the proposed system utilizes these conventional generator components only as the primary AC generation stage. The generated three-phase AC is immediately supplied to an embedded rectifier and DC/DC conversion stage integrated within the generator assembly, producing a regulated −55 V DC output suitable for telecom applications. Consequently, the innovation presented in this work lies not in the generator construction itself, but in the integration of the alternator with embedded power electronic conversion and closed-loop voltage regulation.

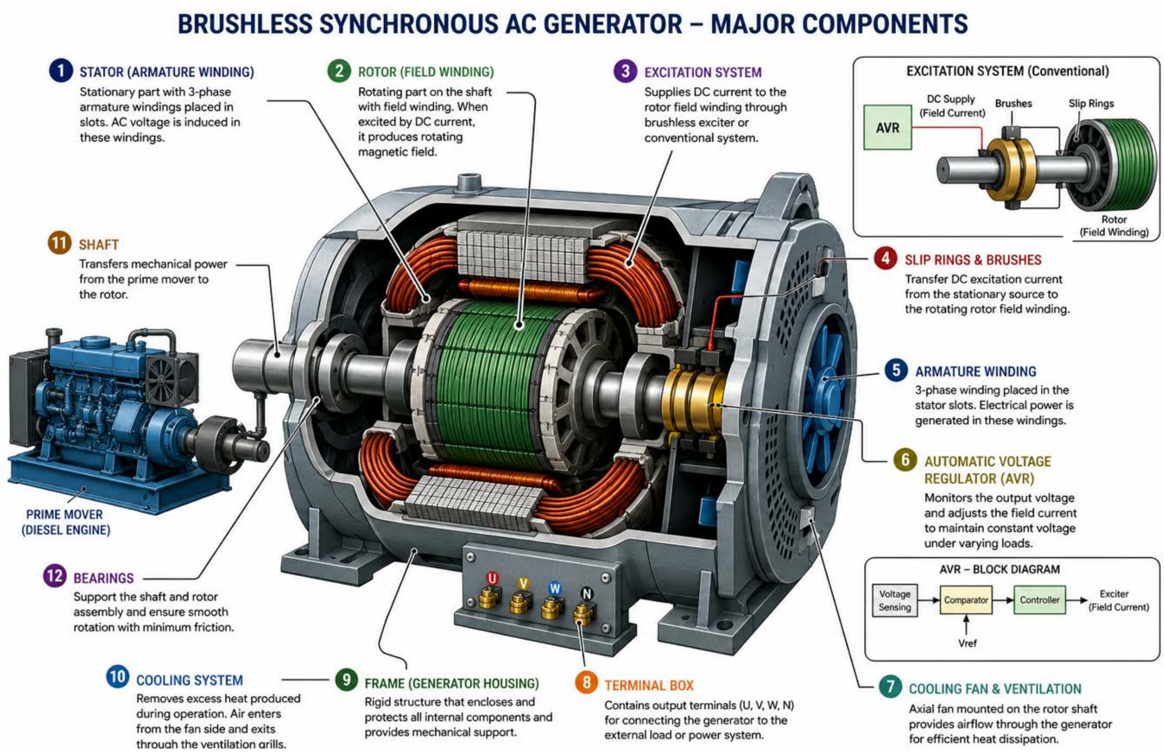

Figure 1. Parts of AC generator.

2.3. Working Principles of AC Generator

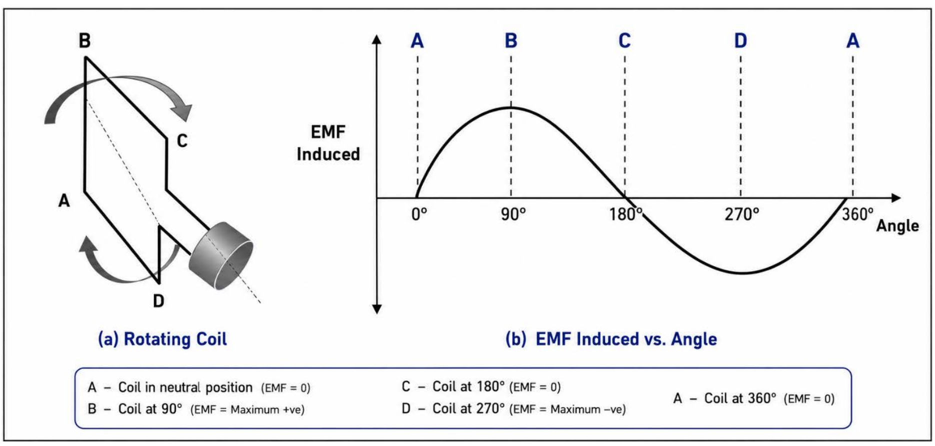

Figure 2. Sinusoidal waveform of AC output.

To create a strong magnetic field, the coil is rotated in the magnetic field. An EMF is induced in one direction as a coil goes up through the magnetic field on one side. An EMF is induced in the reverse direction as the coil rotates and this side of the coil moves down, and another side of the coil moves up. The direction of the induced EMF is determined using Fleming's right-hand rule. Every cycle, this process is repeated, and the EMF generated is of the alternating type.

A graph depicting the output of an AC generator is displayed above in **Figure 2**. The description of the letters is as follows:

The sinusoidal induced EMF equation of an AC generator is:

$$e = E_m \sin(\theta) \tag{1}$$

Where:

e = Instantaneous induced EMF (V);

E_m = Maximum (peak) induced EMF (V);

θ = Angle between the magnetic flux and normal to the coil.

Analyzing the waveform given in **Figure 2**, for different points and putting the value of θ in Equation (1):

At $\theta = 0^\circ$:

Equation (1) => $e = E_m \sin(0^\circ)$ as $\sin(0^\circ) = 0$

Since $\sin(0^\circ) = 0$

So: $e = 0$

When the coil is at 0 degrees, it moves parallel to the magnetic field's direction and so produces no EMF.

At $\theta = 90^\circ$

Equation (1) => $e = E_m \sin(90^\circ)$ as $\sin(90^\circ) = 1$

So: $e = E_m$

When the coil moves at 90 degrees to the magnetic field the maximum EMF is induced as the magnetic flux covers overall area of the coil.

At: $\theta = 180^\circ$

Equation (1) => $e = E_m \sin(180^\circ)$ as $\sin(180^\circ) = 0$

So: $e = 0$

When the coil is rotated 180 degrees, it moves parallel to the magnetic field again, causing no EMF to be generated.

At $\theta = 270^\circ$

Equation (1) => $e = E_m \sin(270^\circ)$ as $\sin(270^\circ) = -1$

So: $e = -E_m$

When the coil is at 270 degrees, it goes back to 90 degrees to the magnetic field, inducing the maximum EMF. The induced EMF in this case is the opposite in direction and hence produces negative peaks.

At: $\theta = 360^\circ$

Equation (1) => $e = E_m \sin(360^\circ)$ as $\sin(360^\circ) = 0$

So: $e = 0$

When the rotation reaches 360 degrees, again the coil comes parallel to the magnetic flux and hence no lines cross the cross section and hence the emf induced is zero.

From the above observations it is concluded that the AC generator gives us a proper sinusoidal waveform [6].

2.4. Usage of AC Generators

There is a wide range of applications where AC generators are used. These applications cover almost every area of life. In Table 1 below are mentioned some highly used AC generator fields.

Table 1. Industrial usage of AC generator.

Application Area	Typical Uses
Power generation	Thermal, hydroelectric, nuclear, gas turbine, and wind power plants
Emergency backup	Hospitals, airports, data centers, banks, educational institutions, commercial buildings
Automotive	Alternators for battery charging and vehicle electrical systems
Marine	Navigation, lighting, communication, auxiliary equipment
Aircraft	Avionics, lighting, navigation, communication systems
Industrial	Motors, pumps, compressors, conveyor systems, manufacturing
Construction	Portable generators for welding, lighting, drills, heavy equipment
Telecommunications	Mobile towers, communication centers, internet infrastructure

3. Need for DC Power and Existing Methods of DC Power Generation

The previous sections discussed the construction, operating principles, components, and applications of AC generators in detail. Due to their simple construction, high efficiency, lower maintenance requirements, and ability to generate electrical power economically, AC generators have become the dominant technology in power generation systems worldwide. Consequently, most industrial, commercial, residential, and utility-scale power generation facilities utilize AC generators as their primary source of electrical energy.

Despite the widespread use of AC generators, many modern applications require direct current (DC) power rather than alternating current (AC). Examples include telecommunication equipment, battery charging systems, data centers, control systems, electroplating facilities, electric vehicle charging infrastructure, communication networks, and numerous electronic devices. In telecommunication networks particularly, most equipment operates on a standardized DC supply of −48 V, making DC power an essential requirement for reliable network operation.

Currently, there are two primary methods for obtaining DC power from a mechanical energy source:

Method 1: AC Generator with External Rectification System

The conventional solution for telecom backup power employs a brushless AC generator coupled with an external DC power system. During utility outages, the generator supplies three-phase AC power to a telecom rectifier cabinet, where rectifier modules convert the AC input into a regulated −48 V DC for telecom equipment. This architecture is widely adopted because of its reliability, modularity, and ease of maintenance.

Despite its widespread use, the separation of the generator and rectification system introduces several drawbacks, including additional equipment, larger installation space, increased cabling, higher installation cost, multiple power conversion stages, and greater maintenance requirements. These limitations become more significant for remote telecom sites where compactness and rapid deployment are essential.

Method 2: Conventional DC Generator

A conventional DC generator produces direct current using a commutator and brush assembly, eliminating the need for an external rectifier. Although this configuration provides a direct DC output, the mechanical commutation system introduces brush wear, commutator sparking, increased maintenance, and reduced operational reliability. Consequently, conventional DC generators have largely been replaced by brushless AC generators in modern industrial and telecom applications. Furthermore, their inability to simultaneously supply both AC and regulated telecom DC limits their practical applicability [7].

4. DC Generators

4.1. Design Parts, Working Principles, and Usage

A DC generator is an electromechanical energy conversion device that converts mechanical energy into direct current (DC) electrical energy. It operates on the principle of electromagnetic induction, whereby an electromotive force (EMF) is induced in a conductor when it cuts magnetic flux lines. DC generators have historically been used in various industrial, transportation, telecommunication, and power system applications where direct current is required.

Although modern power generation systems primarily employ AC generators due to their simplicity and reliability, DC generators remain important in applications requiring direct DC power without external rectification systems.

4.2. Parts of DC Generator

Almost most of the parts of the DC generator is same as AC generator which is discussed in detail in the AC Generator portion. The difference is to use commutators instead of slip rings. The function of commutator is to provide the unidirectional current for every rotation of the coil. We will explain in detail the working principle of commutator.

1) The Anatomy of a Commutator

The Split Ring:

It is not a continuous circle. It is a copper cylinder split into two or more isolated segments.

Mica Insulation:

A thin layer of non-conductive mica separates each copper segment, so they do not short-circuit.

Fixed Brushes:

Two carbon brushes ride on opposite sides of this spinning ring. They do not move; they just press against it.

2) Commutator Working

We know that the emf induced into the rotating conductor is always sinusoidal. The commutator is used to convert it into a unidirectional (dc) emf. Thus "commutation" is the process of converting ac voltage into dc. It is similar to rectification.

The action of commutator is as follows, refer Figure 3, which shows a single turn DC generator, with the commutator in its simplest form. We assume that the commutator has been divided only into two segments namely segments A and B. The simplified construction is shown in Figure 4. The commutator segments A and B are connected to the brushes P and Q respectively. Commutator segments, A and B are connected to conductors' "ab" and "cd" respectively and rotate together.

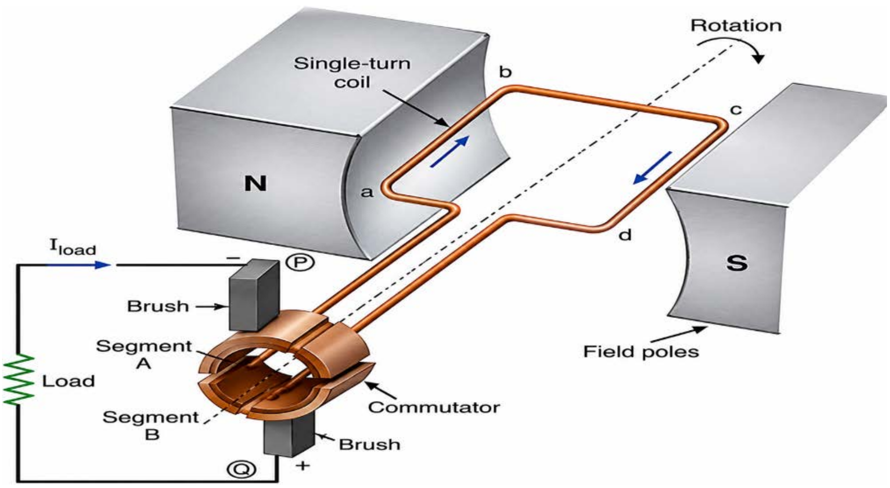

Figure 3. Commutators and brushes.

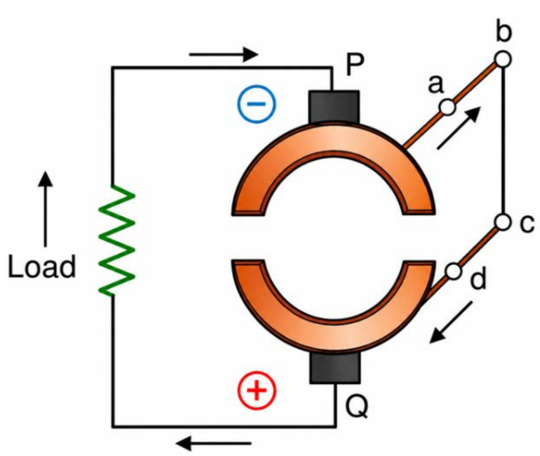

Figure 4. Simplified commutator segments.

According to Fleming's light hand rule, the induced current in coil "ab" and "cd". Hence brush P becomes negative, and Q becomes positive. The current Iload through external load resistance RL flows from bottom to top as shown in Figure 4.

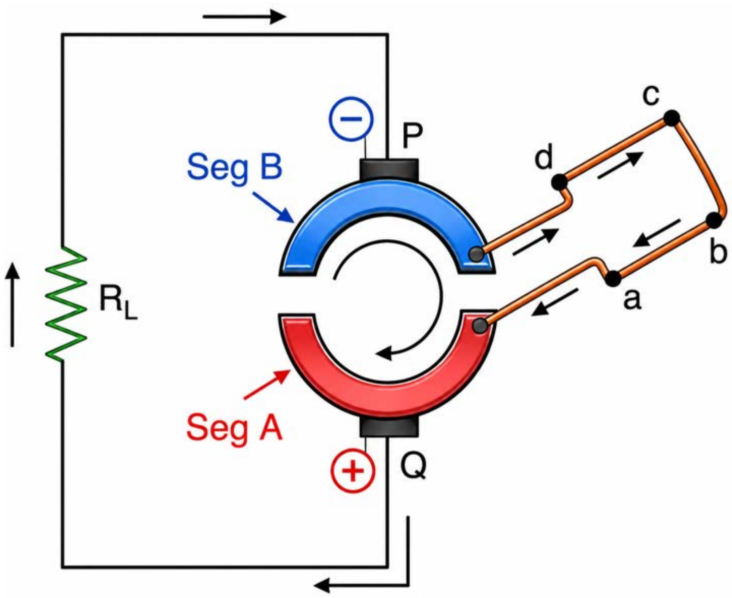

Figure 5. Explaining the working principle.

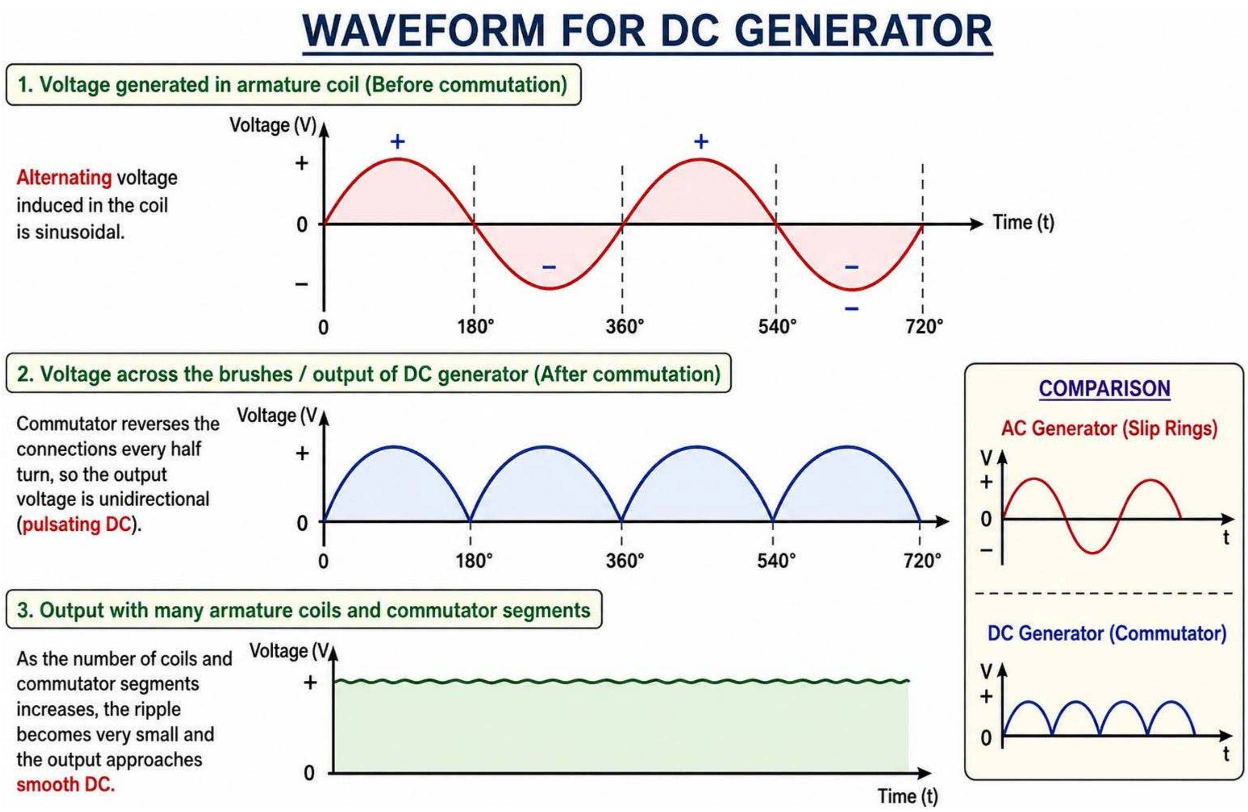

Figure 6. The AC waveform and DC conversion.

After half the rotation, the segments A and B of the commutator will change their positions as shown in Figure 5. So, brush P is in contact with segment B and Q is in contact with segment A. The directions of currents induced in conductor's "ab" and "cd" are reversed as shown in Figure 5. So, brush P continues to be negative and brush Q continues to be positive. Hence the current through the external load continues to flow from bottom to top. Thus, the load current and voltage have become unidirectional. Also, the commutator converts the alternating voltage produced by the single turn alternator into a DC voltage. Thus, a commutator operates as a rectifier which converts the ac voltage to DC voltage. We get the following waveform in Figure 6 above.

In order to remove the ripples from the rectified DC output, the number of commutator segments has increased. But there are also other methods to remove the ripples from the waveform as below:

Increase the number of armature coils, increase the number of commutator segments, use a filter capacitor across the output, use an inductor (choke) in series, use electronic voltage regulation.

But in DC Generator we use number of commutator segments to remove the ripples from the output waveform and to make the DC more efficient and smoother, which is so costly and very difficult for maintenance [8].

5. DC Rectification System

Introduction

Modern telecommunication equipment such as BTS, microwave radios, routers, switches, transmission systems, and optical equipment operate on −48 V DC power. However, commercial utility power and diesel generators typically supply 230/400 V AC. Therefore, a DC Rectification System is installed between the AC source and telecommunication equipment to convert AC power into regulated DC power.

A conventional telecom DC power system converts AC power supplied by the utility grid or a diesel generator into a regulated −48 V DC required by telecom equipment. The system comprises an AC Distribution Board (ACDB), Surge Protection Device (SPD), rectifier modules, DC bus bar, battery bank, DC distribution unit, and a monitoring and control unit.

The ACDB distributes incoming AC power to the rectifier modules while providing protection through circuit breakers and surge protection devices. The SPD suppresses transient overvoltages caused by lightning and switching events, improving system reliability.

The rectifier module is the core of the telecom power system. It converts the incoming AC supply into regulated −48 V DC through an integrated architecture consisting of an EMI filter, bridge rectifier, power factor correction (PFC) stage, isolated DC/DC converter, and output filter. Multiple rectifier modules are generally connected in parallel to provide redundancy, load sharing, and modular expansion.

The regulated DC output is delivered to a DC bus bar, which distributes power simultaneously to the telecom load and the battery bank. During normal operation, the rectifiers supply the telecom equipment while maintaining the batteries in a charged state. In the event of utility or generator interruption, the battery bank automatically supports the DC bus, ensuring uninterrupted service until the primary power source is restored. The DC distribution unit (DCDU) provides protected distribution of the −48 V supply to individual telecom loads through circuit breakers or fuses, while the monitoring and control unit supervises system operation, battery status, alarms, and protection functions.

Although conventional telecom power systems provide reliable DC power, they require separate AC generators, external rectifier cabinets, DC distribution equipment, and associated interconnecting cables. The proposed hybrid generator presented in this work integrates the AC generation stage with the rectification and DC conversion functions into a single compact unit, thereby reducing installation complexity, equipment footprint, and overall system cost. Figure 7 shows the parts of the DC rectification system used in Telecom network.

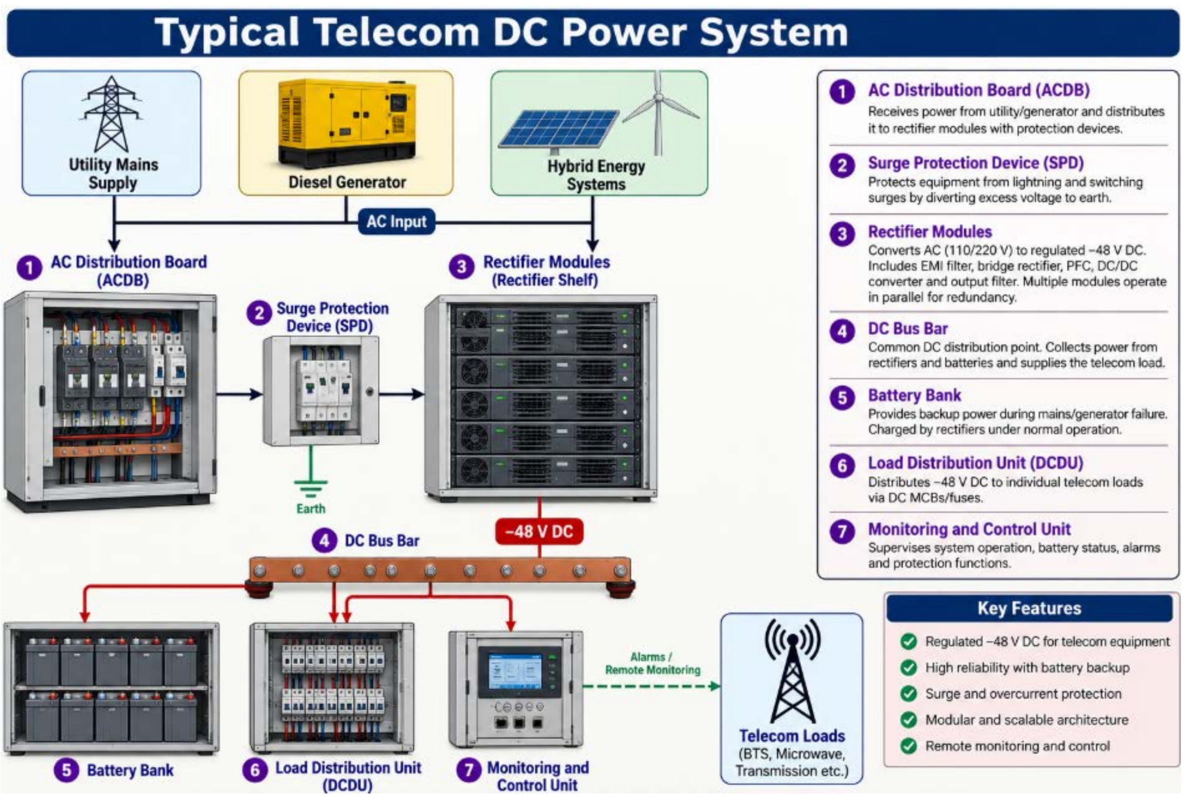

Figure 7. Parts of the DC rectification system.

6. Advantages of Brushless AC Generators as the Basis for the Proposed Hybrid Generator

6.1. Simpler Construction

Brushless synchronous AC generators have a simpler mechanical construction than conventional DC generators because they eliminate the commutator and associated mechanical switching components. This simplifies manufacturing, improves mechanical robustness, and reduces maintenance requirements.

6.2. Higher Reliability and Lower Maintenance

Unlike conventional DC generators, brushless AC generators do not rely on brushes and commutators for power generation. Consequently, problems associated with brush wear, sparking, commutator maintenance, and periodic replacement are eliminated, resulting in improved operational reliability and longer service intervals.

6.3. Higher Efficiency

Brushless AC generators generally exhibit higher efficiency because mechanical losses associated with brush friction and commutator contact resistance are eliminated. Their simple construction also contributes to improved thermal performance and continuous operation under demanding conditions.

6.4. Wide Industrial Acceptance

Brushless AC generators are widely used in utility power generation, standby diesel generator sets, industrial plants, marine applications, renewable energy systems, and telecommunications because of their high reliability, mature technology, and availability over a broad range of power ratings.

6.5. Suitability for Integration with Power Electronics

The three-phase AC output of brushless synchronous generators can be efficiently converted into regulated DC using mature power electronic rectifier systems. This characteristic makes brushless AC generators well suited for integration with embedded rectification systems, as proposed in this research, while retaining the capability to supply conventional AC loads simultaneously.

6.6. Justification for the Proposed Hybrid Architecture

The proposed hybrid AC/DC generator adopts a conventional brushless AC generator as the primary electrical machine because it combines high efficiency, low maintenance, proven field reliability, and compatibility with modern power electronic rectification systems. By integrating the rectification stage within the generator housing, the proposed architecture preserves these advantages while eliminating the need for both a mechanical commutator and a separate external telecommunications rectifier cabinet.

6.7. Comparison of AC and DC Generators

AC generators offer numerous advantages over DC generators, including simpler construction, lower maintenance requirements, higher efficiency, improved reliability, reduced sparking, lower manufacturing costs, higher voltage capability, and greater flexibility. These advantages have made AC generators the dominant technology in modern power generation systems and provide the foundation for the development of advanced DC generation systems based on AC generator architectures with integrated rectification capabilities.

7. Design for the Hybrid Proposed DC Generator

Explanation of the Proposed Next-Generation DC Generator with Built-in Rectification System.

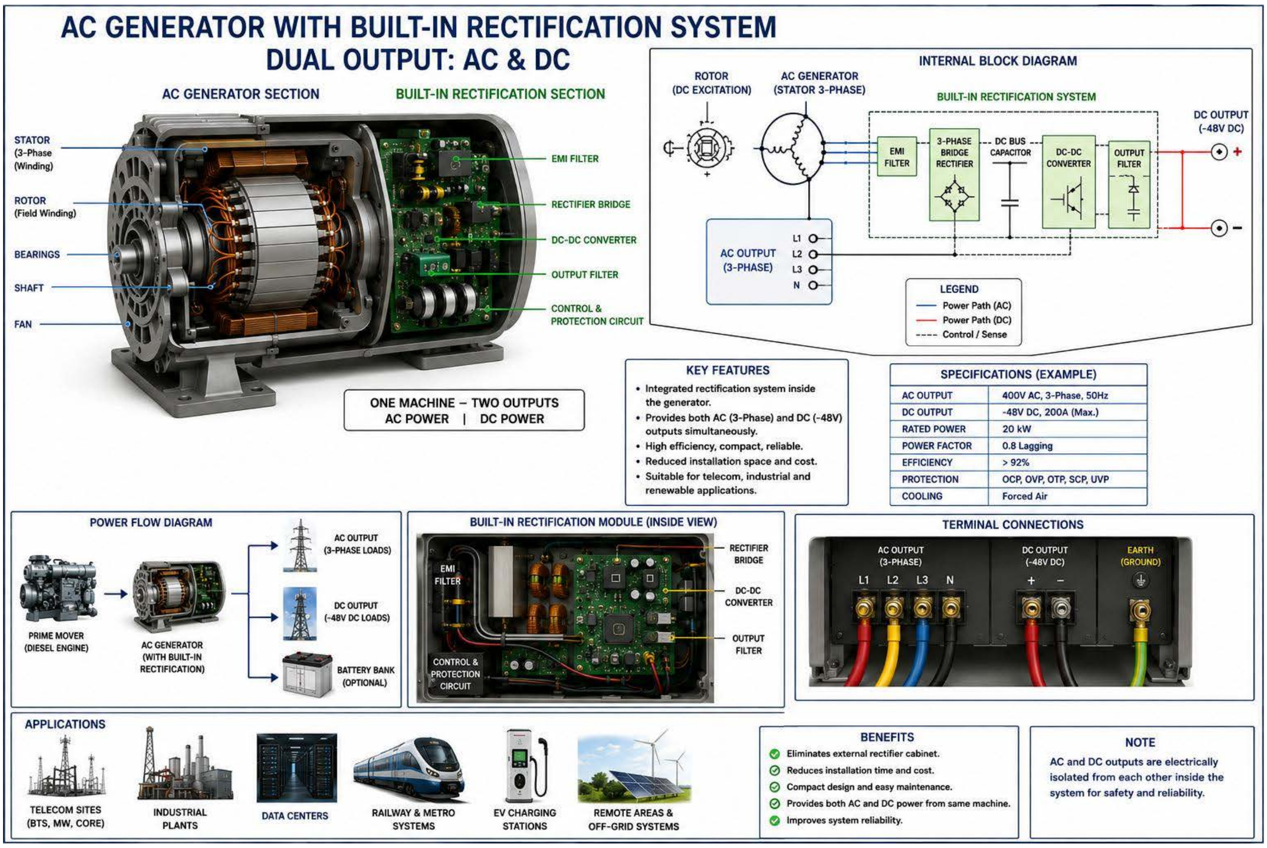

Figure 8. Proposed DC generator with built-in rectification system.

7.1. Proposed Generator Architecture

Figure 8 illustrates the proposed hybrid AC/DC generator, which integrates a mature telecommunications rectification system within the housing of a conventional brushless synchronous AC generator. Unlike conventional telecommunication power systems that require a separate external rectifier cabinet, the proposed design incorporates the rectification, filtering, voltage regulation, and protection stages inside the generator enclosure. Consequently, the generator is capable of supplying both three-phase AC power and regulated −48 V DC power from a single compact unit while retaining the operating characteristics of a conventional AC generator.

The generator consists of a brushless synchronous alternator, rotor, stator, excitation system, shaft, bearings, cooling fan, and an integrated rectification module. The built-in rectification module comprises an EMI filter, three-phase bridge rectifier, DC bus capacitor, DC-DC converter (when required), output filter, and control and protection circuitry to provide stable DC output with low ripple and high reliability.

7.2. Operating Principle

Mechanical power supplied by the prime mover rotates the generator rotor, producing a rotating magnetic field. The rotating field induces a balanced three-phase AC voltage in the stator windings according to the principle of electromagnetic induction. One output is delivered directly as conventional AC power, while the second output is internally routed to the integrated rectification module, where it is converted into regulated −48 V DC for DC-powered equipment. The combined AC and DC outputs must remain within the rated capacity of the generator.

7.3. Key Features

The proposed hybrid generator integrates a brushless synchronous alternator, embedded AC/DC rectification, DC/DC conversion, and closed-loop voltage regulation into a single compact unit. Compared with conventional telecom power systems, the proposed architecture simultaneously provides AC and regulated −55 V DC outputs while eliminating the need for an external rectifier cabinet. This integration reduces equipment count, installation space, cabling, transportation requirements, deployment time, and maintenance costs. The brushless generator architecture further enhances operational reliability by minimizing mechanical wear and simplifying field installation, making the system particularly suitable for remote and mission-critical applications.

7.4. Applications

The proposed hybrid generator is applicable to installations requiring simultaneous AC and regulated DC power. Typical applications include telecommunications infrastructure such as base transceiver stations (BTS), microwave links, and transmission sites, as well as emergency and disaster recovery communication systems, military and mobile communication units, Cell-on-Wheels (COW) deployments, remote industrial facilities, and hybrid renewable-energy or off-grid power systems. The integrated architecture is particularly advantageous in locations where compactness, rapid deployment, and high system reliability are essential [9].

8. Mathematical Comparison between Conventional DC Generator and Proposed AC Generator with Built-In Rectification System

Although both systems ultimately provide DC power to the load, the method of generation is fundamentally different. Conventional DC Generator generates

AC internally in the armature. Uses a mechanical commutator for rectification. Output is pulsating DC. In order to remove the ripples from the output waveform, the number of commutator segments must be increased, which costs more and makes the operation and maintenance more difficult. While the proposed generator generates three-phase AC using a conventional alternator and uses electronic rectification and DC-DC conversion process to produce regulated and filtered DC output. While it can simultaneously provide AC and DC outputs.

Mathematic Comparison:

1) Conventional DC Generator Output

The generated EMF is:

$$E_g = \frac{P\Phi ZN}{60A} \tag{2}$$

Where:

P = Number of poles;

Φ = Flux per pole (Wb);

Z = Total conductors;

N = Speed (RPM);

A = Parallel paths.

The armature generates:

$$e(t) = E_m \sin(\omega t)$$

However, the commutator mechanically rectifies this waveform.

Resulting output:

$$e_{DC}(t) = \left|E_m \sin(\omega t)\right|$$

This is a full-wave rectified waveform.

The average DC voltage becomes:

$$V_{DC(avg)} = \frac{2E_m}{\pi}$$

Note: *(The proof for this equation is available at the end).

or

$$V_{DC(avg)} = 0.637E_m$$

2) Ripple Factor

The ripple factor of a conventional DC generator is:

$$r = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} \tag{3}$$

Where:

$I_{rms} = 0.707I_m$, note: ** (The proof for this equation is given at the end).

$I_{dc} = 0.637I_m$.

Substitute the values of Irms and Idc in Equation (3)

For a full-wave rectified waveform:

$$r \approx 0.482$$

This means approximately: 48.2%.

Ripples exist in the output, and it is pulsating output.

3) Proposed AC Generator with Built-in Rectification

The alternator produces three-phase AC.

Phase voltages:

$$V_a = V_m \sin(\omega t)$$

$$V_b = V_m \sin(\omega t - 120^\circ)$$

$$V_c = V_m \sin(\omega t - 240^\circ)$$

For a three-phase bridge rectifier:

$$V_{DC} = 1.35 V_{LL}$$

Where:

$$V_{LL}$$

is line-to-line AC voltage.

Example

For:

$$V_{LL} = 400V$$

Then

$$V_{DC} = 1.35 \times 400$$

$$V_{DC} = 540V$$

DC-DC Converter Stage

The converter regulates the DC voltage.

For telecom systems:

$$540VDC$$

is converted into

$$-48VDC$$

using:

$$V_o = D \times V_{in} \tag{4}$$

Where:

D = Duty cycle;

V_{in} = Input DC voltage;

V_o = Output voltage.

Output Ripple.

After filtering:

$$V_{ripple} < 1\%$$

Typically:

$$V_{ripple} < 0.5V$$

for telecom applications. Which is nearly pure dc.

9. Voltage Regulation Comparison

Voltage regulation is given by:

$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 \tag{5}$$

Where:

V_{NL} = No-load voltage;

V_{FL} = Full-load voltage.

Conventional DC Generator

Typically, the voltage regulation for the conventional DC generator is given below

$$VR = 5\% - 15\%$$

It is due to brush losses, armature reaction and commutation effects.

Proposed Generator

With electronic regulation:

$$VR < 2\%$$

which is highly desirable for telecom equipment.

10. Efficiency Comparison

Conventional DC Generator:

$$\eta_{DC} = \frac{P_{out}}{P_{out} + P_{cu} + P_{iron} + P_{brush} + P_{mech}} \times 100$$

Typical:

$$85\% - 90\%$$

Proposed Generator:

$$\eta_{overall} = \eta_{alternator} \times \eta_{rectifier} \times \eta_{converter}$$

Assuming:

$$\eta_{alternator} = 95\%,\ \eta_{rectifier} = 98\%,\ \eta_{converter} = 96\%$$

Then:

$$\eta_{overall} = 0.95 \times 0.98 \times 0.96,\ \eta_{overall} = 89.4\%$$

Modern designs can exceed 92% of overall efficiency [10] [11].

11. Simulation MATLAB/SIMULINK

Here is the Simulink model for the proposed generator in **Figure 9**.

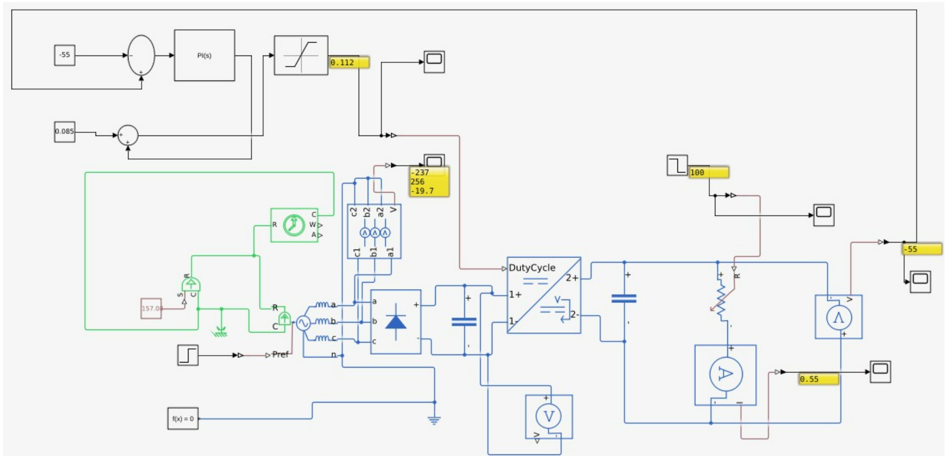

Figure 9. The Simulink diagram.

11.1. Measurement of Voltage Regulation

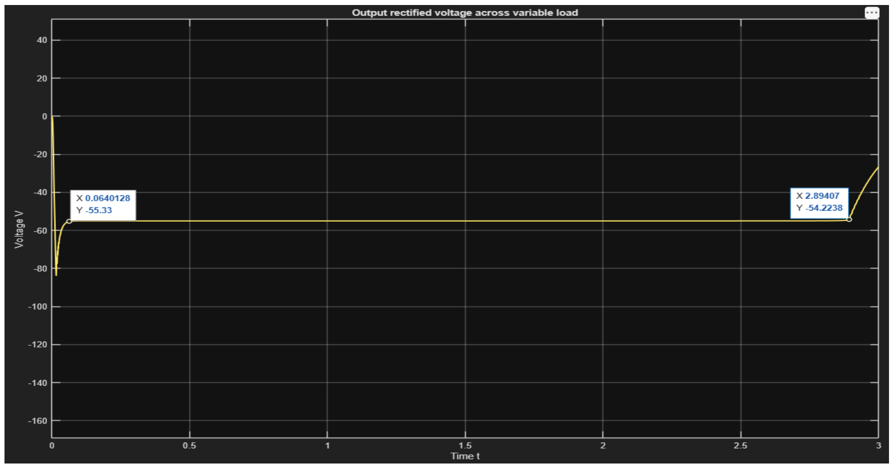

Figure 10. Output rectified voltage across a variable resistor (100 Ω to 10 Ω).

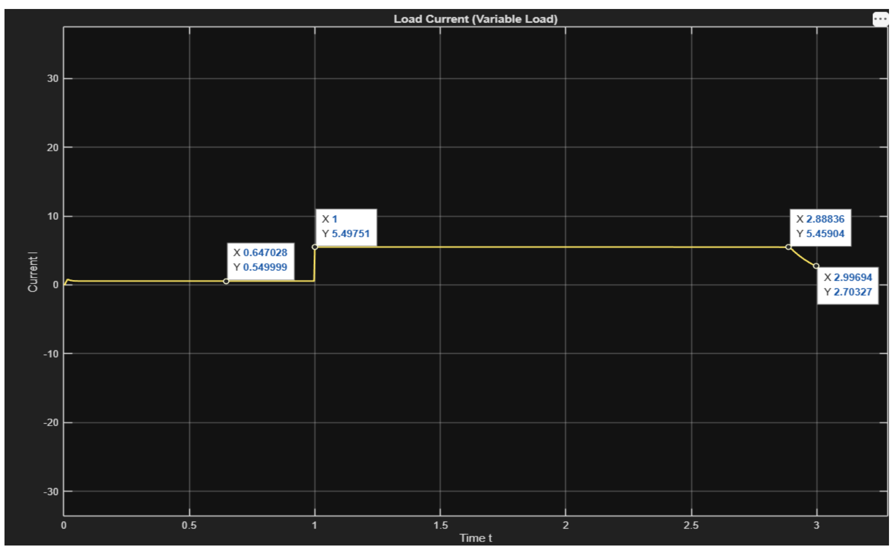

Figure 11. Output current waveform for the variable resistor (100 Ω to 10 Ω).

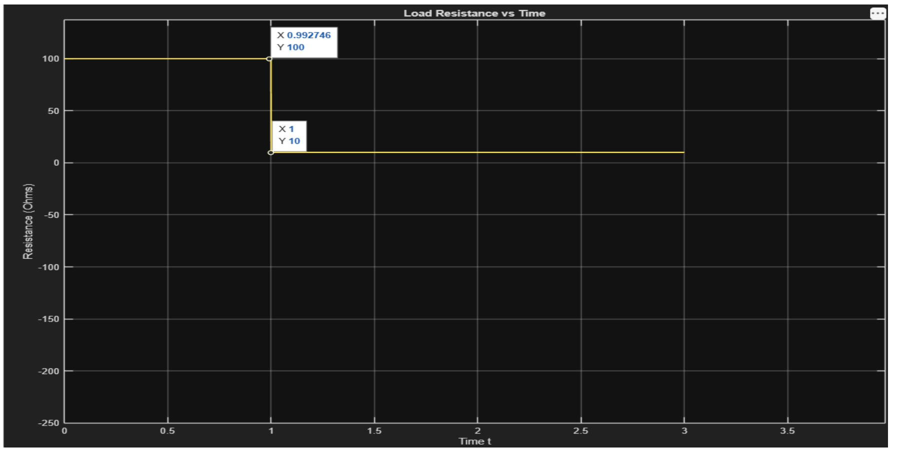

Figure 12. Output waveform for the variable resistor (100 Ω to 10 Ω).

Figure 10 shows us the output rectifier voltage for the variable load. The load resistance parameters are (step = 1, initial resistance = 100 Ω, and Final resistance = 10 Ω).

Figure 11 shows us the output rectifier current for the variable load.

Figure 12 shows us the output waveform for the variable load which changes from 100 Ω to 10 Ω.

From Figure 10 graph:

- Initial regulated voltage (before load change): $V_1 = -55.33$ V
- Final regulated voltage (after load change): $V_2 = -54.2238$ V

For DC telecom systems, we use the absolute values:

$$|V_1| = 55.33 \text{ V}$$

$$|V_2| = 54.2238 \text{ V}$$

Voltage Regulation Calculation

Equation (5) => $\text{Voltage Regulation}(\%) = \dfrac{|V_1| - |V_2|}{|V_1|} \times 100$

Substituting your values:

$$= \frac{55.33 - 54.2238}{55.33} \times 100 = \frac{1.1062}{55.33} \times 100 = 1.999\% < 2.00\%$$

During the dynamic load test, the load resistance was changed from 100 Ω to 10 Ω at 1 s. The output voltage changed from −55.33 V to −54.22 V, corresponding to a voltage regulation of 2.00%. This demonstrates that the PI-controlled DC-DC converter maintained the output voltage close to the nominal −55 V under a tenfold increase in load current.

11.2. Load Current Analysis

The graph in Figure 11 illustrates the load current response of the proposed hybrid AC/DC generator under varying load conditions. As the load resistance decreases from 100 Ω to 10 Ω, the output current increases accordingly, while the regulated output voltage remains nearly constant due to the action of the PI-controlled DC-DC converter. This demonstrates that the proposed system effectively supplies the increased load demand without significant voltage deviation, confirming its capability to maintain stable operation under dynamic loading conditions. The results validate the suitability of the proposed generator for telecom DC power applications, where reliable current delivery and voltage stability are essential. Table 2 below shows the analysis.

Table 2. Load current analysis.

Load	Voltage	Current
100 Ω	≈59.02 V	0.59 A
50 Ω	≈58.90 V	1.18 A
25 Ω	≈58.70 V	2.35 A
10 Ω	≈58.01 V	5.80 A

11.3. Output Voltage Ripple

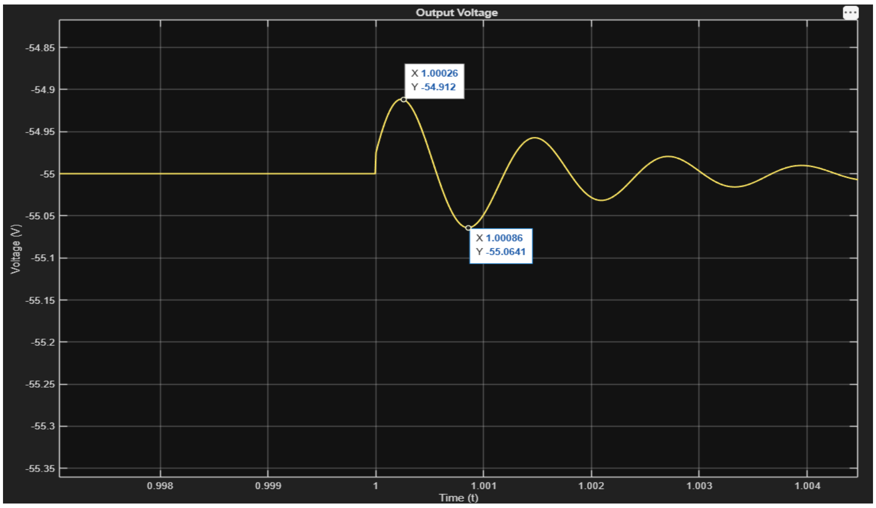

Figure 13. Output voltage ripple analysis.

- Maximum voltage (peak): $V_{\max} = -54.912\ V$
- Minimum voltage (valley): $V_{\min} = -55.0641\ V$

Ripple (Peak-to-Peak)

$$V_{ripple(pp)} = \left|V_{\max} - V_{\min}\right| = \left|-54.912 - (-55.0641)\right| = 0.1521\ V$$

Output voltage ripple = 0.1521 V (152.1 mV peak-to-peak).

Ripple Percentage

Using the average output voltage of approximately 55 V,

$$Ripple(\%) = \frac{0.1521}{55} \times 100 = 0.2765\% < 1\%$$

In Figure 13 we can clearly see the ripples in the output voltage waveform.

The transient response of the regulated DC output voltage following a load disturbance is shown in Figure 13. The maximum and minimum output voltages were measured as −54.912 V and −55.0641 V, respectively, resulting in a peak-to-peak voltage ripple of 0.1521 V. The corresponding ripple percentage is 0.277%, which is well below the typical 1% requirement for telecom DC power systems. The oscillations decay rapidly after the disturbance, confirming that the PI-controlled DC-DC converter provides effective damping and maintains a stable regulated output voltage under dynamic load conditions.

11.4. Settling Time

Settling time is the time required for the output voltage to become stable again after a load change causes a transient variation in the waveform. Refer to Figure 14 below.

Measured Results:

- Load step time: $t_0 = 1.0000$ s.
- Steady-state voltage before load change: $V_{ss} = -54.9999$ V.
- Peak overshoot: $V_{max} = -54.9120$ V.
- Peak undershoot: $V_{min} = -55.0641$ V.
- Settled again at: $t_s = 1.00664$ s.

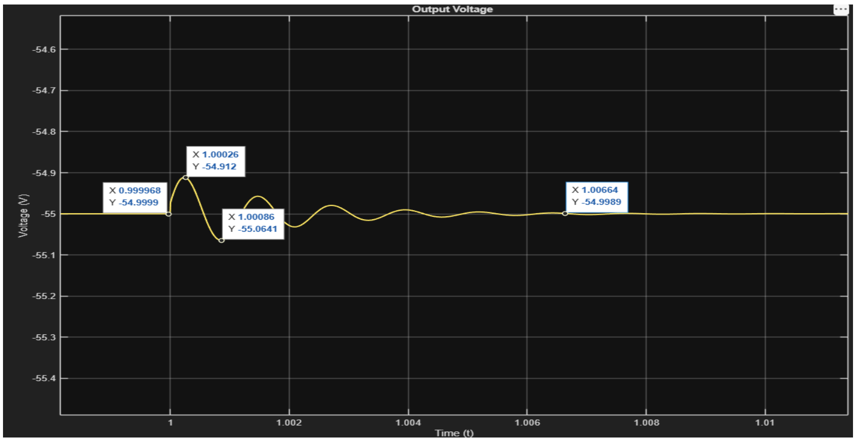

Figure 14. Settling time analysis.

Peak Overshoot

$$\%OS = \frac{54.9999 - 54.9120}{54.9999} \times 100 = 0.16\%$$

Peak Overshoot = 0.16%

Peak Undershoot

$$\%US = \frac{55.0641 - 54.9999}{54.9999} \times 100 = 0.12\%$$

Peak Undershoot = 0.12%

Settling Time

$$T_s = 1.00664 - 1.00000,\ T_s = 0.00664\ s,\ \boxed{T_s = 6.64\ ms}$$

The transient performance of the proposed hybrid AC/DC generator was evaluated under a step load change from light load to heavy load. Prior to the disturbance, the output voltage was regulated at −54.9999 V. Following the load transition, the output voltage exhibited a maximum overshoot of 0.0879 V (0.16%) and a maximum undershoot of 0.0642 V (0.12%) before returning to its regulated operating point. The output voltage settled within 6.64 ms, demonstrating a fast dynamic response and effective damping of transient oscillations by the PI-controlled DC-DC converter. These results confirm the capability of the proposed system to maintain stable output voltage under rapidly changing load conditions, making it suitable for telecom DC power applications.

12. Thermal Management and Protection Design

Since the rectification stage is integrated within the generator housing, appropriate thermal management and electrical protection are incorporated to ensure reliable operation. The rectifier, DC-DC converter (where applicable), and associated power electronic components are mounted on heat sinks located within the airflow produced by the shaft-mounted cooling fan to dissipate semiconductor losses. Electrical isolation is maintained between the AC generator, DC bus, and generator frame using suitable insulation and recommended creepage and clearance distances. The protection system includes overcurrent, short-circuit, overvoltage, and overtemperature protection to safeguard both the generator and connected loads. In addition, the rectification module is designed as a modular serviceable assembly that can be inspected or replaced with minimal disassembly, thereby simplifying maintenance and improving system availability. The detailed thermal design, component selection, and protection coordination will be investigated during prototype development and experimental validation [12].

13. Comparative Summary

In Table 3 there is a comparison between both types of generators.

Table 3. Comparison between conventional DC generator and proposed generator.

Parameter	Conventional DC Generator	Proposed Generator
Internal Generation	AC	3-Phase AC
Rectification	Mechanical Commutator	Electronic Rectifier
DC Output Equation	$0.637E_m$ (single-phase full-wave rectified armature EMF)	$1.35V_{LL}$ (three-phase bridge rectifier from RMS line-line voltage)
Ripple Factor***	48.2%, Depending on armature design, number of coils, commutator segments, and filtering (48.2% for the ideal single-coil full-wave rectified case derived in Section 9)	<1%, (predicted with the proposed LC-filtered rectifier under the stated design assumptions)
Voltage Regulation	5% - 15%	<2%
Maintenance	High	Low
Brushes	Required	Not Required

Continued

Commutator	Required	Not Required
AC Output Available	No	Yes
DC Output Available	Yes	Yes
Output Power	P_{DC}	$P_{AC} + P_{DC}$
Telecom Suitability	Moderate	Excellent

***The two equations are presented to describe the respective voltage-generation mechanisms of the two architectures. Because they are referenced to different electrical quantities (single-phase peak EMF versus three-phase RMS line-to-line voltage), they should not be interpreted as directly comparable numerical values.

14. Conclusion

Refer to Table 3, The analytical comparison presented in this section uses the ideal single-coil full-wave-rectified waveform as a reference for illustrating the operating principle of a conventional DC generator. In practical DC generators, the output ripple depends on the number of armature coils, the number of commutator segments, machine geometry, rotational speed, load conditions, and any additional filtering. Consequently, the analytical ripple factor of 48.2% derived in Section 9 represents only the ideal reference waveform and should not be interpreted as the ripple level of all practical DC generators.

Proof of the formulae:

*For a full-wave rectified sine wave, it is easier to integrate over half a cycle:

$$V_{DC(avg)} = \frac{1}{\pi}\int_0^{\pi} E_m \sin\theta \, d\theta$$

where

$$\theta = \omega t$$

Take E_m outside the integral:

$$V_{DC(avg)} = \frac{E_m}{\pi}\int_0^{\pi} \sin\theta \, d\theta$$

The integral of $\sin\theta$ is:

$$-\cos\theta$$

Therefore:

$$V_{DC(avg)} = \frac{E_m}{\pi}\left[-\cos\theta\right]_0^{\pi}$$

Substituting limits:

$$= \frac{E_m}{\pi}\left[-\cos\pi + \cos 0\right]$$

Since:

$$\cos\pi = -1$$

and

$$\cos 0 = 1$$

then:

$$= \frac{E_m}{\pi}\left[-(-1)+1\right] = \frac{E_m}{\pi}(2)$$

Thus:

$$\boxed{V_{DC(avg)} = \frac{2E_m}{\pi}}$$

**RMS Value of Full-Wave Rectified Wave

The RMS value is

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_m^2 \sin^2\theta\, d\theta}$$

Since the average value of $\sin^2\theta$ over one cycle is: $\frac{1}{2}$

we get:

$$I_{rms} = \sqrt{\frac{I_m^2}{2}},\ I_{rms} = \frac{I_m}{\sqrt{2}},\ I_{rms} = 0.707 I_m$$

Dedication

To my beloved teacher of Electromagnetic Circuits, whose wisdom illuminated my path like a guiding light. Every lesson planted a seed of curiosity, every word inspired confidence, and every encouragement strengthened my determination. This work is a humble tribute to your unwavering dedication and the lasting impact you have made on me and my academic journey.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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