Design Parameters for Enhancing Performance of a Power Generator

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ABSTRACT

This study focused on the design and assembly of a 10kVA rated power generator, with the objective of improving its power rating while minimizing size, weight, and cost. Mathematical relationships were employed to determine the optimal operating conditions for enhanced power output, considering parameters such as the number of armature poles, magnetic flux, stator bore diameter, number of armature conductors per phase, and synchronous speed of rotation. It was discovered that increasing in number of armature conductors per phase and the stator bore diameter had a positive impact on the power rating. The highest power output rating achieved in this study was 725kVA, obtained by increasing the number of armature conductors per phase to 200, while keeping other parameters constant. This finding highlights the importance of maintaining a moderate stator bore diameter to ensure an affordable design for the electrical power generator.

Keywords: Rated power, armature, poles, magnetic flux, stator diameter, synchronous speed

INTRODUCTION

With the world's CO_2 levels steadily increasing and the limited amount of fossil fuels, it is evident that exploring renewable sources for energy production is necessary [1]. Although fossil fuels are currently more convenient and cost-effective, this is mainly due to the existing infrastructure and research invested in their utilization. However, the advantages of fossil fuels, such as high energy density and market dominance, are overshadowed by their negative aspects. In 2004 alone, fossil fuels released a staggering 8749 million metric tons of carbon into the atmosphere, and energy consumption has only increased since then [1]. If we do not take action, our dependence on fossil fuels will lead to a global crisis when they eventually run out.

Fortunately, researchers have been actively investigating various renewable energy sources, ranging from nuclear fusion to harnessing the kinetic energy from streams [2]. Among the prominent renewable energy options are nuclear fission, solar energy (photovoltaic cells), hydroelectric power, and wind power [2]. While nuclear fission has lost support due to concerns about its proximity to residential areas, photovoltaic cells, wind turbines, and hydroelectric power are now seen as the future of renewable energy.

Photovoltaic cells, also known as PV cells, utilize the sun's energy to stimulate current flow through semiconductors, generating electricity. Over the past decade, significant advancements have been made in PV cell technology, making them more affordable, with prices now under $1 per Watt [2]. However, a major limitation of PV cells is their reliance on sunlight, rendering them effective only during the daytime on sunny days. To overcome this limitation, PV cells can be paired with batteries to store energy for use when sunlight is unavailable. However, the cost of batteries and charging units significantly increases the overall system cost, making solar cells less accessible to a large portion of the population.

Both wind power and hydroelectric power operate on the same principle, converting kinetic energy from wind or running water into electrical energy through the rotation of a turbine connected to a generator [3]. Similar to

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solar energy, wind power can only be harnessed when the wind is blowing, while hydroelectric power can be generated as long as there is a current in a stream [4]. However, the conversion of kinetic energy to electric energy can be costly, particularly in the case of low-speed generators, making these forms of energy less readily available in many parts of the world.

In developing countries like Nigeria, where many induction synchronous generators used in civilian applications have been designed with poor machine efficiency, researchers have begun exploring expert systems in the electric power system [5]. This research aims to develop an expert system that determines optimum parameters for designing a power generator capable of efficiently converting mechanical energy from a prime mover into electrical energy, ensuring high generator efficiency and quality consumption of electricity at rated speed.

LITERATURE REVIEW

Basic Principle of Power Generation

Generators work by using rotational energy to spin a magnet across a loop of wire, or vice versa [6]. This produces an Electromagnetic Field in the wire that is proportional to both the number of loops (n) and change in magnetic flux (d/dt).

$$\text{EMF} = n * \frac{d\emptyset}{dt} \qquad (1)$$

From equation (1) it is easy to see that if there was already a generator either changing the speed it rotates at (d/dt) or the number of loops (n) would change the EMF. Now if there was a desired speed then adding loops of wire would cancel out the change in the EMF that came from changing the operational speed of the motor.

Main Components of Synchronous Generators

The main housing of synchronous generators consists of two parts, namely the front and rear brackets. These brackets enclose the internal components and feature slots to facilitate air circulation and dissipate heat. The rear end of the generator houses the electrical connections. One example of a simple three-wire design includes an internal regulator rectifier with three terminals: the B terminal, which serves as the alternator's output to charge the battery; the S terminal, which allows the regulator to sense voltage; and the F terminal, which provides initial power to the electromagnet during startup. The circuit is completed through the car's frame, connecting to and from the battery's negative terminal. The rear end of the unit, typically protected by a cover, houses the internal regulator and rectifier components.

Removing the housing reveals the internal components of the generator. The rotor, which is stationary and does not rotate, consists of laminated sheets with slots along the inner edge. Three sets of copper wires are wound between these slots in a specific order. Each coil set is connected to form a neutral point in a star configuration. Together, these coil sets produce three phases of AC electricity. The other end of each coil connects to the rectifier through the case. At the center of the alternator, there is a coil of wire wound around an iron core and connected to the shaft. The shaft also holds two slip rings, which are connected to opposite ends of the coil. Brushes, located within the rear housing, apply pressure against the slip rings.

These brushes, made of spring-loaded carbon blocks, establish an electrical connection with the slip rings [7]. Initially, a capacitor supplies electricity to the coil through the brushes. As the current passes through the coil, it generates an electromagnetic field. The electromagnet, attached to the rotor shaft, develops a North Pole and a South Pole. When the engine rotates the shaft, the electromagnet also rotates past the rotor's coils. This motion induces a current in the coils, resulting in the generation of electricity.

Rectifying Circuit

The rectifying circuit is used to turn the generated AC voltage into a steady DC voltage which is important because that is the form of energy storage batteries use [8]. A rectifying circuit is shown in figure 1.

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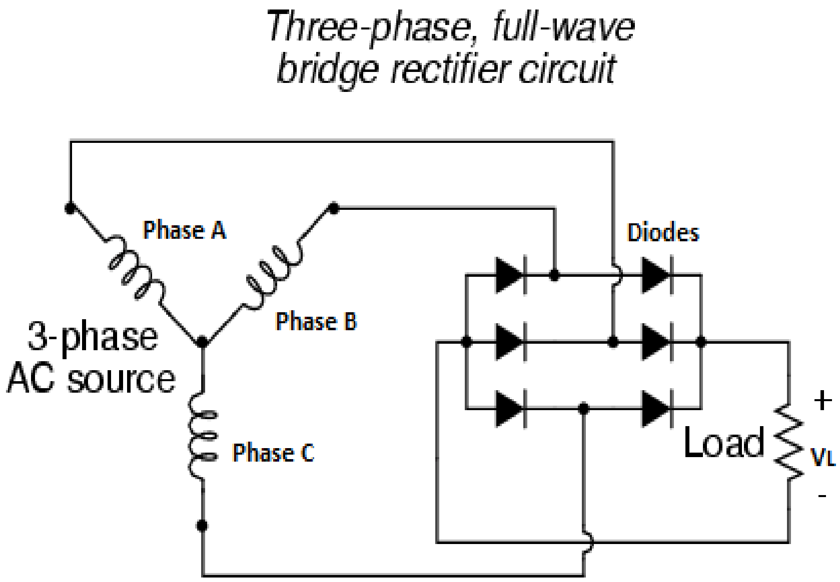

Figure 1: Circuit diagram for a rectifier [2]

Once the alternator is generating electricity, the alternator is able to power the electromagnet by itself via a diode trio which converts a three-phase AC into DC.

Automatic Voltage Regulator

The voltage and current produced by the alternator will vary with the speed of the propeller [9]. The faster the propeller, the faster the alternator also rotates. This increases the voltage and current. To control this, another component is used called the regulator, which is mounted at the rear of the unit. This is an integrated circuit board, which monitors the output of the alternator, and varies the current flowing through the electromagnet to control its strength. The strength of the electromagnet can be used to vary the output from the alternator [10].

Increase or decrease in electromagnetic field strength is enhanced by varying the voltage and current generated in the coil. Hence, the essence of electromagnetism is to control output power of the alternator. Most modern alternators use a diode trio, which converts alternating current of the alternator into direct current to power the electromagnet [11]. Once the alternator is generating electricity on the power supply of the electromagnet, within the regulator, we find a component known as a transistor. The voltage sensor is also connected to the regulator. The transistor is a type of electronics which can be turned on and off 1000s of times per second by a controller. This can be used to control the amount of current flowing.

Self excitation in power generators

Self-excited induction generators (SEIGs) were developed to address issues with reactive power consumption and poor voltage regulation under varying speeds in normal induction generators [12]. Using static power converters helps better control the output voltage of induction generators.

Induction generators are classified by rotor construction, like wound rotor or squirrel cage. The generating schemes can also be categorized based on the prime movers (constant or variable speed) and locations (near power grids or isolated places).

The classifications include constant-speed constant-frequency, variable-speed constant-frequency, and variable-speed variable-frequency schemes [13]. In the constant-speed scheme, the prime mover speed is held stable to operate the generator at 1-5% above synchronous speed on an infinite bus bar. They offer simplicity, easy operation, control and maintenance without synchronization issues at low cost.

Variable-speed operation results in higher output for both low and high wind speeds, increasing annual energy yields [14]. Both horizontal and vertical axis wind turbines benefit. SEIGs suit resistive, frequency-insensitive loads well, especially for standalone wind power systems.

Modern trends aim to replace electrical machines with static excitation systems for higher performance and longer life [15]. Proper generator sizing requires understanding its operating conditions, connected appliances, modes, and stresses to support any over-stresses.

RESEARCH METHODOLOGY

In the research methodology section, the design, assembly process, and materials of the alternator are detailed. The component parts of the alternator and their corresponding materials are listed in Table 1, along with the criteria for material selection. Copper is preferred over aluminum for the windings of the generator due to its higher conductivity, mechanical strength, and thermal stability [15].

The assembly process of the alternator is described, including the tools used for various operations. The steps involved in the assembly process are outlined in Table 1, along with the required equipment and tools for each step.

Table 1: Assembly operation of the alternator

Steps	Operations	Equipment and Tools
1. Welding of the frame	The steel members that make up frame structure for the alternator were welded together	A.C Welding equipment, hammer
2. Winding of Stator coils	The windings for the stator coils were securely placed into the rectangular slots created around the inner periphery of the stator bore	Welding machine, Hammer, Nose pliers
3. Winding of armature coils	The windings for the armature coils were wound around the position provided on the two poles of the armature.	Welding machine, Hammer, Nose pliers
4. Insulation of Stator coils	The insulation of the stator coils was done by fixing insulation papers at the stator slots. This prevents the casing of the alternator from conducting electricity	Flat screw driver
5. Clamping and Soldering	The armature and stator coils were clamped respectively, and the coils were soldered, (start to start, and end to end). Test for continuity was done to ensure that the soldering was correctly done	Soldering bit, G-clamp, Multimeter
6. Assembly of rotating parts	The shaft, shaft bearings and the armature were assembled securely, while ensuring that adequate balancing and eccentricity is achieved	Hammer, spanner,
7. Assembly of casing	The parts of the alternator were assembled into the casing of the alternator, ensuring that it is properly earthed, and securely covered	Spanners, Hammer, Screwdriver
8. Assembly of the Frame	The completed assembly of the alternator is now mounted on the machine frame, using vibration dampers, bolts, and nuts	Spanner, Screwdriver, Hammer

Testing and inspection are carried out after the assembly is completed. The tests include measuring the rotational speed, voltage, current, output power, and magnetic flux of the alternator.

Design calculations are performed to improve the rated power output of the alternator [16]. The parameters that need adjustment to increase the rated power output are determined through mathematical analysis. The design adjustments aim to achieve low cost, minimal size, and reduced weight while meeting specified standards.

The power output equation for a synchronous alternator is presented, indicating its relationship with the other parameters. Equation (1) is provided as the formula for calculating the output power rating of the alternator.

In the section on performance evaluation of the alternator, the focus is on increasing the output power rating by modifying the number of armature winding conductors and the inner bore diameter of the armature. These modifications are substituted into equation 7 to determine the impact on the output power rating. The specific magnetic loading (Bav) is an important parameter and its value ranges from 0.2 Tesla to 0.6 Tesla for an alternator operating at a frequency of 50Hz.

The number of armature conductors (Z) is initially 10, and it is increased from this value. The increase in the number of armature conductor's results in a corresponding increase in magnetic flux, and this effect is taken into account during the evaluation process.

RESULTS AND DISCUSSION

The power rating results obtained in section three are analyzed in order to determine the conditions at which optimum power rating of the alternator can be achieved.

Table 2 shows the power ratings obtained when the number of armature conductors (Z) is increased at different values of specific magnetic loading B_{AV}

Table 2. Number of armature conductors (Z), and increase in power rating

Value of B_{av} (Tesla)	Number of armature conductors, Z	10	50	100	150	200
0.16	P_{rating} (kVA)	10	48	95	143	190
0.3	P_{rating} (kVA)	18	90	180	270	360
0.6	P_{rating} (kVA)	36	180	360	540	725

The data shown in table 2 is represented by figure 2 for clarity.

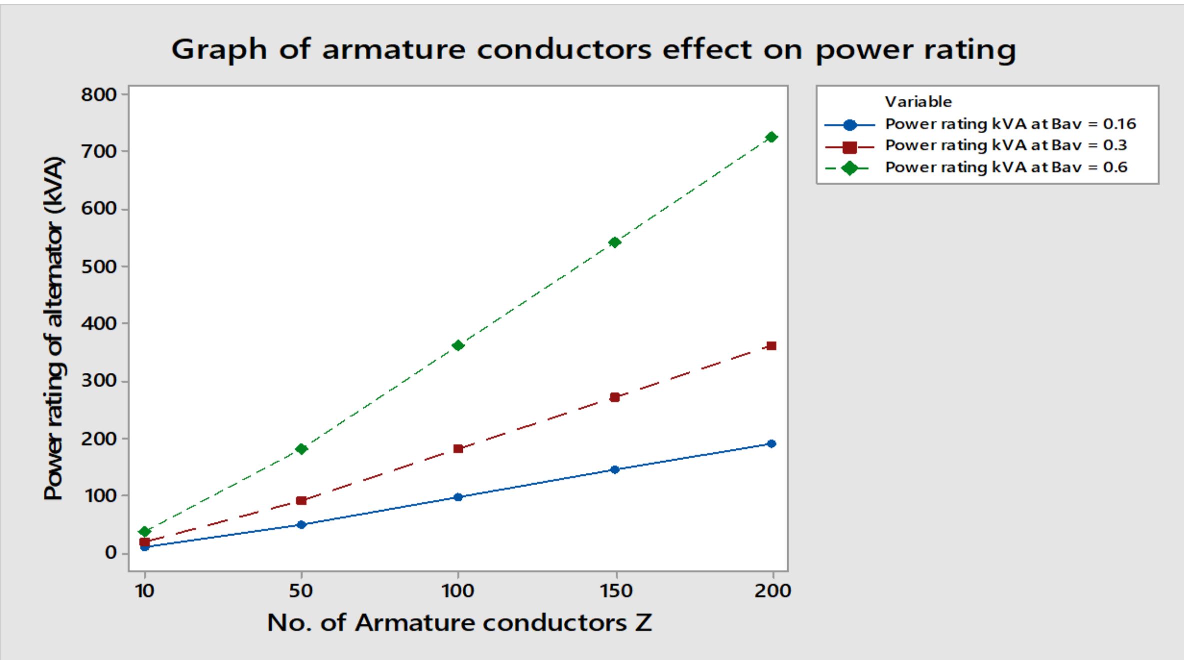

Figure 2: Effect of increasing the number of armature conductors

Analyzing figure 2, it can be seen that the power rating of the alternator increases as the number of conductors in the armature increases. The power rating increases as the specific magnetic loading of the alternator is increased. A more detailed observation showed that increasing the number of armature conductors will also cause an increase in the total electric loading of the alternator (ac).

Consequently, an increase in total magnetic loading increased the copper losses in the stator winding; a phenomenon in which the magnetic flux created in the copper windings forms a resistance to the flow of electric current supply. The effect of copper losses in the alternator was cushioned by adding a capacitor to the output circuit that will increase the current flow.

An increase in total magnetic loading also caused the operating temperature of the alternator to increase. The increase in operating temperature tends to reduce the efficiency of the alternator. To reduce the high temperature of the machine, cooling vents were created on the outer casing of the alternator that will facilitate air flow and cooling in the alternator.

CONCLUSION

The research has made significant contributions to the field of alternator design and optimization. It has provided cost-effective methods for increasing the power rating of an alternator while maintaining its compact design. The findings offer valuable insights for decision making, informing researchers, maintenance technicians, and machine designers about the effects of different methods on weight, compactness, design complexity, and overall cost. The research has also advanced theoretical methods of alternator power optimization and serves as a guide for computer engineers in developing optimization applications.

The conclusion from this work indicates that increasing the number of armature conductors per phase and the inner bore diameter of the stator result in higher power ratings. However, increasing the number of armature conductors per phase yields a greater power output increase compared to increasing the stator bore diameter. It is also noted that increasing the stator bore diameter leads to increased size, weight, and cost. Though the cost is high, but enables long-term durability and maintenance. Therefore, increasing the number of armature conductors is a preferred option as it achieves power increase while maintaining a compact and lightweight design, but its durability and maintenance may be short-termed.

For future research, it is recommended to use efficient coil winding machines for accurate placement of windings. Additionally, exploring different configurations of synchronous generators, such as salient pole, round-rotor, permanent magnet, and brushless excitation, would provide further insight into their effects on generator performance.

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