Modified Alternator design for Automatic Voltage Regulation

Anupama Prakash, Anurag Kumar, Bhanu Pratap Singh

Abstract: For the proper operation of electrical equipment, it is important to have input voltage within permissible range (230V±5%). The input voltage supplied by the utility is generated by alternators. It is a well-known fact that the alternator terminal voltage decreases with an increase in load. In order to meet the consumer's requirement, one needs to regulate the voltage of an alternator. This paper proposes the manner in which the design of the alternator can be modified to minimize the voltage regulation of an alternator.

Keywords : Alternator, compensating winding, power diode, voltage regulation.

I. INTRODUCTION

The voltage regulation of an alternator is defined as "the rise in voltage when full-load is removed (field excitation and speed remaining the same) divided by the rated terminal voltage. This shows that the terminal voltage of an alternator decreases with the increase in load. For the optimum operation of the equipment, it is important to regulate this change in the voltage from no load to full load within a permissible range.

In any Synchronous generator, the voltage obtained across the terminals should be as constant as possible for delivery of sufficient power supply. This terminal voltage is dependent on certain factors, which are: speed, load, power factor, and temperature rise. Any small change in these factors affects the terminal voltage. so the design of an appropriate regulation device is needed for keeping the voltage constant.

Voltage regulators are of two types- manually or automatically controlled. Manually controlled voltage operators use the following methods for voltage regulation: tap changer method, auto transformer method, and an induction regulator method. In densely interconnected systems, regulating the terminal voltage manually is not advantageous, so we need equipment that regulates the terminal voltage regularly and makes the voltage generation efficient.

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Keeping the above issues in mind, Automatic Voltage Regulators (AVRs) are designed and used all over the world. C.V. Reddy, et.al have designed a triggering circuit for a fully controlled thyristor bridge converter which supplies current to the field of the alternator and also fabricated an analog feedback circuit to automatically control the output voltage of the alternator [1].

Nirgudkar et.al, have designed a digital AVR which adjusts the excitation voltage and current for the control of the system. However, this type of AVR controller must have capabilities to acquire the demanded transient response that is able to overcome the time-delay of exciter and to damp out the inherent instability [2].Csaba Blága et.al, have use PWM technique to control the field voltage. This type of control introduces harmonics in the system and thus is not desirable [3]. B. K. Sahu et.al, have discussed the design of Proportional, Integral, and Derivative (PID) controller to an Automatic Voltage Regulator (AVR) tuned by Simplified Particle Swarm Optimization algorithm [4].

Publication No. US3617857 (A) relates to a voltage regulator with an oscillator circuit which has the output fed into a stationary, primary winding of a rotary transformer device which, in turn, has a secondary winding rotatable with the rotor shaft of the alternator. This is applicable only to brushless alternator [5].

In the patent, US2014176087 (A1) pulse width modulation method is used to control the current in the field winding. [6].The patent US4045718 (A) is a multiple voltage electrical supply system, which supplies a plurality of D.C. voltages [7].

In all the above referred papers, the focus is to control the field voltage by using power electronics devices or controllers. The power electronics devices introduce harmonics in the system which introduces losses in the system and thus reduce the overall efficiency of the system.

In this paper, an attempt has been made to modify the design of a synchronous generator by introducing the compensating winding in addition to field winding. The compensating winding is wound on the rotor along with the field winding and the current flowing in the compensating winding is proportional to the load current. The flux produced by the compensating winding interacts with the flux produced by the field winding and thus helps in regulating the terminal voltage of the alternator in the permissible range irrespective of the load. The design and principle of operation is discussed in section 2.1 and 2.2 respectively.

A prototype model was developed and tested in the laboratory. This small modification in the design not only improves the voltage regulation but also improves the efficiency of the alternator.

II. RESEARCH METHOD

It is a well-known fact that with the increase in load the output voltage of an alternator decreases, which leads to poor voltage regulation. The equivalent circuit of a conventional alternator is as shown in Fig.1.

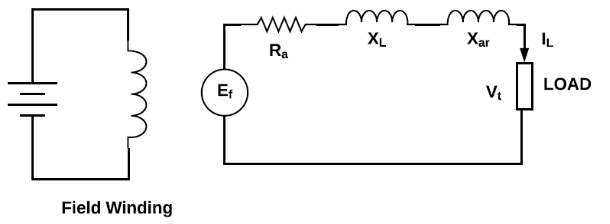

Fig. 1. Per phase equivalent circuit of an alternator

The excitation voltage per phase of an alternator is given by

$$E_f = 4.44 k_w \emptyset N f \qquad (1)$$

Where,
f= frequency of induced emf in Hz
$\emptyset$= flux per pole in weber
k_w= winding factor
N= number of armature turns per phase

An examination of Figure.1 reveals that terminal voltage per phase (V_t) for any value of armature current I_L is given by,

$$\bar{V}_t = \bar{E}_f - \bar{I}_L R_a + j\bar{I}_L (X_{ar} + X_L) \qquad (2)$$

At no load, I_L=0 therefore

$$V_t = E_f \qquad (3)$$

And at any other load,

$$\bar{V}_t = \bar{E}_f - \bar{I}_L R_a + j\bar{I}_L (X_{ar} + X_L) \qquad (4)$$

Thus for an alternator, the voltage regulation at constant field and speed is given by

$$(E_f\text{-}V_t)/V_t \qquad \text{in p.u.}$$

Ideally voltage regulation should be zero, however practically the permissible range of voltage regulation is $\pm 5\%$. Thus it is important to keep the voltage regulated in the permissible range, for the alternator operating under different load conditions.

A. Design

In the proposed design of an alternator as shown in Fig.2, there are two windings on the rotor; main field winding and compensating winding. The compensating winding is wound on the rotor in a fashion that the flux produced by it supports the main field winding flux. The main field winding draws energy from the D.C. source (like in a conventional alternator) and the compensating winding draws energy from the rectified output of the armature winding. The armature winding is connected to the primary winding of isolating transformer. The secondary winding of isolating transformer is connected to bridge rectifier. The output of the bridge rectifier is connected to the compensating winding. The bridge rectifier changes A.C current into D.C current, which is then fed to the compensating winding to add flux to the main field flux.

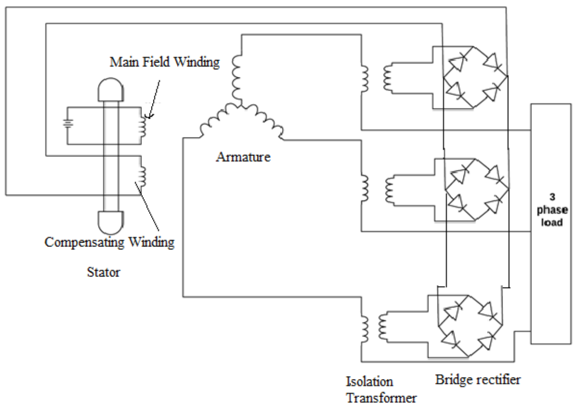

Fig. 2. Proposed Design of an alternator

B. Principle of Operation

As discussed in the previous section, we know that with the increase in load, the armature current (I_L) increases which increases $\bar{I}_L R_a + j\bar{I}_L(X_{ar} + X_L)$ and therefore decreases V_t. As per the proposed design (as shown in Fig.2), one can observe that with the increase in I_L, the bridge rectifier's output current increases. Therefore, the input current for the compensating winding increases, which increases the flux associated with it. Since the compensating winding is wound to support field flux, the total excitation flux increases and therefore induced EMF (Ef) which is directly proportional to the excitation flux, also increases. Thus, the increase in $\bar{I}_L R_a + j\bar{I}_L(X_{ar} + X_L)$ with the increase in load is compensated by the increase in Ef as shown in equation (4). The terminal voltage (V_t) which was earlier decreasing with load now remains almost constant. Thus by using this method, one can achieve voltage regulation as per the requirement by selecting proper turns-ratio of the isolating transformer.

C. Experimental Set-Up

In order to test the proposed design, a 2.5 kVA, 415V, 1500 RPM, 3-phase, 50 Hz star connected alternator is used in the laboratory. The alternator is driven by a D.C. shunt motor of 2 H.P., 220V, 8A at 1500 RPM. The block diagram of the complete set-up is shown in Fig.3.

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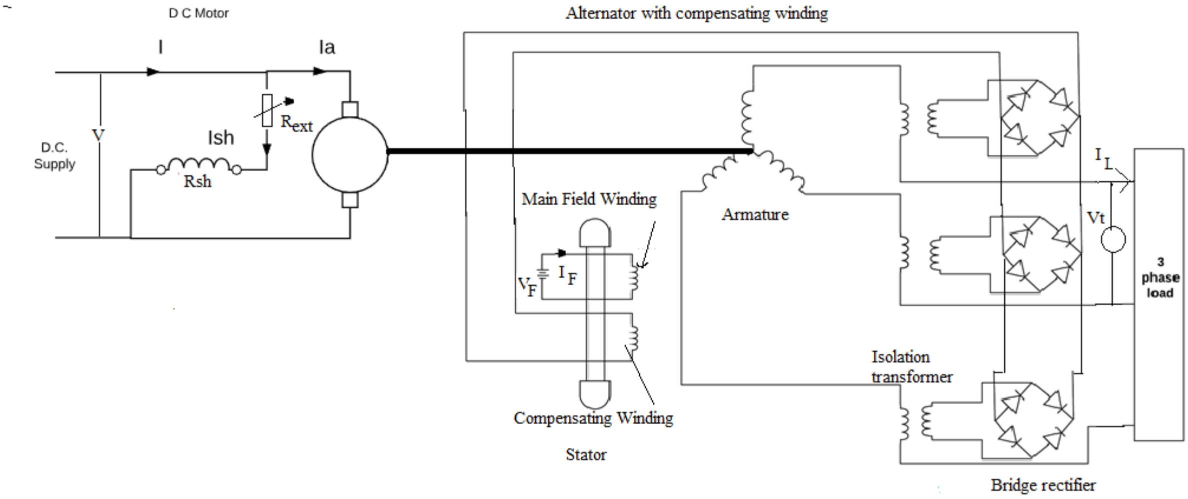

Fig. 3. Complete motor and Alternator circuit diagram

The total number of field poles is 4, and field winding is excited by external D.C. supply. The speed and excitation current of the alternator is kept constant during the experiment. In this set up, field winding is on the stator and armature winding is on the rotor contrary to the general block diagram given in Fig.2, as the alternator is a machine of small rating.

The specifications of the coil used for the compensating winding has been listed in the Table 1.

Table 1. Compensating Winding Parameters

S.No	Parameter	Value
1.	Number of turns	35 turns/pole/phase
2.	Thickness	21 gauge
3.	Material Used	Aluminium

In compensating winding, 35 turns are added for each phase on every field pole. So the total number of turns of compounding on each pole is 105 turns. Since there are 4 poles in the alternator; there are 520 turns in the compound winding which are in series with the armature to support the main field flux. The required number of turns is calculated using the chart sheet of alternator. The compensating winding is wound along with the field winding as shown in Fig. 4.

Fig. 4. Addition of Compensating winding to Field Winding

The alternator is fitted with the compensating winding along with the main field windings on the stationary poles as shown in Fig.5.

Fig. 5. Alternator with stationary field and compensating windings

III. RESULT AND DISCUSSION

The alternator was made to run at a load of 600W and 1200W, both without and with compensating winding in the circuit and the parameters are tabulated in Table 2 and Table 3 respectively.

A. Voltage Regulation

1) Without Compensating winding

Table 2. Test result without compensating winding

Parameters	No Load	At Load 600W	At Load 1200W	At Load 1800W
RPM	1500	1500	1500	1500
Field current (I_F)	0.58A	0.58A	0.58A	0.58A
Line Voltage (V_t)	412 V	380 V	340 V	300V
Line Current (I_L)	12:00 AM	0.187 A	1.484 A	2.9A

%Voltage regulation= $\frac{V_t\,noLoad - V_t\,at\,load}{V_t\,no\,load}$

Therefore % Voltage regulation (%V.R.) at 600 W

%V.R. = ((412-380)/412)*100= 7.77%

And % Voltage regulation (%V.R.) at 1200 W

% V.R. = ((412-340)/412)*100= 17.48%

And % Voltage regulation (%V.R.) at 1800 W

% V.R. = ((412-300)/412)*100= 27.18%

2) With Compensating winding

Table 3. Test result with compensating winding

Parameters	No Load	At Load 600W	At Load 1200W	At Load 1800W
RPM	1500	1500	1500	1500
Field current (I_F)	0.58A	0.58A	0.58A	0.58A
Line Voltage (V_t)	412 V	410 V	400 V	398V
Line Current (I_L)	0 A	0.75 A	1.56 A	3.2A

% Voltage regulation (%V.R.) at 600 W with compensating winding

%V.R. = ((412-410)/412)*100= 0.48%

And % Voltage regulation (%V.R.) at 1200 W with compensating winding

% V.R. = ((412-400)/412)*100= 2.9%

And % Voltage regulation (%V.R.) at 1800 W with compensating winding

% V.R. = ((412-398)/412)*100= 3.39%

Table 4. Comparison table for voltage regulation

Load	% Voltage Regulation Without compensating winding	%Voltage Regulation with compensating winding
600 W	7.77%	0.48%
1200W	17.48%	2.9%
1800W	27.18%	3.39%

The results in Table 4 demonstrate that with the help of compensating winding, voltage can be regulated effectively. By using different number of turns of compensating winding, we can regulate the voltage at any load.

B. Efficiency

As discussed in section 3.1, the addition of compensating winding improves voltage regulation. This improves the efficiency of the alternator as demonstrated below.

1) Without Compensating winding

Efficiency has been calculated for a bulb (resistive) load of 1200W

Prime mover specification:

DC shunt motor- 2 H.P., 220V, 8A, 1500 RPM.

From Swinburne test:

Iron and F& W losses=120W

R_a=1.721Ω

The above alternator without compensating winding when driven by DC motor at 1500 RPM gave the following results

DC Motor:

V=215V, I_a=5.55A, I_{sh}=0.55A, $R_{sh}+R_{ext}$=390.5Ω

Alternator:

V_L=340V, I_L=1.4A, V_F=60V, I_F=0.5A

Output of DC motor:

= $V(I_a + I_{sh}) - \{Iron + F\&W\ losses + I_{sh}^2(R_{sh} + R_{ext}) + I_a^2 R_a\}$

= (215*6.1)-{120+0.55^2(390.5) +5.55^2(1.721)}

= 1311.5 W

Efficiency of Alternator without compensating winding

$$\%\eta = \frac{\sqrt{3}V_t I_L cos\theta}{V_F I_F + DC\ motor\ output} \times 100$$

$$\%\eta = \frac{\sqrt{3} \times 340 \times 1.484 \times 1}{60 \times 0.58 + 1311.5} \times 100$$

=65.15%

2) With Compensating winding

The above alternator with compensating winding when driven by DC motor at 1500 RPM gave the following results

DC Motor:

V=215V, I_a=7.15A, I_{sh}=0.35 A, $R_{sh}+R_{ext}$=660Ω

Alternator:

V_t=400V, I_L=1.5A, V_F=60V, I_F=0.58A

Output of DC motor:

= $V(I_a + I_{sh}) - \{Iron + F\&W\ losses + I_{sh}^2(R_{sh} + R_{ext}) + I_a^2 R_a\}$

= (215*7.5)-{120+0.35^2(660) +7.15^2(1.721)}

= 1323.67 W

Efficiency of Alternator with compensating winding

$$\%\eta = \frac{\sqrt{3}V_t I_L cos\theta}{V_F I_F + DC\ motor\ output} \times 100$$

$$\%\eta = \frac{\sqrt{3} \times 400 \times 1.5 \times 1}{60 \times 0.58 + 1323.67} \times 100$$

=76.5 %

Table 5. Comparison Table for Efficiency

Load	% Efficiency Without compensating winding	% Efficiency with compensating winding
1200W	65.15%	76.5%

The results in Table 5 demonstrate that compensating winding not only improves the voltage regulation but also improves the efficiency of the alternator.

IV. CONCLUSION

An innovative and simple design of an alternator has been developed to achieve the minimum voltage regulation for any value of load. However it was also observed that it not only improves the voltage regulation but also improves the efficiency of the alternator.

The patent with the following CBR No. 27100 and application no. 201711030834 has been applied in Aug'2017 for the above concept.

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