Design and Construction of Automatic Voltage Regulator for Diesel Engine Type Stand-alone Synchronous Generator

Myinzu Htay and Kyaw San Win

***Abstract*—** Diesel-electric stations have some advantages over other types of station, particularly in comparatively small sizes. A diesel station can be started and stopped quickly as and when required. It does not need any warming period, and need not be kept running for a long time before picking up load. There are thus no standby losses as in steam stations.. A diesel station does not need a large amount of water for cooling. For this station,, synchronous generator is used to generate electricity.

This paper presents the excitation control system in generator operation. The topic of this paper involves the design and construction of excitation control (or) Automatic Voltage Regulator (AVR) for the synchronous generator.

It is necessary to develop the electronic control system for the machine. The Automatic Voltage Regulator (AVR) is widely used in electrical power field to obtain the stability and good regulation of the electric system. The characteristics of alternator output required are constant voltage and constant current. To get the constant output, alternator field excitation is controlled by Automatic Voltage Regulator (AVR). The Automatic Voltage Regulator maintains the constant voltage up to certain level of load current independently of generator speed and load. This paper deals with the design and construction of excitation control for synchronous generator and introduces the electronic control technology. The main objective of this paper is to modify the AVR with SCR device technology.

On completion of this paper, the constructed circuit will improve the overall effectiveness of the synchronous generator. This includes a more accurate measurement of voltage and current, as well as improving the response time and system stability.

Keywords : Automatic Voltage Regulator , Synchronous Generator, Field Control Circuit

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I. INTRODUCTION

Constant voltage at the generator terminals is essential for satisfactory main power supply. The terminal voltage can be affected by various disturbing factors (speed, load, power factor, and temperature rise), so that special regulating equipment is required to keep the voltage constant, even when affected by these disturbing factors.

Power system operation considered so far was under condition of steady load. However, both active and reactive power demands are never steady and they continually change with the rising or falling trend. Therefore, steam input to turbo generators (or water input to hydro-generators) must be continuously regulated to match the active power demand, failing which the machine speed will vary with consequent change in frequency which may be highly undesirable. Also the excitation of generators must be continuously regulated to match the reactive power demand with reactive generation, otherwise the voltages of various system buses may go beyond the prescribed limits.

The voltage regulator may be manually or automatically controlled. The voltage can be regulated manually by tap-changing switches, a variable auto transformer, and an induction regulator. In manual control, the output voltage is sensed with a voltmeter connected at the output; the decision and correcting operation is made by a human being. The manual control may not always be feasible due to various factors and the accuracy, which can be obtained, depending on the degree of instrument and giving much better performance so far as stability.

In modern large interconnected system, manual regulation is not feasible and therefore automatic generation and voltage regulation equipment is installed on each generator. Automatic Voltage Regulator (AVR) may be discontinuous or continuous type. The discontinuous control type is simpler than the continuous type but it has a dead zone where no single is given. Therefore, its response time is longer and less accurate.

Modern static continuous type automatic voltage regulator has the advantage of providing extremely fast response times and high field ceiling voltages for forcing rapid changes in the generator terminal voltage during system faults. Rapid terminal voltage forcing is necessary to maintain transient stability of the power system during and immediately after system faults. Response time variation can cause the AVR to degrade the system stability.

Electronic control circuit is now used for the field control circuit as the closed loop system to obtain stable output voltage. Electronic control circuit is simple but the simple is the best. By using this control circuit for the system, the system cost is decreased and system reliability and design flexibility are increased.

A.. Aim and Objectives

In this paper, the automatic voltage regulator is designed with electronic control circuit technology using SCR. Voltage regulators are used for the following advantages:

(1) to have better system voltage regulation,
(2) to improve stability and
(3) to reduce over-voltage on loss of load.

The aim and objectives are expressed briefly. They are: to study the advanced features of excitation control system, to study and modify the control techniques used in control system, to improve the industrial consumer products with SCR .

II. PRINCIPLES OF SYNCHRONOUS GENERATOR

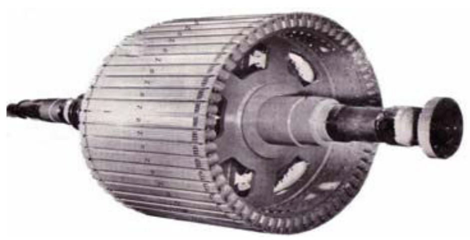
The operation of a generator is based on Faraday's law of electromagnetic induction. If a coil or winding is linked to a varying magnetic field, then electromotive force or voltage is induced across the coil. Thus, a generator has two essential parts: one that creates a magnetic field, and the other where the energy is induced. The magnetic field is typically generated by electromagnets.

These windings are called field winding or field circuits. The coils where the electro motive force energies are induced are called armature windings or armature circuits. With rare exceptions, the armature winding of a synchronous machine is on the stator, and the field winding is on the rotor. The field winding is excited by direct current conducted to it by means of carbon brushes bearing on slip rings or collector rings

The rotor of the synchronous generator may be cylindrical or salient construction. The cylindrical type of rotor has one distributed winding and a uniform air gap. These generators are driven by steam turbines and are designed for high speed 3000 or 1500 r.p.m (two and four pole machines respectively) operation. The rotor of these generators has a relatively large axial length and small diameter to limit the centrifugal forces.

The salient type of rotor has concentrated windings on the poles and non-uniform air gaps. It has a relatively large numbers of poles, short axial length, and large diameters. The generators in hydroelectric power stations are driven by hydraulic turbines and they have salient pole rotor construction. The cylindrical and salient type rotors are shown in Figure (1). The rotor is also equipped with one or more short-circuited windings known as damper windings. The damper windings provide an additional stabilizing force for the machine during certain periods of operation. When a synchronous generator supplies electric power to a load, the armature current creates a magnetic flux wave in the air gap which rotates at synchronous speed. This flux reacts with the flux created by the field current, and electromagnetic torque results from the tendency of these two magnetic fields to align. In a generator this torque opposes rotation and mechanical torque must be applied from the prime mover to substain rotation. As long as the stator field rotates at the same speed as the rotor and no current is induced in the damper windings. However, when the speed of the stator field and the rotor become different, currents are induced in the damper windings. Currents generated in the damper windings provide a counter torque. In this way the damper windings can keep the two speeds.

(a)



(b)

Fig. 1. Two Types of Rotor Construction:
(a) Cylindrical Type and
(b) Salient Type
Source: Hubret,C. (1991)

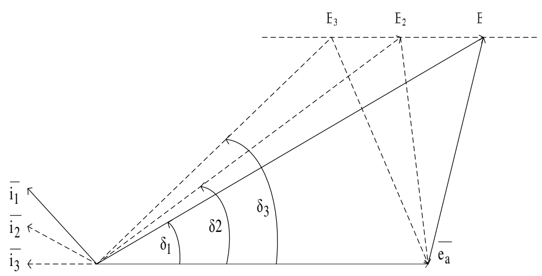
A.. Active and Reactive Power Control

The synchronous generator converts mechanical shaft power into three-phase electrical power P, absorb or deliver Q vars to the power system. The active and reactive power into the machine are

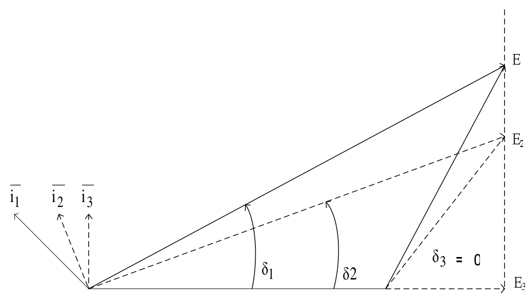
$$\bar{P}_{in} = \quad (\bar{e}_a^2 / \bar{X}_s) \quad \bar{Q}_{in} \quad \tan\delta \qquad (1)$$

$$\overline{Q}_{in} = (\overline{e}_a^2 / \overline{X}_s) \quad \sqrt{(\overline{E}_i \, \overline{e}_a / \overline{X}_s)^2 \quad \overline{P}_{in}^2} \qquad (2)$$

Referring to 1, assuming constant terminal voltages $\overline{e}_a$ and a constant synchronous reactance $\overline{X}_S$ the real power into or out of a synchronous machine is a function of the power angle δ when the vars are held constant. Referring to 2, assuming constant terminal voltage $\overline{e}_a$ and a constant synchronous reactance $\overline{X}_S$, the vars into or out of a synchronous machine are a function of the excitation $\overline{E}_i$ when the real power is held constant. Thus, the real power P in or out of the synchronous machine is related directly to the mechanical power into or out of the shaft. In the case of steam turbine generators, this mechanical power is controlled by regulating the steam into the turbines. The vars, on the other hand, are controlled by regulating the current to the field winding. Fig. (2) illustrates voltage phasor diagrams for loci of constant P and constant Q. In Fig. 2(a), the locus of $\overline{E}_i$ for constant illustrates that the major change occurs in the magnitude of $\overline{E}_i$, but there is some secondary influence upon the power angle δ. In Fig. 2(b), the locus of $\overline{E}_i$ for constant Q, illustrates that the major change occurs in the power angle δ, but there is some secondary influence upon the magnitude of $\overline{E}_i$.



(a)



(b)

Fig. 2. The Locus of $\overline{E}_i$ for Constant P and Constant Q

(a) Constant P (b) Constant Q

Source: Hubret,C. (1991)

III. Aims of Excitation System for Generator

The aims of excitation system are:

(1) To control voltage so that operation is possible nearer to the steady-state stability limit;

(2) To maintain voltage under system-conditions to ensure rapid operation of protective gear;

(3) To facilitate sharing of the reactive load between machines operating in parallel.

A . Excitation Control System

The excitation may be provided through slip rings and brushes by means of DC generators mounted on the same shaft as the rotor of the synchronous machine. However, modern excitation systems usually use AC generators with rotating rectifiers, and are known as brush-less excitation. A salient pole rotor equipped with a brush-less excitation system is shown in Fig.3. Brushless excitation is provided by a small three-phase exciter armature, a three-phase rectifier, and control circuitry, all mounted on the same shaft. But, for the small KW rating of the stand-alone synchronous generator, self-excitation is always used to obtain stable output voltage.

The excitation system fulfils two main functions.

(1) It produces DC voltage (and power) to force current to flow in the field windings of the generator. There is a direct relationship between the generator terminal voltage and the quantity of current flowing in the field windings as shown in Fig.4.

(2) It provides a means for regulating the terminal voltage of the generator to match a desired set point and to provide damping for power system oscillations. Varying the field excitation is an effect on power factor, armature current, power angle, voltage and reactive power flow.

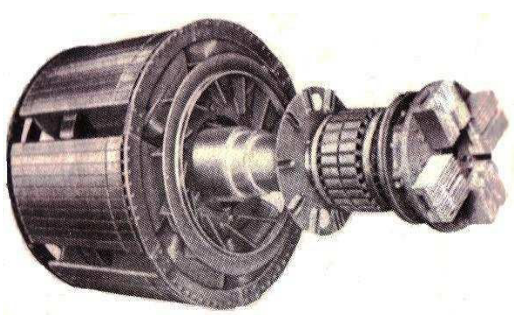


Fig.3. Salient-pole Rotor with Brush-less Excitation System

Source: Hubret,C. (1991)

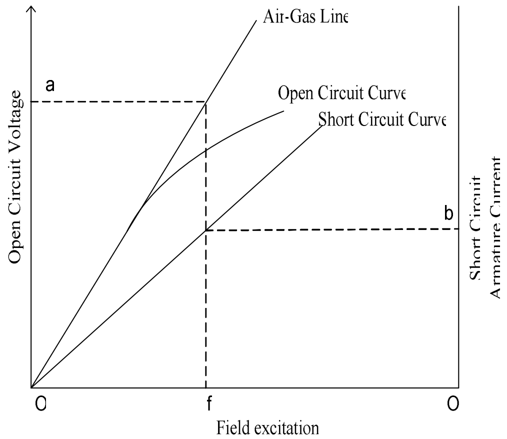


Fig.4. Saturation Curve of Synchronous Generator
Source: Fitzgerald, Kingsley and Kusko (1971)

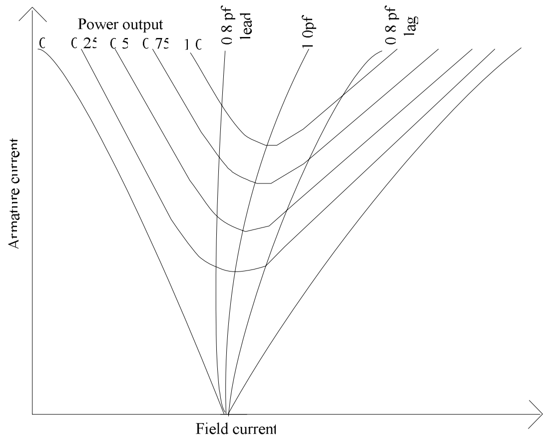


Fig.5. Synchronous Generator V-curves
Source: Fitzgerald, Kingsley and Kusko (1971)

B. Self-Excitation Control System (or) Electronic Main Exciter

Power rectifiers of the ignitron type have been used for many years in industrial applications and have given reliable and efficient performance. Their use as main exciters for a-c synchronous machines has been limited, principally because they cost more than a conventional main exciter. The electronic main exciter, however, offers advantages over rotating types.

An electronic exciter consists essentially of a power rectifier diode fed from an a-c source of power and provided with the necessary control, protective, and regulating equipment. The coordination of these component parts presents problems that must be solved in meeting the excitation requirements of a large a-c generator.

The output of a rectifier is only as reliable as the source of a-c input power. Thus, this a-c source might be considered a part of the rectifier, and so far as service as an excitation source is concerned, it must be reliable. Three sources have been used in operating installations:

(1) a-c power for the rectifier taken directly from the terminals of the a-c generator being excited.

(2) a-c power taken from a separate a-c supply that is essentially independent of the a-c generator terminals.

(3) a-c power taken from a separate generator which supplies power to the rectifier only, and which has as its prime mover the same turbine that drives the main a-c generator.

The first type is used for this paper. In the first of these, the electronic main exciter is self-excited, since its power supply is taken from its own output, and in the second and third forms, it is separately excited.

C. Power Factor and Armature Current Control

The power factor at which a synchronous machine operates and hence its armature current can be controlled by adjusting its field excitation. The relationship between armature current and field current at a constant terminal voltage and with a constant real power is shown in Fig.5. This curve is called V curve because of its characteristics shape. For constant power output, the armature current is a minimum at unity power factor and increases as the power factor decreases.

The dashed lines are loci of constant power factor called compounding curves. This curve is showing how the field current must be varied as the load is changed in order to maintain constant power factor. Points to the right of the unity power factor compounding curve correspond to over excitation and lagging power factor; points to the left correspond to under excitation and leading power factor. The V curve and compounding curve constitute one of the generator's most important characteristics.

The effect of change in field excitation on armature current and power factor is shown in Fig.6. The output power of a synchronous generator is

$$P_{3\Phi} = R\left[3VI^{*}{}_{a}\right] = 3|V||I_{a}|\cos\theta \qquad (3)$$

For constant developed power at a fixed V, $I_a \cos\theta$ must be constant. Thus, the tip of the armature current phasor must fall on a vertical line. Reducing the excitation from E_1 to E_3 caused the angle of the current phasor (and hence the power factor) to go from lagging to leading.

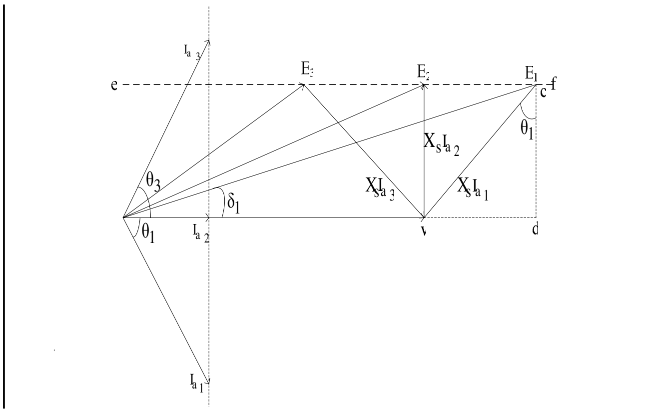


Fig.6. Variation of Field Current at Constant Power
Source: Hubret,C. (1991)

But there is a limit beyond which the excitation cannot be reduced. This limit is reached when δ = 90°. Any reduction in excitation below the stability limit for a particular load will cause the rotor to pull out of synchronism.

IV. Definition of Automatic Voltage Regulator

A voltage regulator is defined as a device for varying the voltage of a circuit or for automatically maintaining it at or near a prescribed value. From this, it would appear that the term automatic voltage regulator covers the apparatus used in the methods of obtaining a constant voltage. There are two general methods of obtaining a constant direct or alternating voltage is;

(1) By the control of the output voltage of a generator. In the case of alternating voltage the frequency is also under control, and it may be necessary to use some type of frequency stabilizer for varying of frequency with different load and input conditions.

(2) By the corrections of the normal supply voltage. Where the input and output voltage are both alternating. They are normally of the same frequency, and the output frequency, therefore, cannot be controlled.

In order to distinguish between the apparatus used in the two methods, the one used in method (1) By the control of the output voltage of a generator is called a generator automatic voltage regulator and the one used in method (2) By the corrections of the normal supply voltage will be termed a supply automatic voltage regulator.

V. Requirements for Automatic Voltage Regulator

Voltage regulators for synchronous generators must satisfy the following conditions:

(1) Regulation to counter disturbances must take place as rapidly as possible (high-speed regulators).

(2) There should, as far as possible, be no derivation from the set voltage in stationary installations.

(3) In the event of the generator terminals being short-circuited the excitation must be controlled, so that the generator relay can act satisfactorily to prevent any continuous feed into the short circuit.

(4) The revolving field must be protected against overload by a limit device in the regulator.

(5) The rated voltage must be easily adjustable on the regulator.

(6) Proper sharing of reactive load must be assured where several generators are connected in parallel.

VI. Design Specification of Automatic Voltage Regulator

An automatic voltage regulator can be designed, and it is necessary to know certain factors about the input and the required accuracy of the output voltage, together with, certain information on the load.

A. *Supply-type Automatic Voltage Regulator*

In the supply-type automatic voltage regulator, it is necessary to state the type of input, whether direct or alternating, its nominal voltage and, if alternating, its nominal frequency. Most automatic voltage regulators are operated over a limited range of input voltage. If the frequency of input is likely to vary, the range of variation of the frequency may have a considerable influence.

The output voltage is to be variable; the range of variation must be stated. The maximum output current must be known and also the range of variation of output current over which the regulator is to operate. When the output is alternating it is necessary to specify the power factor of the load, as certain designs will only operate over a small range of power factor, around unity. In three phase regulators it may be necessary to maintain the three phase voltage at 120 degrees to each other, as well as maintaining them constant in magnitude. Certain information may also be specified concerning the maintenance, operation and reliability.

The accuracy of maintenance of the output voltage may be divided into two general classes; (1) short period accuracy, this is, the accuracy over a period of minutes, due to changes of input or load and (2) long-period accuracy-this is the accuracy over a period of hours or days, due to changes in ambient temperature, ageing of components, vibration instability of components.

There are two other factors connected with the output voltage that may be important.

(1) Response time: All regulators take a finite time to effect a change in the supply voltage or load. This time is referred to as the time constant of the regulator, but in most cases it is termed as response time. In some cases, the response time is depending on the magnitude of the change of output voltage, but the rate of change remains constant. The maximum allowable response time depends upon the type of application. It is always desirable to make the response time as small as possible to reduce the transients in the output voltage.

(2) Waveform distortion: It is important in AC voltage regulators and the ripple voltage in DC voltage regulators.

Care should be taken to reduce the distortion as much as possible. The distortion is expressed as the total percentage of harmonics relative to the pure sine wave.

B. Generator-type Automatic Voltage Regulator

It is a control device which automatically regulates the voltage at the exciter of an alternator, to hold the output voltage constant within specified limits. Probably due to the fact that this part of the equipment is often of different manufacture from the generator.

One can only express the performance in terms of the whole equipment as this is determined by the characteristics of the generator (and exciter, if used). When referring to the performance which is used by the term automatic voltage regulators will imply the whole equipment and not just that part which controls the field current. In the specification for an automatic voltage regulator of this type it is necessary to bring in the characteristics of the machine. The design of the regulator will depend on;

(1) The characteristics of the driving source since changes in speed cause variations of voltage

(2) The maximum and minimum load on the generator

(3) In the case of alternating current, the power factor of the load, since this, in conjunction with (2), will determine the range of field current required

(4) The regulation of the generator

(5) The magnetization curve of the generator

(6) The characteristics of the exciter (if used).

In the case of small machines most of this information may be given by stating the field current at minimum speed and maximum load, and the field current at maximum speed and minimum load. When a regulator is being designed for a large machine (e.g. an alternator in a large power station) more information is required, and the designer of the machine and of the regulator must work in closed harmony if a successful result is to be achieved. The short period accuracy of the output voltage is usually specified as the percentage change of load, speed and power factor. The long period accuracy may not be so important.

VII. CIRCUIT DESIGN OF THE AVR FOR THE SYNCHRONOUS GENERATOR

The circuit arrangement of the field control circuit of the synchronous generator is shown in Fig.7. In this system, the output voltage of the generator is sampled through the transformer and is rectified by simple circuit and the bridge rectifier. In the initial state condition, the output of the generator may be 25V or 30V which depends on the electromagnetic field in the machine, at the time, the 12V relay is normally close position. At the time, the gate voltage is fed to the synchronous generator field coil until the output voltage is 230V. Now, 12V relay is normally open position.

When the mains supply voltage falls, Q_2 produce negative current to the bridge circuit and the bridge circuit supplies positive current to the gate of SCR and the required current is fed to the field coil and the output voltage of the synchronous generator is increased. When the output is 230V, the output positive current of the bridge is balanced with the output negative current of the Q_1.

When the main supply voltage raises, Q_2 will give a little current is fed to the gate of SCR and the required field current is fed to the field coil and absorbs the required reactive power from the supply line.

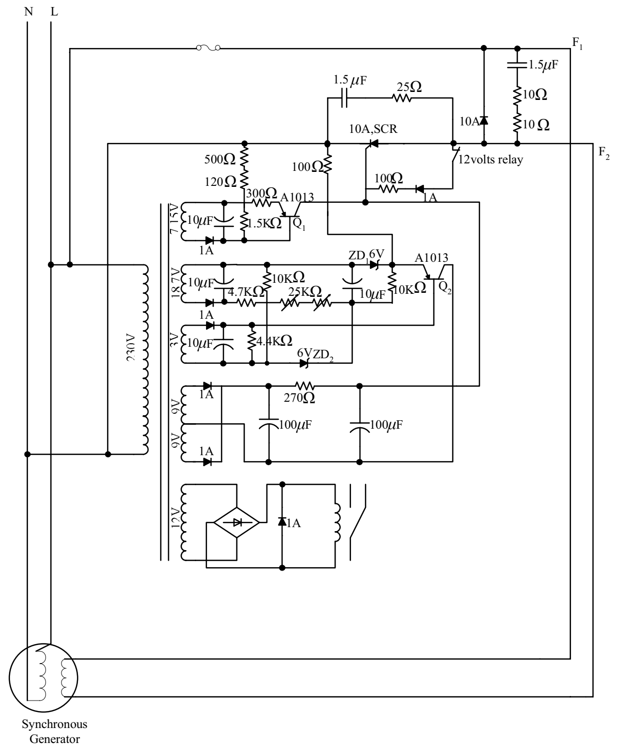


Fig.7. Over all Circuit of AVR for the Diesel Engine Type Synchronous Generator

Fig.8. AVR Design for the Diesel Engine Type Synchronous Generator

VIII. Tests and Results

These results are obtained by feeding the variable over or under input voltage to the electronic control circuit, and 100 watts bulb is used as a field coil. The output of the generator voltage must be stable although the various input voltage pass through electronic control circuit.

TABLE (I) RESULTS OF FIELD VOLTAGE AND FIELD CURRENT WHEN THE INPUT VOLTAGE FLUCTUATION IS OCCURRED

Input Voltage	Output Voltage	Voltage Difference	Field Voltage (D.C)	Field Current (D.C)
190	230	-40	85 V	80 mA
200	230	-30	75 V	65 mA
205	230	-25	70 V	57.5mA
210	230	-20	65 V	50 mA
215	230	-15	60 V	42.5mA
220	230	-10	55 V	35 mA
225	230	-5	50 V	27.5mA
230	230	0	45 V	20 mA
235	230	+5	40 V	12.5mA
240	230	+10	35 V	5 mA

IX. Conclusion

In this paper an automatic voltage regulator which can be used for 10 kVA alternator's field control applications has been designed and tested. In industry, it is hard to find a typical constant control system, and even when one is found it may not be economically feasible for a small lab to purchase. This paper takes AVR control card cost into consideration

The advantages of this AVR card is that the system cost is decreased and system reliability and design flexibility are increased. This AVR card is well suited to the high production requirements of mass production. If this AVR card is produced in the nation, it can give the benefit for the technical support and economy. So, the industrial product of this project can feed the benefit for the nation.

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