Automatic Voltage Regulator Design for Single Phase Generator of Microhydro Power

[1]Azhar.Har, [2]Said Aiyub, [3]S.Subhan, [4]M.Kamal, [5]Y.Yaman

Lecture Research
Electrical Engineering
Polytechnic State of Lhokseumawe, Lhokseumawe, Indonesia

***Abstract-* The Automatic Voltage Regulator is implemented in microhydro power to obtain the stability and utility anxieties. In order to get output of the alternator, the field excitation is controlled by the AVR. This voltage regulator maintains the constant voltage up to certain level of the load current, which is independent of the generator speed and load. In this paper, the excitation control for the generator is designed by using silicon-controlled rectifier in order to improve the overall effectiveness of the synchronous generator. The design is implemented and tested on a 3.0 kW single-phase synchronous generator of microhydro power as the voltage controller. The AVR is designed for 10 various field control of alternator. It also provides constant output voltage in 220.2-220.5V, and feeding the variable load specifically 2100 Watts on the terminal generator. The variation of the field voltage and field current varies within the range of 180-185V and 65-69mA, respectively. The results show that the designed AVR are very effective for operation of a controller, since by using AVR it is possible to design stabilizers, which handle a voltage swing as high as 80% on the input. These also include its fast response and ruggedness.**

***Index Terms-* The automatic voltage regulator, the field excitation, the single phase generator, micohydropower.**

I. Introduction

Today, the developments of alternative energy in any sources are seeking such as exploiting the energy from water into potential energy [1]. It has a prospective that can be applied to obtain electrical energy on a Micro or Pico watts. The hydropower that has a maximum electrical output of five kilowatts (5kW) is come under the category of micro hydro. Microhydro system exploits the energy in flowing water at capacities up to 5 kW [2]. It recognizes as a viable option to electrify remote areas with regard to economical, environmental, and social perspectives. Micro hydro produces one of the lowest generating costs amongst off-grid energy options [2]. This system is beneficial than other larger hydro system as it has low cost, can be installed anywhere, eco-friendly and easily available to consumer.

New microhydro technology has made it more economical as power source in the developing country. Generally, Pico or micro hydro system is installed at rural and hilly areas. In this system water (from lake and small river) firstly stored in a reservoir. This stored water is flows downhill through a pipe. The running water in the penstock has sufficient kinetic energy to rotate the blade of a turbine. In turn, it also rotates the rotor of a generator, which produce electricity [3].

Fixed 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, though it is affected by the disturbing factors. A voltage regulator is an electrical regulator designed to maintain a constant voltage level. It may use an electromechanical mechanism, either passive or active. Depending on the design, it may be used to regulate one or more AC or DC voltages. With the exception of passive shunt regulators, all modern electronic voltage regulators operate by comparing the actual output voltage to some internal fixed reference voltage [4]. Any differences that could occur can be amplified and used to control the regulation element in such away as to reduce the voltage error. This forms a negative feedback control loop; increasing the open-loop gain tends to increase regulation accuracy but reduce stability (avoidance of oscillation or ringing during step changes).

A trade-off between stability and the speed of the response is also changed. If the output voltage is too low (perhaps due to input voltage reducing or load current increasing), the regulation element is commanded up to a point to produce a higher output voltage by dropping less of the input voltage (for linear series regulators and buck switching regulators or to draw input current for longer periods (boost type switching regulators); if the output voltage is too high, the regulation element is normally commanded to produce a lower voltage. However, many regulators have over current protection; so that they entirely stop sourcing current (or limit the current in some way) if the output current is too high, and some regulators may also shut down if the input voltage is outside a in the given range. The objective of this work involves developing a single-phase automatic voltage regulator for the synchronous machine to be used in micro-hydro power plant. The control strategy is aimed to generate and deliver power to the interconnected system economically and reliably while managing the voltage and field current within limitations.

II. Excitation System For Generator

The standard method to supply field current used the direct current (DC) generator and connected with the synchronous machine by using shaft. For high-speed generators, normally it used a gearbox to reduce the exciter speed to standard speed around 700 until 1000 rpm. The main purpose for this method is to avoid commutation has a problem with DC generator. Slip ring method is the common practice to feed the exciter output with generator rotor. The exciter is installed separately from the direct coupled of pilot exciter. The main exciter controlled the field current value for the generator excitation system.

Generator Excitation

The main purpose of excitation system for generator is to supply the power source to the rotor field coil. Excitation system produces the field current and it controlled by the AVR. This field current controller is important to ensure the generator running in the appropriate voltage range. It also controlled the value of current when generator connected to a massive load. It either receives or deliveries the required level for reactive power (kVAr). It is several factors for the good running condition of generator. The important thing is the combination of excitation system and automatic voltage regulator must follow these requirements:

- Control the machine voltage accurately in response to slow changes in power or reactive VAr demand.
- Limit the magnitude of voltage excursions in response to sudden changes in load.
- Maintain steady-state stability.
- Ensure transient stability in response to system faults.

Excitation Control System

The excitation could 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 [4]. The excitation system fulfills two main functions:

- 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 illustrated in Figure 1.
- 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 [4].

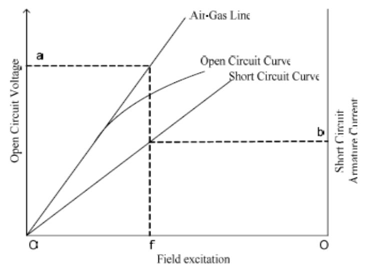

Figure 1. Saturation Curve of Synchronous Generator

Self-Excitation System

The self-excitation system equivalent scheme is presented as a series connection of inductances and resistances of windings and voltage source of dependent on circuit's current electromotive force as illustrated in Figure 2. Self-excitation process comprises two stages. During first one previously charged capacitor is discharged through excitation winding L_f. In the applied generator the excitation winding parameters are L_f = 17 mH and R_f= 2 Ω [5].

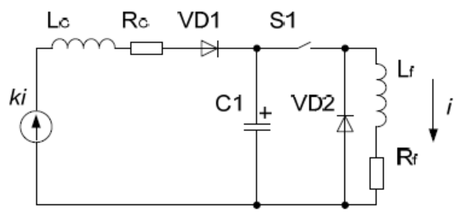

Figure 2**.** The self-excitation system equivalent scheme

This stage depends on circuit parameters and capacitor C_1 initial voltage U_{c1}:

$$L_f \frac{di}{dt} + \frac{1}{C_1}\int idt - U_{c1} - U_{C1} = 0, \qquad (1)$$

where $C_1$is capacity of capacitor C_1.

At the second stage the capacitor is used as filter and further self-excitation depends on rise of electromotive force connected with rise of current. The scheme can be described as

$$(L_G + L_G)\frac{di}{dt} + i\left(R_G + R_f - k\right) + \frac{1}{C_1}\int idt = 0, \qquad (2)$$

The process could be developing only if $k > (R_G + R_f)$. Indicator k characterizes connection between the equivalent electromotive force of generator and current in excitation winding and it depends on rotation speed of generator [5].

Power Factor And Armature Current Control

The power factor at which a synchronous machine operates and hence adjusting its field excitation is able to control its armature current. The relationship between armature current and field current at a constant terminal voltage and with a constant real power is illustrated in Figure 3. This curve is called curve due to its characteristics shape [3]. For constant power output, the armature current is a minimum at unity power factor and increases as the power factor decreases. This curve is showing how the field current must be varied as the load is changed in order to maintain constant power factor. The V curve and compounding curve constitute one of the generator's most important characteristics. The output power of a synchronous generator is, self-excitation system equivalent scheme is presented as a series connection of inductances and resistances of windings and voltage source of dependent on circuit's current electromotive force as illustrated in Figure 2. Self-excitation process comprises two stages. During first one previously charged capacitor is discharged through excitation winding L_f. In the applied generator the excitation winding parameters are L_f = 17 mH and R_f= 2 Ω [5].

$$P_{3\varphi} = R(3VIa) = 3|V||I_a|cos\theta \quad (3)$$

For constant developed power at a fixed $V.I$a cos θ must be constant. Thus, the tip of the armature current phase must fall on a vertical line. Reducing the excitation can cause the angle of the current phase (and hence the power factor) to go from lagging to leading. Any reduction in excitation below the stability limit for a particular load can cause the rotor to pull out of synchronism. 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 [3]. The design of the regulator depends 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) The power factor of the load which will determine the range of required field current; 4) The regulation of the generator; and 5) The magnetization curve of the generator and the characteristics of the exciter (if used).

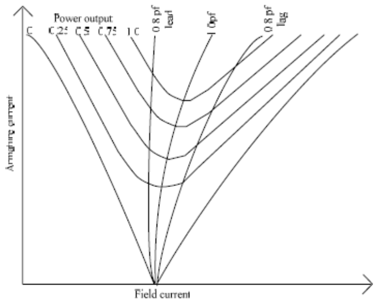

Figure 3. *Synchronous generator V-curves*

Automatic Voltage Regulator For Generator

The AVR is appropriately used for supplying power to the fields of either brushless or commuter type exciters and could maintain the AC generator voltage within ±1% of the pre-set value in parallel, as the load varies between no load and rated load and a frequency changes more than ±4%. Upon application or rejection of rated load, the generator voltage recovers to ±1% within 0.3 second on most AVR exciter in AC generator combination. The AVR is suitable for operation in ambient temperature up to 50ºC and will deliver a power output of 150 Watts with a maximum current of 3 A. Under some circumstances the AC generator wave shape changes considerably from no load to rated load. It is due to the type of load; hence the rms average or peak voltage does not stay in proportion. In this situation, i.e., greater than 10% harmonic distortion, the voltage regulation may be outside the quoted limit.

The AVR can be operated in two controlled conditions. It is from manual control or automatic control with standard limited parameter that required for generator. This controlled must be provided if it not available for the generator system to ensure its smooth running without any troubleshooting.

Basic Principles For AVR

As a signal proportional to generator terminal voltage obtained from the rectified output of a voltage transformer is compared to a stabilized reference voltage obtained within the regulator. If it detected any abnormal circumstances, different or error signal, it amplified and controlled the excitation supply, increased or decreased the input to the main field winding or exciter field. The main purpose is to reduce the error signal to zero or an acceptable value. Adjustment of the set voltage is obtained either by adjustment of the reference voltage or by adjusting the proportion of machine voltage compared to the reference voltage. The stabilizing loop is included to prevent hunting as illustrated in Figure 4.

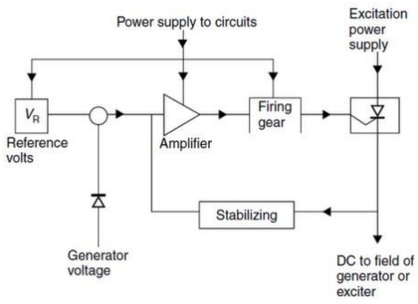

Figure 4. Basic diagram for AVR circuit

III. Concept For Developing The Circuit

In order to achieve the modification on the AVR, the development of the trigger section (regulating unit) is essential. For this design, the synchronization of the triggers is taken from an isolation transformer. This synchronizing input signal is input into the active 50Hz filter, which ensures that a pure sinusoidal voltage source is always used for this circuitry [3]. In order to produce the firing angle of the output pulse, a comparator amplifier is used to compare the output signal of the output amplifier with a linear ramp and pedestal wave shape. During the period of firing angle, this delay angle together with an electronic logic circuit is combined with a stable multi-vibrator to give a train of pulse that reduces the switching loss of thyristors. With this train of pulses, the converter, containing the SCRs can be used successfully to control its load. The triggering section comprises of different modules, which are synchronization and phase angle control, synchronizing pulse generator, ramp generator, the comparator, and pulse generation. Upon completion of these modules, a full-wave converter circuit is developed to test on the trigger section circuitry.

Synchronization and Phase Angle Control

The circuit consisted of an active filter and a high gain synchronous amplifier made out from the op-amp chip. The active filter is tuned to $50Hz$ to ensure that no transients or electrical noise on the supply are interfering with the triggering operation. In principle, this synchronizing input signal is a full-wave rectified signal, which is later used to generate firing pulses to thyristors that is fired during either the positive going half-cycle or the negative going half-cycle of the waveform [3].

Synchronizing Pulse Generator

Figure 5(a) shows the circuit module with a fixed voltage of 0.6 Volt formed by the voltage divider R and D, IC op-amp acts as a comparator comparing the rectified synchronous signal and this fixed voltage. The output waveform in Figure 5(b) illustrates that the expected result is a square wave signal of short pulse duration. The duration of the pulse depends on the magnitude of the input signal [3]. In order to achieve compatibilities with the controller currently used in the laboratory, a circuit diagram of a single-phase controller circuit available in the laboratory is used as references. Therefore, modifications were made from that to produce a three-phase AVR required for the closed loop system.

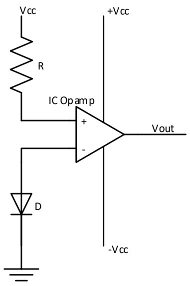

Figure 5(a). *Synchronous pulse generator*

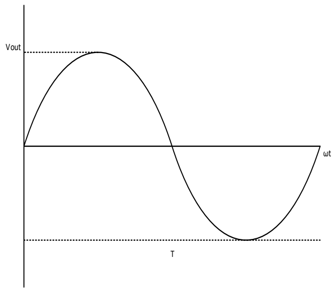

Figure 5(b). *Output waveform*

Signal Processing Circuit

The feedback signal is being processed and fed back into the trigger section of the module [3]. From the converter, a DC voltage is fed into the voltage feedback amplifier module. This module compares all the signals, which influence the performance of the thyristor-bridge. It compares the actual load current signal with the available reference voltage. The output signal is sent to the current amplifier module, which is an inverting amplifier with its feedback path completed by the entire module. The current limiter module is applied to decrease the current of the circuit to prevent overloading that may damage the system.

IV. DESIGN OF THE AUTOMATIC VOLTAGE REGULATOR

Synchronous generator 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 [3]. Power system operation considered so far is under the steady load condition. 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 varies with the consequent change in frequency, which may be highly undesirable. In addition, 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. Tap-changing switches, a variable autotransformer, and an induction regulator can regulate the voltages manually. In manual control, the output voltage is sensed with a voltmeter.

AVR Design For The Synchronous Generator

The circuit arrangement of the field control circuit of the synchronous generator is illustrated in Figure 6. 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 $220V$. Now, $12V$ relay is normally open position. When the mains supply voltage falls, $Q2$ produce negative current to the bridge circuit and the bridge circuit supplies positive current to the gate of the SCR and the required current are fed to the field coil and the output voltage of the synchronous generator is increased. When the output is $220V$, the output positive current of the bridge is balanced with the output negative current of the $Q1$ while the main supply voltage rises, $Q2$ gives a little current which is fed to the gate of the SCR and thus the required field current is fed to the field coil and absorbs the required reactive power from the supply line. The AVR is linked with the main stator windings and the exciter field windings to provide closed loop control of the output voltage. The AVR voltage sensing terminals continuously sample the output windings for voltage control purposes. In response to this sample voltage, the AVR controls the power fed to the exciter field, and hence the main field, to maintain the machine output voltage within the specified limits. Compensating for load, speed, temperature and power factor of the generator. The AVR includes an optimized stability circuit to provide good steady state and transient performance of the generator.

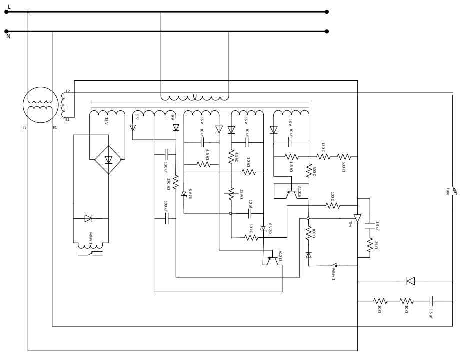

Figure 6. *Overall circuit of AVR for Microhydro power*

Tests and Results

These results are obtained by feeding the variable load below 3 kW (specifically 2100 Watts) on the terminal generator. The output of the generator voltage must be stable although the various input voltage pass through electronic control circuit. Results of field voltage and current are listed in Table 1.

Table 1 Field voltage and current

Field voltage (Volt)	Field current (mA)	Output voltage (Volt)
185	65	220,5
184	66	220,4
185	65	220,5
183	67	220,3
183	67	220,3
180	69	220,2
184	66	220,4
185	65	220,5
184	66	220,4
185	65	220,5

V. Conclusion

In Microhydro power application, it is hard to find an automatic voltage regulator, which provides constant output at a reasonable price. Therefore the main consideration of this work is to provide a constant output 220 Volt at a reasonable cost. The proposed AVR is designed for 10 various alternator's field control. The standard servo controlled voltage stabilizers handle a variation of more than 40% of the input voltage, while using AVR it is possible to design stabilizers, which handle a voltage swing as high as 80% on the input. The designed AVR provides constant output voltage of 220.2-220.5V, whereas the variation of the field voltage and field current varies within the range of 180-185V and 65-69mA, respectively.

VI. Acknowledgment

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