Improving the Control of a Synchronous Generator at Kpong Hydroelectric Generating Station Using SCADA and PLCs*

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Abstract

Large synchronous electric generators are critical components of every electric power plant and hydroelectric power plants are no exception. Even though faults seldom occur in generation stations as compared to transmission and distribution substations, one incident of fault in the generator has a greater impact. In order to protect the generator from both external and internal faults, digital generator control and protection is required. While protection and control systems operate together, this research chose to zoom-in on the control aspect of the Synchronous Generator (SG). This paper proposes a modern control system for the control of a SG at the Kpong Hydroelectric Generating Station (HGS). A Simulink version of MATLAB was used to model the Kpong generating unit connected to an infinite bus and simulated. Results of the behaviour of the power system when a three phase to ground fault occurred had been established. Finally, a modern control system for SG control, incorporating Supervisory Control and Data Acquisition (SCADA) and Programmable Logic Controllers (PLCs) has been suggested for the Kpong HGS, and the demonstration using the winTR SCADA software and RSLogix micro PLC software on hydro generator active power control and control actions that take place when stator/core temperatures go beyond some acceptable levels has been achieved.

Keywords: Data Acquisition, Programmable Logic Controllers, Synchronous Generator

1 Introduction

The tripping of two to three generators at the same time in a power plant could cause a nationwide blackout. In order to protect the generator from both external and internal faults, digital generator protection and control systems are used (Kim *et al*., 2015).

The root cause of these blackouts is pointed to the failure of aged key components at the Akosombo HGS and the lack of appropriate relays to prevent the transfer of a major system disturbance from Ivory Coast's Electric Power System to that of Ghana between which there exists a tie-line (Anon., 2012).

Aged control equipment of Kpong HGS has been left for quite some time now without replacement. There is, therefore, the need to conduct a comprehensive study to assess the requirements for the design of a suitable modern control system for the Kpong GS. The Kpong GS is located in the Eastern Region of Ghana, West Africa, and was established in July 1982. It consists of the Kpong Dam and a four-unit, 160 MW Hydropower Plant, 15 miles (24 km) downstream of Akosombo Dam, together with the associated 35 miles (60 km) double circuit, 161 kV transmission line to Tema (Ayensu, 2013).

1.1 General Overview of Hydroelectric Power Generation

The production of electricity usually starts from a source of raw material from a dam known as storage plants, from Pumped Storage or Run-of-river hydro power station. The water flows from upstream through the penstocks to turn a hydraulic turbine. The turbine, also known as prime mover, couples to a SG by a shaft system such that the rotor turns as the turbine runner turns. Fig. 1 is a picture of the runner used in the Kpong HGS.

Fig. 1 Four-Blade Turbine Runner at Kpong HGS

In large SGs for hydro energy production, the generator field windings are placed on the rotor while the stator contains the heavy armature windings.

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The generated voltage is then stepped up to the required transmission levels for transmission to the national grid. The transfer of electrical power to the grid from an incoming SG can only be successful, provided the conditions required for generator synchronisation are met. Fig. 2 shows the block diagram of components for a typical hydroelectric system.

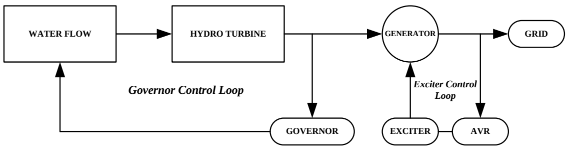


Fig. 2 Block Diagram of Components of a Typical Hydroelectric System

1.2 Synchronous Generator

Electric power is the main source of energy for carrying out many functions, as it is a clean and efficient energy source, which can be easily transmitted over long distances (Vasudevan *et al.*, 2006). With the availability of power transformers for changing the voltage levels to a very high value (14.4 kV to 161 kV for the Akosombo GS or 13.8 kV to 161 kV for the Kpong GS), the use of AC power has increased rapidly and the DC power is used only at remote places.

A SG is an electrical machine producing alternating electromotive force or voltage of constant frequency. In Ghana, the standard commercial frequency of AC supply is 50 Hz.

1.3 Control of a Synchronous Generator

Control systems are an integral part of modern-day plants or industry. A control system consists of subsystems and processes such as plants assembled for the purpose of obtaining a desired output with a desired performance, given a specified input (Nise, 2011). Providing a stable voltage is the basic function of a generator and therefore, the first requirement for a generator control unit.

In an electric power station, there are two fundamental possible ways to control the SG: torque control from the drive; and reactive power control using excitation of the magnetic field. The quality of electrical power, frequency, voltage and capacity of delivering reactive power and ratings for unsymmetrical loads has to meet standards common to the grid.

The control system of the SGs at the Kpong HGS consists of old-fashioned electromechanical relays, mechanical/hydraulic speed governor and a static exciter. This paper seeks to introduce Programmable Logic Controllers and a Supervisory System in the control of the SG. Data from the unit's instruments are obtained manually resulting in human errors. Fig. 3 shows the block diagram of the existing control unit at the Kpong GS indicating the lack of visual aid (SCADA).

The Kpong GS is also faced by other problems i.e. early detection and rapid correction of temperature rise in the SG core and stator windings, which cannot be effectively dealt with using electromechanical relays.

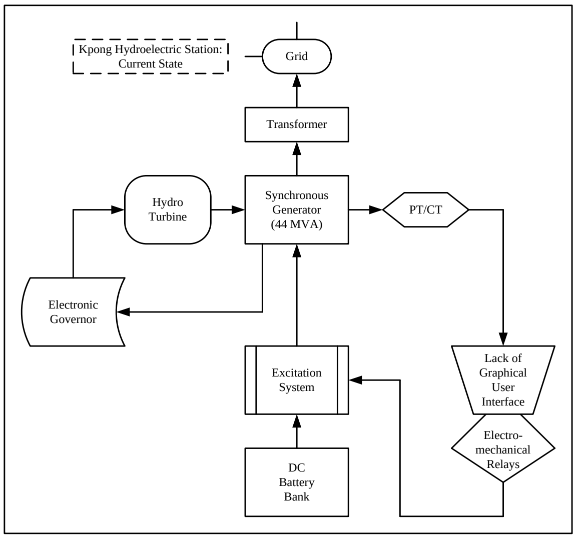


Fig. 3 Block Diagram of Current State of a Unit Control System at Kpong HGS

This paper, therefore, seeks to design a PLC to monitor the temperature of the SG core and stator and take quick actions to save the generator from damage; demonstrate active power control of the SG using PLC; and finally demonstrate in real time, data acquisition from a SG using the SCADA.

1.3.1 Analogue Generator Control Unit

Until today, most generator controllers still use the magnitude based analogue control (Kundar, 2011). In the analogue world, the most straightforward useful information about the generator is magnitude, although the SG has its vector attribute. So, the simplest and most popular way is the voltage regulation control based on the magnitude in the analogue world. Fig. 4 (Xiangfei, 2005) shows the block diagram of a typical magnitude based analogue voltage controller, in which, V_{ref} is the input reference voltage value, V_{fd} and I_{fd} are excitation voltage and current and V_{POF} is the voltage at the point of reference. The control algorithm is often Proportional Integral Differential (PID) or lead-lag or both. This type of controller has relatively simple configuration and is therefore easier to implement. It gives cheaper solutions but time-consuming and tedious.

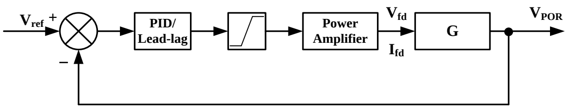


Fig. 4 Typical Analogue Voltage Controller

1.3.2 Digital Generator Control Unit

The invention of the digital computer is a milestone in technology, which has greatly changed the world. The digital computer or microprocessor has been applied to many industries where analogue systems have been formerly used. As early as 1970's, the digital excitation control was proposed (Anon., 2005). With rapid development of digital technology predicted by Moore's rule, the use of the digital computer in the heart of excitation control system, has become economically feasible and technically satisfactory.

Fig. 5 (Anon., 2005) shows a high-level block diagram of a typical digital excitation controller. All the blocks inside the dash line are implemented by digital technology, usually microprocessors/digital signal processing (DSP).

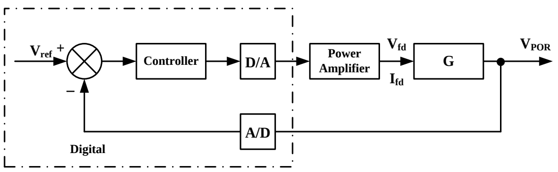


Fig. 5 Typical Digital Excitation Controller

Although the application of high-performance microprocessor on the excitation controller has made it possible to adopt more sophisticated control algorithm, at the beginning stage of the utilisation of the microprocessor, the controller is a digital counterpart of the analogue controller. From the structure point of view, most of the digital controllers are only using one loop structure (Ula and Hasan 2013; Xiangfei, 2005). In this kind of control structure, the only closed loop is the outer voltage loop as shown in Fig. 6 (Xiangfei, 2005).

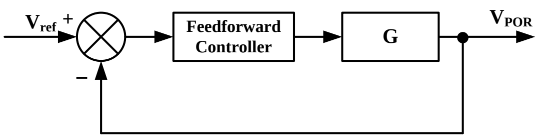


Fig. 6 One Loop Structure of Digital Generator Control Unit

Though this kind of structure can reach the zero-error control at a steady state, its simple structure makes it inadequate for the higher control requirement, especially for the brushless SG. A multiloop control structure was proposed by Ghazizadeh and Hughes (2014) and Erceg *et al*. (2015), where an auxiliary loop was added to the one loop control unit and applied to the conventional Automatic Voltage Regulator (AVR) as shown in Fig. 7 (Ghazizadeh and Hughes, 2014; Erceg *et al*., 2015).

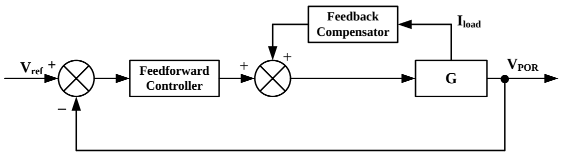


Fig. 7 Two Loop Structure of Digital Generator Control Unit

The control performance of a conventional AVR varies greatly with generators and load conditions. Using load current feedback compensator can account for the influence of the generator load and, obviously improve the AVR performance. Erceg *et al*. (2015) proposed an internal excitation current (I_{ex}) loop plus AVR control as shown in Fig. 8. The internal loop tries to maintain the specified current value per AVR output as close as it can and thus, improve the dynamic performance.

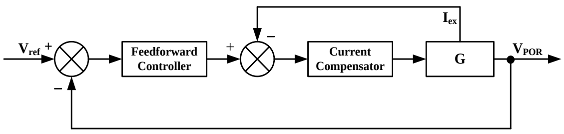


Fig. 8 Internal Excitation Current Loop Plus AVR Control

The digital control system is relatively immune to component value variance and problems related to aging and temperature drift. The digital Generator Control Unit (GUC) implements the control algorithm inside the microprocessor instead of operational amplifiers, resistors and capacitors in the analogue GCU. Once the outside signal is digitised, it becomes fixed and immune to the variance regardless of the source.

1.4 Methods of Improving SG Control System

The world's first electric power generator was perfected by Werner Siemens in 1866, in which part of the generator's working current is utilised to power the field windings, hence eliminating the need for permanent magnets.

Paserba *et al*. (2002) presented an enhanced generator control for the improvement of power system voltage stability. The research described various means to improve power system voltage stability by enhancing generator reactive and active power control and voltage control along with application examples. Also, Youn and Sun (2015) proposed a fuzzy PID control technique for improving SG excitation. The authors had the concern that, the current power system has become more complicated, highly efficient and rapidly changing and therefore, the traditional PID control technology is unable to meet the needs of current power system. They proposed a control system that could change the control parameters in real time i.e., the fuzzy PID excitation control system. The results of their studies showed that, the fuzzy PID control system had high performance and good real-time control, and also had better stability than the traditional PID control system.

1.5 Use of PLC and SCADA in SG Control System

The treatment of automation and control of power generation is focused on voltage regulation and stability improvement of synchronous machines in the ideal configuration when the generator is connected to an infinite bus and in multi-machine configurations. Emphasis is put on the 3rd order model of the generator with and without controls, whereby the basic behaviour and control principles are developed. Further, speed regulation and frequency control for single machines and for turbine-generators within several areas, as well as the centralised control structures are presented. Sequence control for startup and shutdown of generating units are briefly discussed (Glavitsch, 2011; Ivanic, 2013).

Faced with decreasing revenues and increasing regulatory oversight, hydro operators are driven to introduce more automation solutions to their facilities so as to better meet licensing requirements, control cost, improve reliability, and increase efficiency (Peacock and Mahoney, 2011). Industrial-grade control and automation systems are designed to monitor equipment status, to facilitate troubleshooting, and to provide remote telemetry and control. By far, the most common solution implemented in the small to large hydro industry is the use of programmable logic controllers (PLCs) coupled with a graphical human machine interface (HMI) and SCADA. Properly designed and implemented, this powerful combination can provide a full set of features to the system (Peacock and Mahoney, 2011).

Kumar *et al*. (2015) proposed a PLC based automatic excitation control of SGs. The research involved the control and monitoring of output voltage of a SG by using PLC and SCADA.

2 Resources and Methods Used

This section presents the data obtained from field studies, the model of the SG at Kpong HGS using MATLAB/Simulink tools. RSlogix micro starter lite PLC software was used to demonstrate the control of SG active power, the control of alarming and tripping circuits when the generator temperature rises to specified values and the control of generator ambient temperature during shutdown to prevent condensation and corrosion of the SG. WinTr SCADA software was then used to present and display data acquisition and remote control via the internet.

Other resources were used in the research: the control system for SG at Kpong HGS involving the excitation system and the governor.

Fig. 9 shows a single line diagram of the four units-network of the Kpong HGS. There are four SGs, which are vertical-shaft, water wheel driven type with thrust bearing, guide bearing and main bearing bracket below the rotor.

2.1 Excitation System

The excitation system of the Kpong GS is configured as presented in the schematic diagram in Fig. 10. Standard excitation system voltages defined in ANSIC50-12 are 62.5, 125, 250, 375 and 500 V DC. The Kpong GS excitation system adopted a 125 VDC.

2.2 Functional Block of SG Unit in MATLAB/Simulink

The short circuit time constants for the SG at Kpong GS were obtained by applying the equations *1*, *2* and *3* according to IEEE standards (Juan *et al*., 2010).

$$T'_d = x'_d \frac{T'_{do}}{x_d} \tag{1}$$

$$T''_d = T''_{do} \frac{x''_d T'_{do}}{x_d T'_d} \tag{2}$$

$$T''_q = \frac{x''_q}{x_q} T''_{qo} \tag{3}$$

Table 1 presents the parameters of the generator unit components at the Kpong GS.

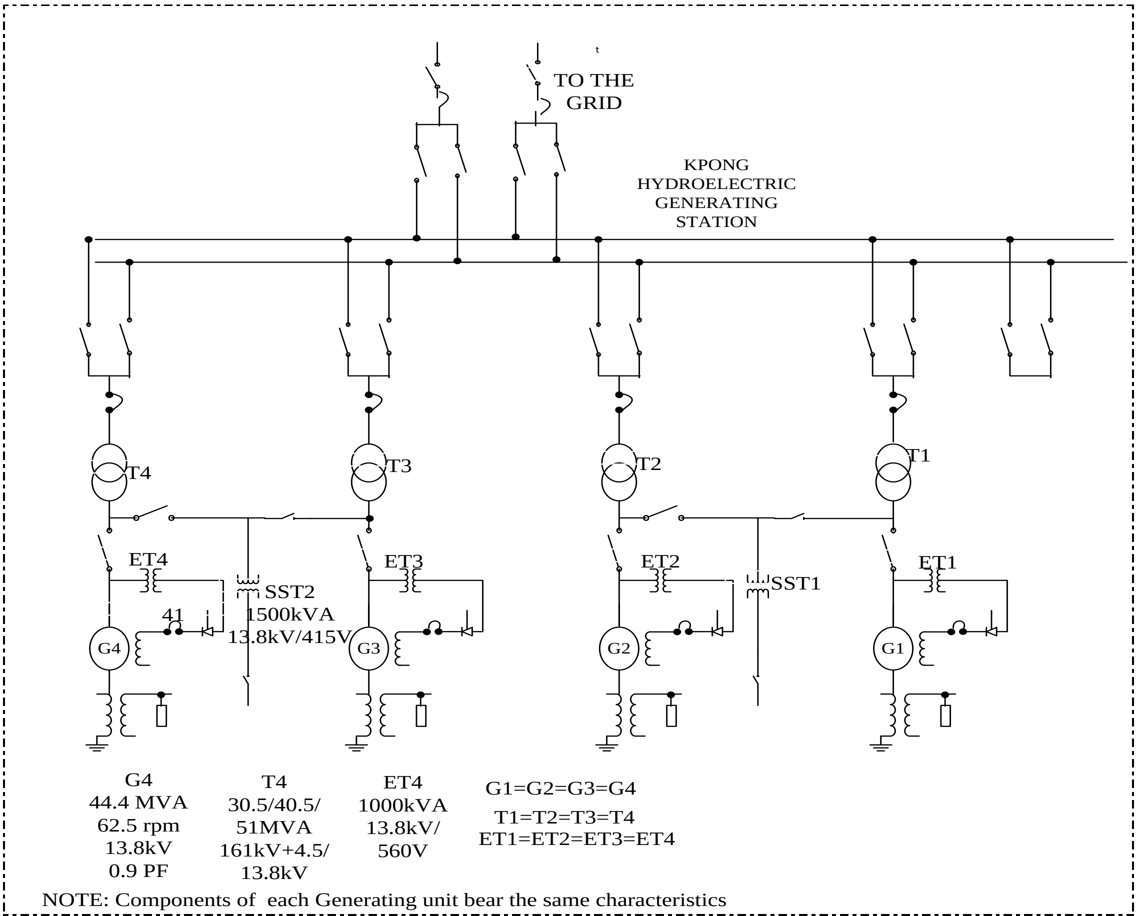


Fig. 9 Single Line Diagram of the Kpong HGS

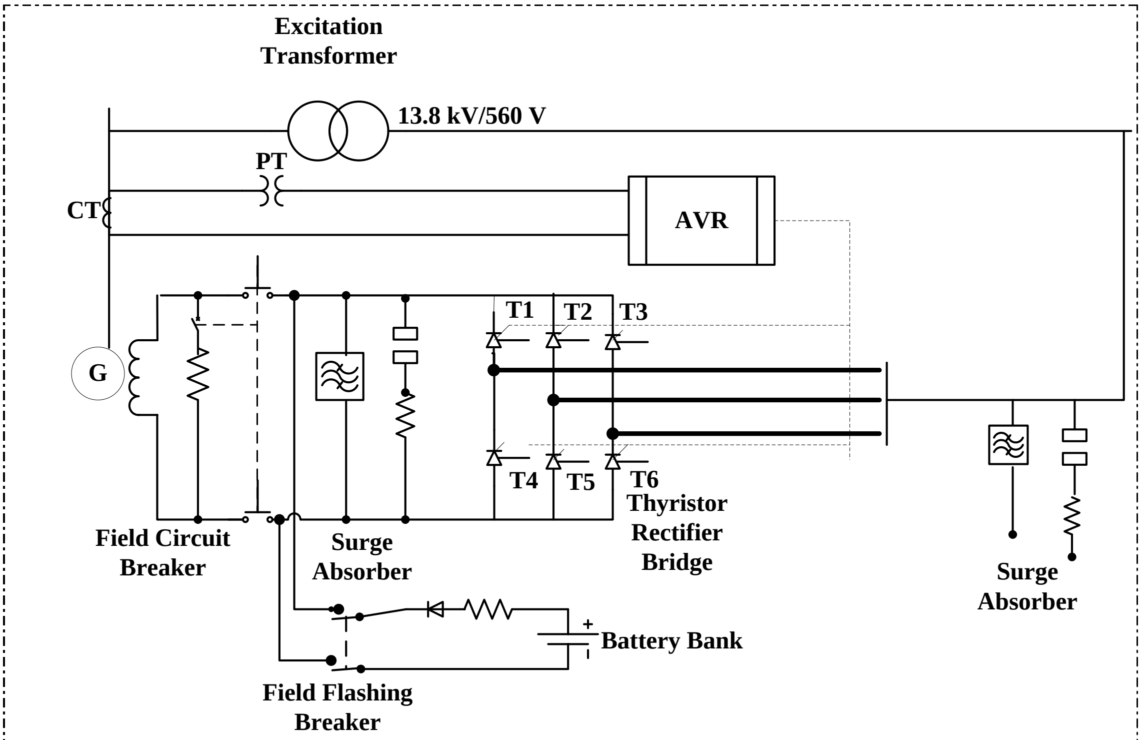
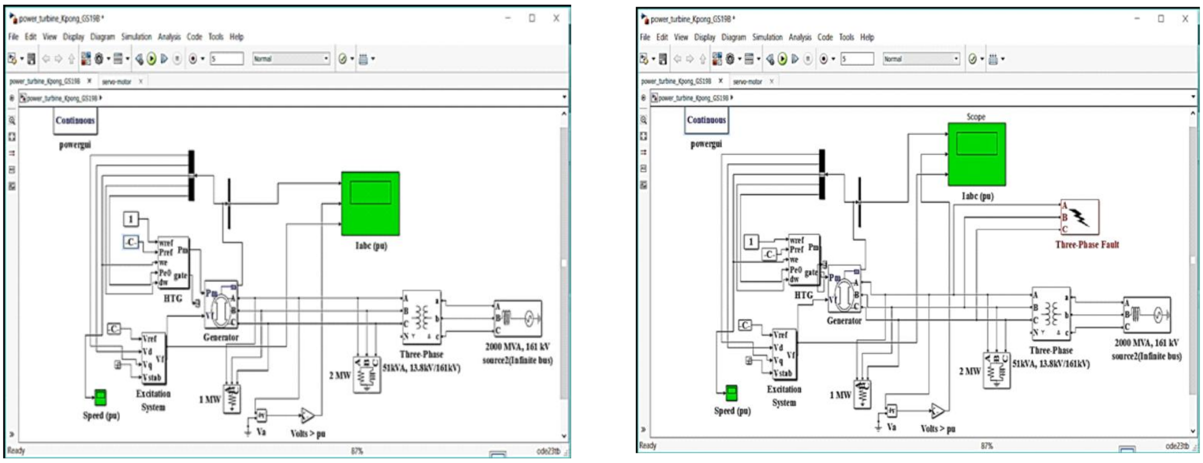


Fig. 10 Static Excitation System Configuration at Kpong HGS



(a) (b)

Fig. 11 (a) Simulink Model of a Synchronous Machine in Steady State connected to an Infinite Source; (b) Simulink Model of a Synchronous Machine in Transient State–3 phase Fault Activated

Table 1 Parameters of Generator Unit Components of Kpong GS

Generator Parameters		Exciter Parameters		Governor Parameters		Step-up Transformer Parameters	
R_s	0.0482	T_r	0.020	R	0.04	Rated Voltage	13.8 kV/169 kV
X_d	0.880	T_c	0.030	r	1.00	Rated Power	30.5/51 MVA
X'_d	0.600	T_b	0.180	T_r	10.00	Base MVA	51
X''_d	0.280	T_a	0.025	T_f	0.05	%imp @ 75^0C	10.60%
X_q	0.600	K_a	100	T_g	0.50	Winding T_{rise}	55^0C
X'_q	0.320	Vr_{min}	−3	V	0.24	Rated Current	1276/2134:104/174
X''_q	0.289	Vr_{max}	5.2	G_{max}	0.90	BIL HV	650
Xl	0.270	K_e	0	G_{min}	0.10	BIL hv	110
T'_{do}	0.289	K_f	0.056	T_w	2.42	BIL MV	110
T''_{do}	0.046	T_f	0.762	A_t	1.25	Per unit imp	0.20784
T'_{qo}	4.500	I_{fd}	–	D	0.40	Angle	30
T''_{qo}	0.046	–	–	–	–		–
T'_d	0.197	–	–	–	–	–	–
T''_d	0.021	–	–	–	–	–	–
T''_q	0.022	–	–	–	–	–	–

(Source: Kpong HGS, 2017)

2.2.1 MATLAB Model of SG in Steady State Conditions

The Simulink tool in MATLAB R2014a was used to model the SG, the exciter and the turbine-governor. The modeling was done using Simulink blocks and taking model parameters of the SG, the excitation system and the turbine governor from the Kpong HGS. Such parameters can be found in Table 1. Simulation of the power system was performed in steady state in Fig. 11(a). The waveforms generated by the scopes for stator currents and voltage as well as the rotor speed and field voltage were recorded.

2.2.2 MATLAB Model of SG in Transient State Condition

The power system in its steady state was subjected to a sudden disturbance through a three-phase fault. Fig 11(b) shows the model configuration, where the arrow points to the three-phase fault block. The reason for conducting this test was to determine the behaviour of the system during fault conditions. Results of that were also recorded.

2.3 Proposed Design

Fig. 12 shows the block diagram of the Kpong HGS in its proposed state.

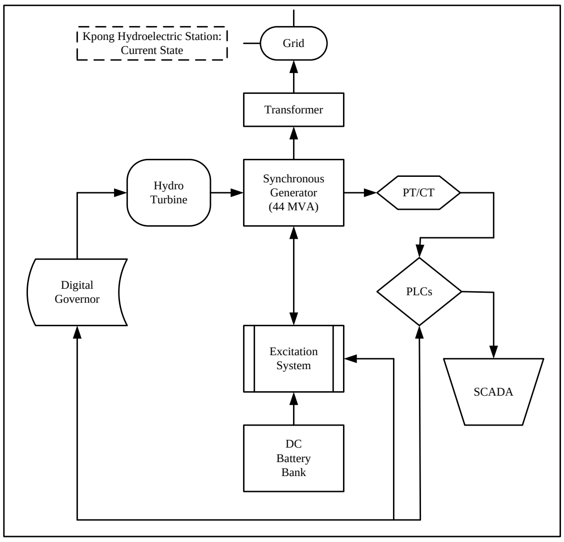


Fig. 12 Block Diagram of Proposed Kpong GS Unit Control System Incorporating SCADA and PLCs

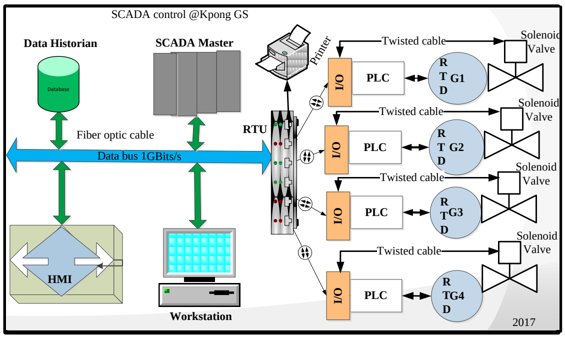


Fig. 13 Modern SCADA Architecture for the SGs at Kpong HGS

This research concentrated on the replacement of the old electromechanical relays with PLCs and SCADA system and placing emphasis on the temperature monitoring and active power control of a SG in the Kpong HGS. Fig. 13 shows a modern SCADA architecture for the SGs at the Kpong HGS.

2.4 Materials Used for the SCADA and PLC Control System

2.4.1 Supervisory Control and Data Acquisition

The main brain of the automation system is the SCADA system. Choosing the right SCADA technology is a very crucial step in the life of the particular system to be monitored and controlled (Anon., 2015). The best SCADA system is the one that can easily communicate with all PLCs, meet the present needs of the hydro plant, and also be able to meet future needs.

The control center consists of a control server referred to as SCADA Master, which utilises the Human Machine Interface (HMI) as the agent between operators and the controlled processes. Win-Tr is a SCADA software that is capable of monitoring and saving data from field devices. Win-Tr SCADA software is chosen for this work because of an in-built Modbus TCP/IP for PLC connection and can also be connected through wide area network (WAN) for remote monitoring and control.

2.4.2 Programmable Logic Controller

The PLC is basically a digital electronic apparatus, such as the industrial grade computer, which has a programmable memory for storing instructions to implement specific tasks for control, (Lima *et al.*, 2015). In the early days of development of PLC, it was purposed to replace hardwired relays in control panels. PLCs are advantageous due to their ability to be reprogrammed using the ladder logic diagram. PLC program can be reached via a programming interface in an engineering workstation and are able to communicate via a fieldbus network. Data from a PLC is stored in a data historian with all components connected on a local area network (LAN).

2.5 Active Power Control

At the hydroelectric generating power stations, active power control is achieved by controlling Wicket Gate position at a particular head of water in the reservoir. Fig. 14 shows the various components involved in active power control at the Kpong hydro power station.

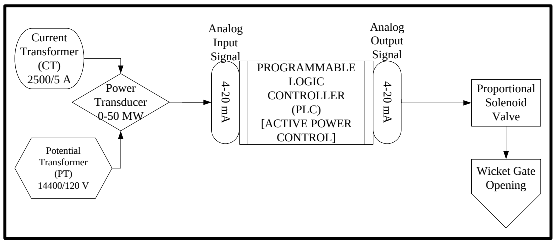


Fig. 14 Components Involved in Active Power Control at Kpong Hydroelectric Generating Station

In the case of active power control at Kpong GS, the application is dynamic and therefore require a proportional solenoid valve that is robust in nature and direct-acting. The chosen valve needs to be able to withstand frequently commanded pressure changes. Thus, a heavy-duty cycling type is needed since the adjustment of the wicket gate opening and closing is continuous. Power supply to the solenoid is also considered, which is 24 VDC and input signal control of 4-20 mA from the PLC. The maximum pressure for the Kpong GS oil in the accumulator is 350 bar. The proportional valves are small electronic flow controllers. Users can vary input current to the solenoid, and the output flow of the valve varies accordingly. The greater the input current, the greater the flow through the valve. Table 2 gives details of the various parameters and their corresponding values applied in active power control at the Kpong GS.

Table 2 Parameters Involved in Active Power Control

Active Power (MW)	Actuator Current (mA)	Valve Response (% Opening)
0.0	4.0	0.0
5.0	6.0	12.5
10.0	8.0	25.0
15.0	10.0	37.5
20.0	12.0	50.0
25.0	14.0	62.5
30.0	16.0	75.0
35.0	18.0	87.5
40.0	20.0	100.0

The power controller is adjustable between 0 MW and 40 MW at the Kpong hydroelectric generating station. The power controller is part of the speed controller and the deviation between the set-point (35 MW) and the actual power produced causes an increase or decrease in the gate opening via the valve response. It can be seen in the Table 3 that, at 0 MW active power demand the PLC sends 4 mA current signal to position wicket gate (closed) at 0% position, while at 40 MW power the PLC sends a 20 mA to the proportional solenoid valve to fully open wicket gates to 100%. The ladder diagram for these actions was developed using RSlogix PLC software by Allen-Bradley and the simulation block diagram is shown in Fig. 15.

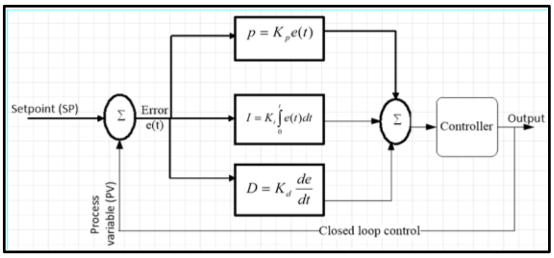


Fig. 15 Process Control Block Diagram Using PID Equation

Thus, the PID equation is:

$$Output = K_p e(t) + K_i \int_0^t e(t)dt + K_d \tfrac{de}{dt} \qquad (4)$$

where; K_p is the proportional gain;
e(t) is the error signal;
K_i is the integral gain; and
K_d is the derivative gain.

Equation 4 then gives Equation 5 as the standard form of the equation:

$$Output = K_c[e(t)dt + {}^1\!/_{T_i} \int e(t)dt + T_D \frac{d(pv)}{dt}] + bias \qquad (5)$$

Thus, K_c is the controller gain, with reference to the Proportional;
$1/T_i$ is reset term, with reference to the Integral; and
T_D is the rate term, with reference to the Derivative.

3 Results and Discussion

3.1 Field Studies Results

Generator Capability Curve

The generator capability curve is a P-Q plot diagram used to estimate the steady state instability limit for a specific generator operating at rated voltage. It is a composite of three curves along the MW axis and MVAR axis: i) stator winding limit; ii) the rotor winding limit; and iii) the stator end iron limit.

Fig. 16 show the generator capability curve for a SG at the Kpong HGS.

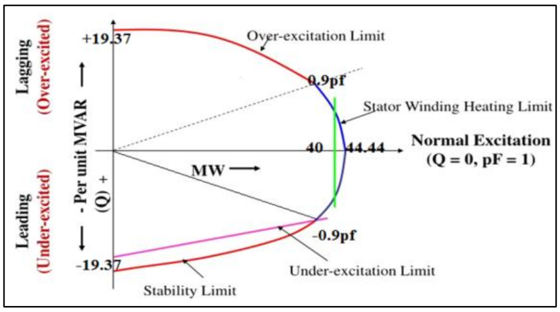
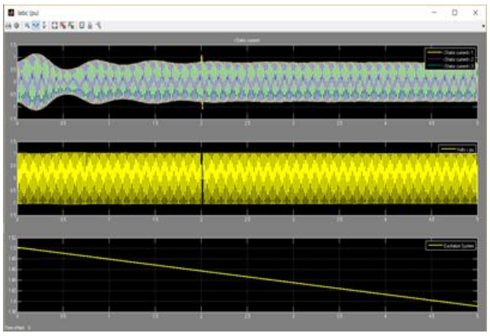


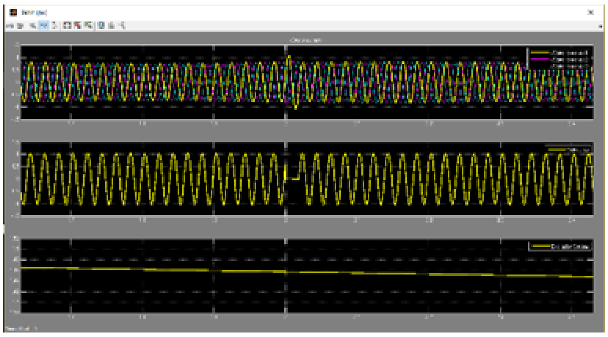
Fig. 16 Generator Capability Curve at Kpong HGS

3.2 Simulation Results

Results of MATLAB Simulink

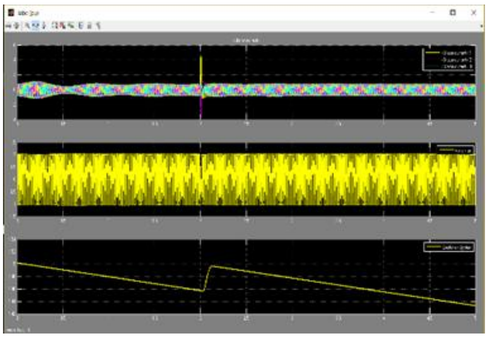
Some MATLAB Simulink results showing a Phase A to Ground Fault; Phase A and B to Ground; and Transient Fault (Phase A, B and C to Ground); with various cycles demonstrated to ascertain various levels of stability and instability in the system.

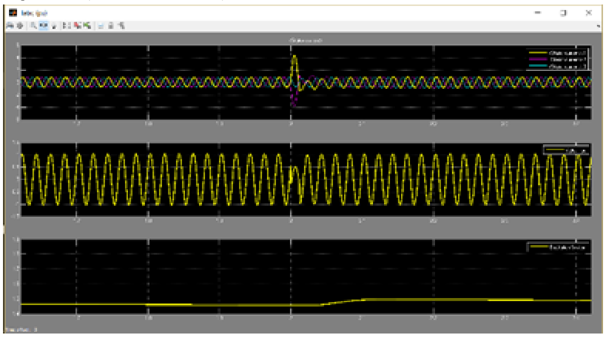




(a) (b)

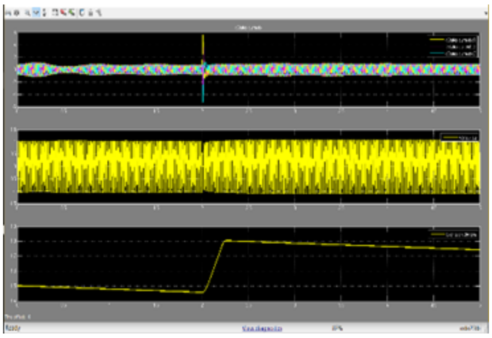
Fig. 17 (a) Phase A to Ground Fault for a duration of 10 ms or 0.5 cycles (very stable); (b) Phase A to Ground Fault for Duration of 10 ms or 0.5 Cycles (zoomed out)

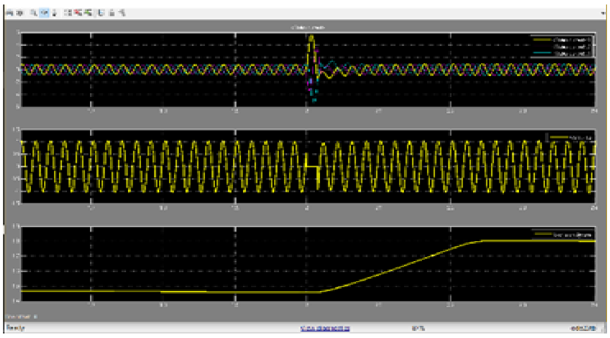




(a) (b)

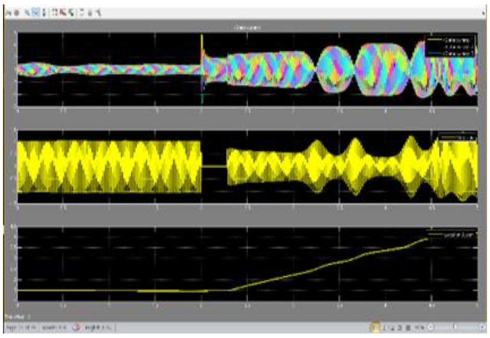
Fig. 18 (a) Phase A and B to Ground for duration of 10 ms or 0.5 cycles (stable); (b) Phase A and B to Ground for 10 ms or 0.5 cycles (zoomed out)

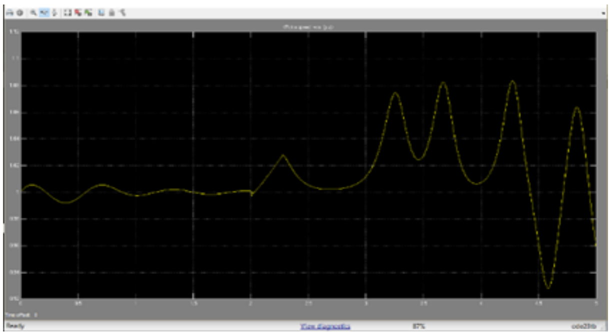




(a) (b)

Fig. 19 (a) Transient Fault (Phase A, B and C to Ground) for a duration of 10 ms or 0.5 cycles; (b) Transient Fault (Phase A, B and C to Ground) for a duration of 10 ms (zoomed out)





(a) (b)

Fig. 20 (a) Transient Fault (Phases A, B and C to Ground) for 275 ms or 13.75 cycles (unstable); (b) Rotor Speed Deviation for 275 ms or 13.75 cycles of Transient Fault (Heavy Oscillation)

3.3 Discussion

This section gives interpretation of the results obtained from the field studies as well as the simulations in the MATLAB/Simulink and then that of the SCADA and PLC software.

3.3.1 Field Study Results

The result of the field studies shown in Fig. 16 indicates the generator capability curve of the SG at the Kpong HGS. It is important to know at first hand the acceptable operating regions of the generator in order to design an appropriate control system for it. It can be seen that, the active power at 0.9 power factor is 40 MW and the active power at unity power factor is 44.44 MW. This indicates that, if power factor control is improved, the generator can produce active power above 40 MW. Even a gain of 2 MW is enough to change economic fortunes.

Additionally, reactive power for the generator can go further from 19.37 MVAR to 26 MVAR but it is rather better to control excitation to ensure that reactive power production reduces drastically to avoid rotor and stator winding temperature rise, and that can, in turn, prolong the life span of the generator.

3.3.2 Discussion of MATLAB Simulation Results under Steady State Condition

The steady state condition of the SG is the state, in which, the machine operates in an acceptable stability region within the generator capability curve, as shown by the functional block model in Fig. 11(a), where the three-phase fault block was not active. The presence of AVR in the control system provides nominal excitation power to the field windings to keep the stator terminal voltage within nominal operating range.

3.3.3 Discussion of Simulation Results under Transient Fault Condition

With the introduction of a single phase to ground fault, the system dynamics did not change much. Fig. 17(a) and Fig. 17(b) indicate a dip in terminal voltage when a single phase to ground fault occurred; a corresponding swell in stator current at the t = 2 s for instance, for a duration of 10 ms was also observed. The fault was cleared at 2.01 s. The duration and type of fault usually would cause a lot of changes to the power system. In this case, the generator terminal voltage and stator current was slightly affected and got quickly restored to normal.

When a two phase to ground fault was introduced, Fig. 18(a) and Fig. 18(b), the waveforms of the stator currents and terminal voltages of the SG for a short duration of 10 ms or 0.5 cycles, the voltage decreased, while the stator current increased to about 4 times the rated stator current and then decreased back to acceptable equilibrim state.

A look at Fig. 19(a) and Fig. 19(b) show the subjection of the power system to a transient fault, a fault involving all three phases to ground, for the same short duration of 10 ms and the system recovered without the generator going out of step. The duration of the transient fault was then extended to find out at what duration the system would lose synchronism or go out of step. Thus, the system was able to remain stable with transient (three – phase to ground) fault for a duration of 20 ms as seen in Fig. 19(a) and Fig. 19(b). The power system again remained stable for a transient duration of 200 ms, 250 ms, 260 ms, and 270 ms. The power system however, failed to recover after a transient fault duration of 275 ms. The stator current and the terminal voltages never recovered their equilibrium states and hence the sytem became unstable. This can be seen in Fig. 20(a), which show the unstable voltages and Fig. 20(b) show the rotor speed deviation, which continued to oscillate even after the fault was cleared. It became clear from the excitation graph that, the AVR raised excitation voltage when the terminal voltage dipped and lowered excitation voltage at the moment the terminal voltage swelled. Consequently, the transient fault currents went high to 6 times the nominal stator currents.

As the system experienced a sudden short circuit, the SG terminal output power dropped rapidly, followed by a rapid acceleration of the generator rotor. The natural action to compensate for the voltage loss is that, AVR increased the excitation voltage, V_f, from 1.5 pu to 4 pu.

Thus, less than the critical fault clearing time of the power system was discovered as 270 ms. Any fault duration beyond this critical value causes the generator to go-out-of-step and loss synchronism of the system. The waveforms show that, the SG at Kpong HGS requires a faster control and protection system.

The calculation of the fault clearing time include the relay operating time plus circuit breaker contacts opening time. The circuit breaker at the Kpong GS is a Live Tank Circuit Breaker with operating time of 3 cycles (60 ms). It is therefore obvious that, the fault clearing time would be: Fault clearing time (T_{fc}) = Relay Operating Time(T_r) + Circuit Breaker Operating Time (T_{cb}) = $T_{r+}T_{cb}$ = 205 ms+60 ms = 265 ms.

The PLCs used to coordinate with multifunctional Solid State Relays (SSRs) to achieve operation time in 1 ms to 1.5 ms would overcome this problem since digital relays SSRs with operating speeds, according to National Instruments is around 1 ms to 1.5 ms. This means, the fault clearing time must be less than 270 ms for the Kpong GS and PLCs in combination with multifunctional relays can be used, since they provide quiker rensponse as compared to the electromechanical relays.

3.3.4 Discussion on SCADA Results

The use of WinTR SCADA achieved the objective of polling and displaying the stator and core temperature values. It became possible to remotely perform settings in the WinTR SCADA software server via internect connectivity. Thus, by the use of modbus TCP/IP address, Url: "168.17.45:8376/_1.
.html", an operator could make changes at a remote area.

3.3.5 Discussion on PLC Results

The control of active power was demonstrated in a PLC ladder logic using RSLogix micro lite started with the application of a PID block. The limitation experienced was that, the tuning of the PID was not going to be accurate without a real PLC to download the program to it.

The alarm setpoint temperature value for the generator stator and core was set at 65^0C and the setpoint value for trip was set at 80^0C. The alarm coil remains OFF when the process variable temperature is 64^0C. The alarm coil turns ON at the moment the temperature rises to 65^0C. The trip circuit would activate, only after the temperature rises to 80^0C.

3.4 Costing

Table 3 is a presentation of the estimated cost of materials for the proposed project to aid in performing the cost benefit analysis without installation cost.

Table 3 Materials Cost

ITEM	NAME	QTY	UNIT COST ($)	AMOUNT ($)	SOURCE
Active Power Control					
1	Current Transformer	1	–	–	Existing-Kpong GS
2	Potential Transformer	1	–	–	Existing-Kpong GS
3	SINEAX 530 Power Transducer	1	283.78	283.78	www.gmciuk.com
4	SIEMENS SICAM TM 1703 AI 6300 Analog Input/Output Module	2	400.00	800.00	www.ebay.ie
5	Proportional Solenoid Valve	2	1000.00	2000.00	www.aliexpress.com
Temperature Control					
6	Universal Transmitter 4116	1	375.00	375.00	www.ebay.com
7	RTD (pt100), Stator Slot Sensor	32	116.00	3712.00	www.Tcdirect.com
8	RTD, PT100 with Terminal Head	14	12.50	175.00	www.Tcdirect.com
9	Digital Relay	2	78.00	156.00	www.Tcdirect.com
10	Surface Heater	8	250.00	2000.00	www.alibaba.com
SCADA System					
11	SICAM RTU	1	2936.96	2936.96	www.ebay.com
12	Workstation Desktop Computer	2	1500.00	3000.00	www.dell.com
13	Industrial Ethernet Rail Switch-IE-3000-8TC-E	3	2927.47	8782.41	www.industrialnetworking.com
14	License for Engineering SCADA System-Ignition SCADA Software	1	9950.00	9950.00	https://inductiveautomation.com/pricing/ignition
Communication					
15	12 Strand Gel-Filled OSP Outdoor Multimode 12-Fiber Optical Cable, 2000 ft	2	1636.00	3272.00	www.ebay.com
16	NTP Time Server LANTIME M300/GPS	1	1500.00	1500.00	www.ebay.com
17	Remote Control Router Switch-EC51410 VPN Router	1	788.00	788.00	www.industrialnetworking.com
18	Cisco Firewall Edition (ASA5512-K9)	1	935.61	935.61	https://www.amazon.com
19	Spectre Network Gateways	1	599.00	599.00	www.industrialnetworking.com
20	Miscellaneous			8253.15	
			Total	**$49,518.91**	

4 Conclusion and Recommendations

4.1 Conclusion

A Simulink tool in MATLAB was successfully applied to build a SG connected to an infinite bus, in this case, considered as the grid. Simulation studies under normal and system disturbance conditions were performed and results obtained in the form of waveforms. The second aspect of the research then used SCADA and PLC software, WinTR and RSLogix Micro 1100 to demonstrate how data such as the generator stator and core temperatures can be recorded and displayed for the Kpong HGS. The active power control of the unit was also done using a PID block diagram from RSLogix Micro 1100. Thus, the control of SG at the Kpong HGS was improved by the use of the digital PID controller from RSLogix software instead of the previously used governor PID controller, which used chains of electromechanical relays with lots of physical wiring in its circuitry. Costing the project for one complete unit showed that, an estimated amount of $49,518.91 (USD) is needed to execute the project. This amount is far less than the cost of losing one SG. In fact, a 1 MW SG cost around $150,000 (USD). A 40 MW SG like the one at Kpong, would cost far more. Therefore, it is better to improve the control system to safeguard the generator.

4.2 Recommendations

(i) This research therefore, recommends that, SCADA and PLC control systems be adopted for the control of the SG at the Kpong HGS.

(ii) Future works could tackle the use of SCADA and PLCs to control reactive power and program for the control of the generator ambient temperature during shutdown to prevent condensation at the Kpong GS.

References

Anon. (2005), "Aerospace – Characteristics of Aircraft Electrical Systems", *ISO* 1540, Vol. 12, Issue: 3, pp. 255 – 258.

Anon. (2012), "FFC Report- Public Utilities Regulatory Commission", *www.purc.com.gh/ purc/sites/default/files/ffcreport.pdf.* Accessed: October 25, 2015.

Anon. (2015), Tips for selecting the right SCADA system for your needs, *www.wonderware.com.* Accessed on: June 1, 2017.

Ayensu, E. S. (2013), *Lake of Life: Celebrating 50 years of the Volta River Authority*, Bruce Marshall Publishers, Portugal, 220 pp.

Erceg, G., Erceg, R. and Idzotic, T. (2015), "Using Digital Signal Processor for Excitation System of Brushless SG", *Proceedings of the 25th Annual Conference of the IEEE*, San Jose, USA, Vol. 3, Issue 29, pp. 1355-1360.

Ghazizadeh, M. S. and Hughes, F. M. (2014) "A Generator Transfer Function Regulator for Improved Excitation Control", *IEEE Transactions on Power Systems*, Vol. 13, Issue 2, pp. 56 – 67.

Glavitsch, H. (2011), "Automation and Control of Electrical Power Generation and Transmission Systems", *Control Systems, Robotics and Automation*, Vol. XVIII, pp. 1 – 10.

Juan, A. A., Faulin, J., Ruiz, R., Barrios, B., and Caballé, S. (2010), "The SR-GCWS hybrid algorithm for solving the capacitated vehicle routing", *Applied Soft Computing*, Vol - 10, Issue 1, pp. 215-224.

Ivanic, B. (2013), "AVR for a SG with a Six-Phase PM Alternator and Rotating Excitation System", *MSc Thesis Report*, Uppsala University, Uppsala, 97 pp.

Kim, Y. S., Park, Y. Y., Lee, K. M., Lee, H. J., and Park, C. W. (2015), "Modeling and Fault Simulation of Generator Control System using PSCAD/EMTDC", *International Conference on Power Systems Transients*, Cavtat, Croatia, pp. 1-5.

Kumar, G., Gite, V., Gulame, P. and Karodi, S. M. (2015), "PLC Based Automatic Excitation Control of SG", *International Journal for Scientific Research and Development*, Vol. 3, Issue 04, pp. 182 -184.

Kundar, P. (2011), *Excitation Systems, Chapter 8 in Power System Stability*, McGraw-Hill, Inc, pp. 315-377.

Lima, C., Grau, A., Joao, M. and Martínez, H. (2015), A MATLAB/Simulink framework for PLC controlled processes, Available at: *www.intechopen.com*; Accessed on: March, 19, 2017.

Nise, N. S. (2011), *Control Systems Engineering*, John Wiley and Sons, Sixth Edition, California State Polytechnic University, Pomona, 926 pp.

Paserba, J. J, Shimomura, M., Tanaka, S., Shoup, D. J. and Hellested, R. T. (2002), "Enhanced Generator Controls for the Improvement of Power System Voltage Stability", *Symposium of Specialists in Electric Operational and Expansion Planning*, Salvado, Brazil, pp. 1 – 13.

Peacock, I. and Mahoney, K. (2011), "The ABCs of Small Hydro Upgrade and Automation", Industry Application, Available at: *www.IA08303003E.pdf.com*, Accessed on: November 26, 2016.

Petruzella, F. D. (2011), *Programmable Logic Controllers*, McGraw Hill Publishers, New York, 4th ed., pp 414.

Ula, A. and Hasan, A. R. (2013), "Design and Implementation of a Personal Computer Based Automatic Voltage Regulator for a SG", *IEEE*

Transactions on Energy Conversion, Vol. 7, Issue 1, pp. 19 – 26.

Vasudevan, K., Rao, G. S. and Rao, P. S. (2006), “Electrical Machines II”, Available at: *www.synchronousmachines.pdf.com*, Accessed on: November 20, 2016.

Vedrana, J., Kresimir, M. and Zeljko, S. (2010), “Excitation System Models of Synchronous Generator”, Available at: *www.475822.Final_ paper_SiP2010_Jerkovic.com*, Accessed on: November 27, 2016.

Xiangfei, M. (2005), “Digital Generator Control Unit for Synchronous Brushless Generator”, *MSc Thesis Report*, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 172 pp.

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