Stability Analysis of An Automated Regulator for Alternator Terminal Voltage and Reactive Power Control

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Abstract- The design involves the establishment of a Proportional and Integral (PI) control system from a linear mathematical model using some primary module transfer functions. All parameters are fed into a MATLAB command window to compute the transfer function for each module, and the over-all closed-loop transfer function of the system. The tuned parameters are then tested in the linear system before applying to the non-linear synchronous generator circuits, modelled for a grid power system. The tuned Controller is used to feedback a voltage component of the reactive power output, when compared to a reference value, to an excitation system. The output of this is then channelled to the generator as d.c. voltage pulses to observe its stability. Linear and non-linear output plots are obtained. This research work uses MATLAB R2015a version.

Indexed Terms- reactive power, var, excitation, AVR, transfer function, tuning, optimization.

I. INTRODUCTION

A power system is faced with the task of generating and transmitting electrical power for consumption with emphasis on consumer satisfaction along with optimum reliability and system stability.

The most effective means of providing bulk power has been made possible with alternators or synchronous generators in power plants [5]. Synchronous generators can generate or absorb reactive power depending on their excitation [4].

II. REACTIVE POWER

In electrical power systems, to convert electrical energy into a rotational energy, a magnetic field has to be created in between the gaps of stator and rotor of the machine. This magnetic field is the medium through which the rotor and the stator can interact. Energy conversion takes place in this medium. It forms the electrical connection between the rotor and the stator. The power to create the magnetic field is the reactive power, and is rated in Volt-Ampere Reactive (VAR). The VAR does no useful work, but is required for active work to be done. It travels along the power system, being absorbed and discharged continuously by the loads.

Due to the relative motion between the magnetic field and the armature, the armature conductors cut the flux of the magnetic field, and hence there's a changing flux linkage with the armature conductors. When a load is connected, current begins to flow. The reactive power is used for rotor excitation. The real power output is primarily a function of the energy flow rate into the prime mover. Changing the excitation changes the VARs, not the MW. The way and manner the generator behaviour changes with excitation is of importance. The excitation would enhance power system stability with optimal power transfer if properly controlled. The excitation control device is the Automatic Voltage Regulator (AVR). Its function is to keep track of the generated reactive power at all times and under any working load condition in order to keep the voltage within pre-established limits [3]

III. EXCITATION

Increasing or decreasing the excitation current is done by the AVR. Increasing the excitation current increases the generator terminal voltage. An islanded generator would experience a terminal voltage rise above pre-set limit. In distributed generation, the generator would produce and transfer more VARs into the power system in the grid. In that process it exports more VARs than the grid demands, and the terminal voltage would try to rise [2]. The other generators would react by dropping their excitations slightly and becoming more under-excited. They would then use the VARs so produced by the over-excited generator to provide part of their excitation. This can only be possible with AVRs, otherwise they all fall out of synchronism and the power system fails. Raising the excitation also results in a shift in Power Factor. The power factor becomes lagging. It is worth noting that the generator convention holds that "VARs out is lagging, while VARs in is leading". That is to say if the generator exports VARs, it's on a lagging power factor. If on the other hand, VARs flow into the generator, it is on a leading power factor. Controlling the excitation is controlling the reactive power produced, which in turn controls the terminal voltage and improves the power factor. Over-excitation could as well overheat the generator windings if we combine a high MW output plus high VAR output for export. On the other hand, under-excitation absorbs reactive power, which in turn affects the power system. The generator terminal voltage falls, and the VARs begin to flow into the generator from the power system if connected to the grid, as discussed. This is the case of the "VARs in".

IV. POWER FACTOR

The power factor becomes a leading power factor. If the rotor current is reduced too much, the magnetic field will become so weak that the generator loses stability and falls out of synchronism with other generators in the power system. Voltage collapse is inevitable. In order to operate at optimum excitation, every generator is provided with its excitation capability map, whether it's absorbing or supplying VARs and MW. Inductive loads draw a lagging current, and so they have a lagging power factor (positive). Such loads also consume the reactive power in the system. To decrease the power factor in the lagging direction from 1.0 is by increasing the excitation applied to the machine. On the other hand, when a power system supplies capacitive loads, it is supplying a leading current and the power factor is a leading power factor. This means the injection of more reactive power into the system. To decrease the power factor in the leading (negative) direction from 1.0, decrease the excitation of the machine. When the excitation is exactly equal to the amount required to equate the generator terminal voltage with the grid voltage, the VAR flow will be zero, at unity power factor. When the excitation is increased above the amount required to make the generator terminal voltage exactly equal to the grid voltage (boost the grid voltage), lagging VARs will flow into the generator stator windings [1]. The power factor becomes less than unity in the lagging direction. To restore the power factor is by decreasing the excitation. Thirdly, when the excitation is decreased below the amount required to make the terminal voltage exactly equal to the grid voltage (buck the grid voltage), leading VARs will flow in the generator stator windings. The power factor becomes less than unity in the leading direction. To restore the power factor is by increasing the excitation. In the same vein if the generator loses excitation (loss of field), the generator runs at a speed above the synchronous speed. In that situation the alternator becomes an induction generator which draws a magnetizing current or reactive power from the system. As the alternator is not designed to work as an induction machine, the machine windings heat up and deform. Since the generator cannot handle all these disturbances, the need for the AVR now becomes inevitable. The AVR is introduced into the system for safety and economic reasons. The reactive power and the terminal voltage as well as the power factor are so inter-related that the control of one parameter affects the other parameters.

V. THE AVR

In the ideal AVR model, a sensor comprising a power transformer with integral filter and a bridge rectifier module is used to constantly measure the alternator voltage and current. It then sends a rectified d.c feedback voltage signal to the comparator module of the controller. The comparator also receives a reference d.c. voltage and then establishes an error signal output, which is used by the controller to calculate the amount of dc voltage needed for excitation. Each time the generator voltage is more than the reference value, the controller increases the controlling angle of the thyristors which reduce the field current to return the generator terminal voltage to the reference point and vice versa. The control loop here with the PI-Controller is designed as a masked sub-system. It already has a comparator in it, so it receives the reference and reactive power signals and compares before taking decision on how to instruct the excitation system.

VI. RESEARCH METHODOLOGY

There is a standard table of values whereby the transfer function of each module can be deduced from given parameters.

A range of values are selected from the table, and used in calculating the transfer functions of the various devices used in the close-loop control. The transfer functions are fed into a SIMULINK block and simulated. The first simulation is done with zero controller gains. Signal constraint box is later used to derive gains. The gains are then optimized, and finally tuned to arrive at acceptable values. These gain values are then used to simulate a linear excitation control loop, before applying to a non-linear control loop to observe how stable the control loop could be. The Exciter here is a thyristor bridge, while the Sensor is a Power transformer to measure the generator terminal voltage. There are other loop components like Phase Locked Loop (PLL); the Pulse Generator, all within the Exciter cabinet.

Table 1. Standard Parameters for AVR [4]

Device	Transfer function	Parameter Limits
PI Controller	$Kp + \frac{Ki}{s}$	$0.2 \le k_p/K_i \le 2$
Amplifier	$\frac{K_A}{1+\tau_A S}$	$10 \le K_A \le 40$; $0.02S \le \tau_A \le 0.1\,S$
Exciter	$\frac{K_E}{1+\tau_E S}$	$1 \le K_E \le 10$; $0.4\,S \le \tau_E \le 1.0S$
Generator	$\frac{K_G}{1+\tau_G S}$	K_G depends on load (0.7-1.0); $1.0S \le \tau_G \le 2.0\,S$
Sensor	$\frac{K_T}{1+\tau_T S}$	$0.001S \le \tau_T \le 0.06S$

VII. TRANSFER FUNCTIONS

From the Table, the various transfer functions are as follows:

Amplifier: $\frac{K_A}{1+\tau_A S} = \frac{10}{0.1+S}$ = G1 (K_A = 10, τ_A = 0.1)

Exciter: $\frac{K_E}{1+\tau_E S} = \frac{1}{1+S}$ = G2 (K_E = 1; $\tau_E = 1.0$)

Generator: $\frac{K_G}{1+\tau_G S} = \frac{1}{1+S}$ = G3 (K_G = 1.0; $\tau_G = 1.0$)

Sensor: $\frac{K_T}{1+\tau_T S} = \frac{1}{1+0.05S}$ = H (K_T = 1; $\tau_T = 0.05$)

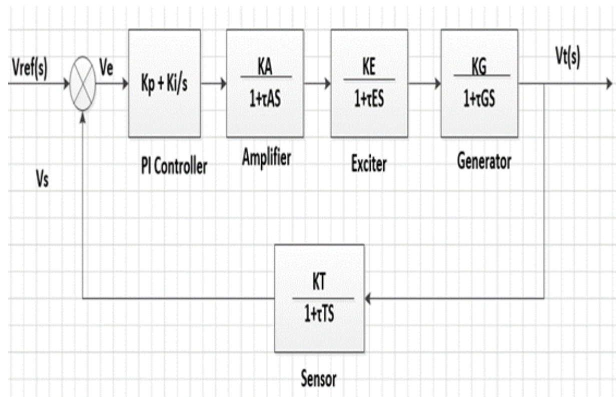

Fig. 1: Block diagram of the AVR system

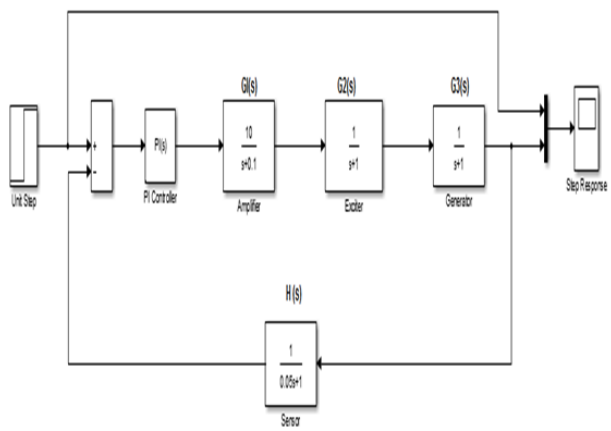

Fig. 2: SIMULINK Model of Transfer Functions

VIII. SIGNAL OPTIMIZATION

Optimization tool is used to generate the initial Proportional and Integral gain constants before further tuning. It involves the simulation of the AVR loop using signal constraints block. Permissible iterations are carried out until feasible solution is achieved.

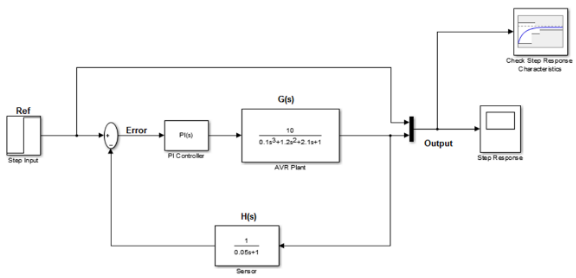

Fig.3: Simplified block with signal constraints

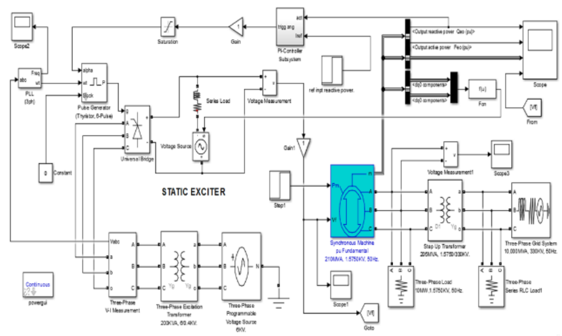

Fig. 4: SIMULINK Model for the Non-Linear Control loop

IX. CONTROLLER TUNING

Loop tuning is another means of realizing optimum Controller gains before simulating the AVR loop for Controller behaviour. Spurious signals come when the generator output voltage is higher or lower than set point. Loop tuning is achieved with the MATLAB PID-TUNER. The Tuner is capable of injecting unwanted signals into the plant, and at the same time generates the Controller response to every disturbance.

X. THE NON–LINEAR CONTROL LOOP

The non-linear control loop is a MATLAB SIMULINK model for the reactive power control, using a Static excitation system to supply field voltage to a synchronous generator connected to a grid network system. The static excitation system consists of a Phase Locked Loop, Pulse generator and a controlled bridge rectifier. The bridge rectifier is supplied from an auxiliary power supply system. The rectifier suppliers the excitation current directly to the main field of the synchronous generator. [3]. The excitation system controls the Voltage and enhances generator stability.

The AVR, previously configured as a PI-Controller with already tuned parameters is a major part of this voltage and reactive power control loop. It receives the generator output voltage and current, or reactive power and compares to the actual value obtained from the generator before sending an output voltage to the Pulse generator which then feeds the universal bridge with pulses of d.c voltage signal. The error signal generated by the AVR determines whether to raise the excitation current or reduce the excitation current by the rectifiers.

XI. SIMULATION RESULTS

- Open loop simulation: The open-loop output curve is characterized by instability along the line. Heavy over-shoots and under-shoots engulf the plot. This shows the absence of a Controller.
- Closed loop simulation: The closed-loop step response has initial oscillations with heavy over-shoots. It also forms a new reference point after the transient period has elapsed. This terminal voltage is not desirable in power system. It does not track the reference input unit step value. Steady state error is high. This is the effect of not using a Controller to track the output terminal voltage. There is that possibility that every loop disturbance would result in oscillations with great over-shoots and a larger steady state error.

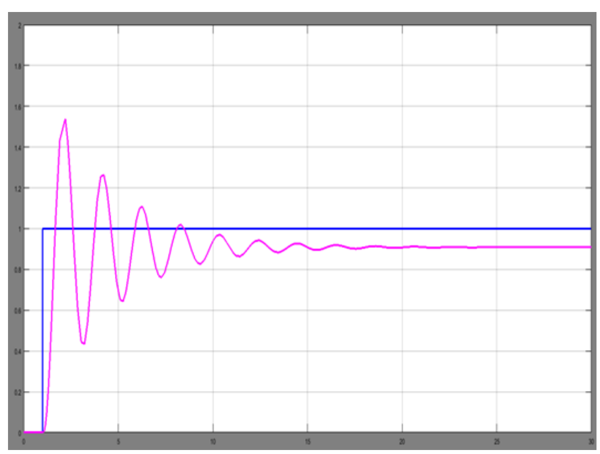

Fig. 5: Step Response for Non-compensated loop.

- Optimization simulation: The essence of optimization, as earlier discussed was to generate a series of curves from the software in different iterations until a perfect curve is obtained. There is that liberty of optimizing to a tune of fifty iterations before making success. The first iteration shown her was not feasible. The iteration did not converge so did not generate the Proportional (Kp) and Integral (Ki) controller gains.

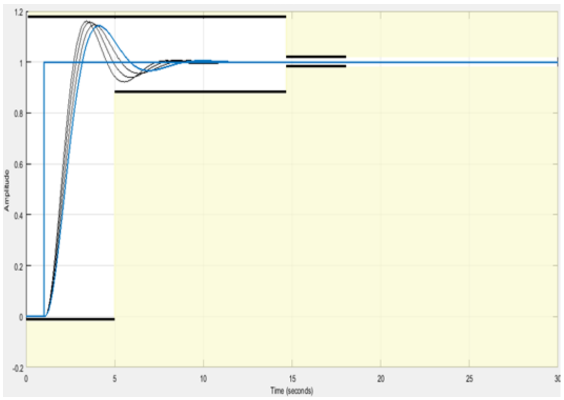

Fig. 6: First Optimization Iteration

The second optimization iteration produces a final single curve.

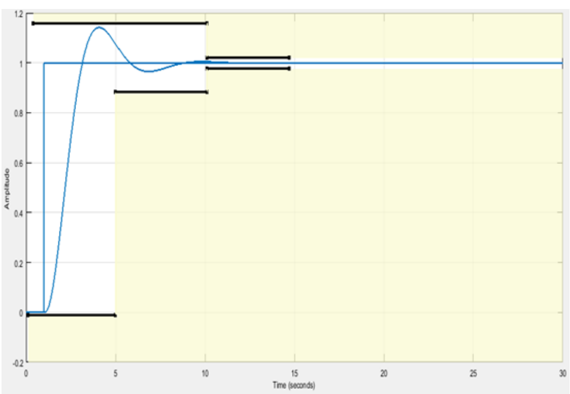

Fig. 7: Converged Iteration

The final iteration produces a feasible solution with the following Controller Gains: Ki = 0.0935 and Kp = 0.1404.

Despite the convergence, certain system parameters were sacrificed to arrive at this successful solution. The optimization block parameters reveal the following:

Steady-state error (e_{ss}) = 0.9984;
Rise Time (t_r) = 1.41s
Settling Time (t_s) = 6.92s;

Percent Over-shoot = 14.3%

Closed-loop stability: Stable.

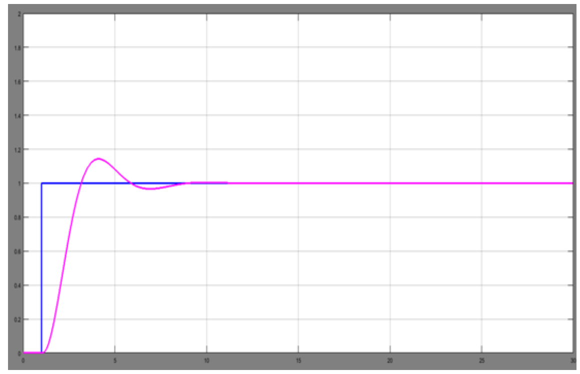

Fig. 8: Step Response after Optimization.

The Overshoot is not desirable, so Loop Tuning was used to further work on the percent overshoot, using the SIMULINK.

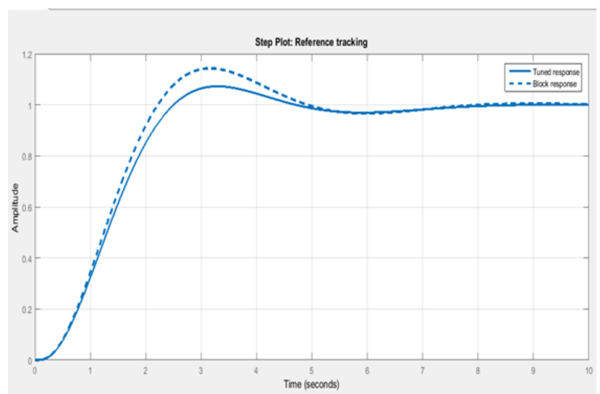

Fig. 9: Controller Reference Signal Tracking

The dotted lines depict the Optimized plant and the solid lines represent the tuned plant. The two situations achieve plant stability, but a better signal tracking is obtained from the tuned plant. The overshoot now falls within an acceptable limit as obtained on the Controller parameter table:

Table 2: Tuned and Optimized Parameters.

Controller Parameters

	Tuned	Block
P	0.13532	0.1404
I	0.077252	0.0935
D		
N		

Performance and Robustness

	Tuned	Block
Rise time	1.57 seconds	1.41 seconds
Settling time	6.9 seconds	6.92 seconds
Overshoot	7.23 %	14.3 %
Peak	1.07	1.14
Gain margin	18 dB @ 3.05 rad/s	17 dB @ 2.94 rad/s
Phase margin	60 deg @ 0.807 rad/s	53 deg @ 0.871 rad/s
Closed-loop stability	Stable	Stable

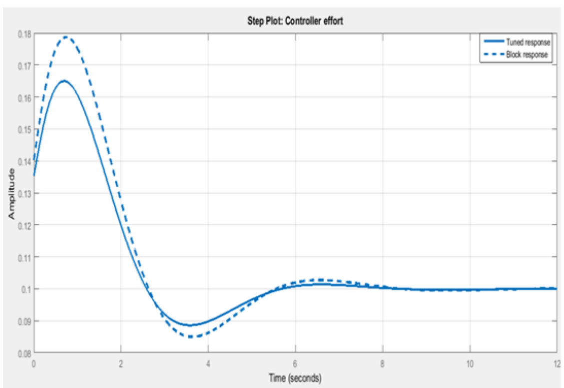

Fig. 10: Controller Effort

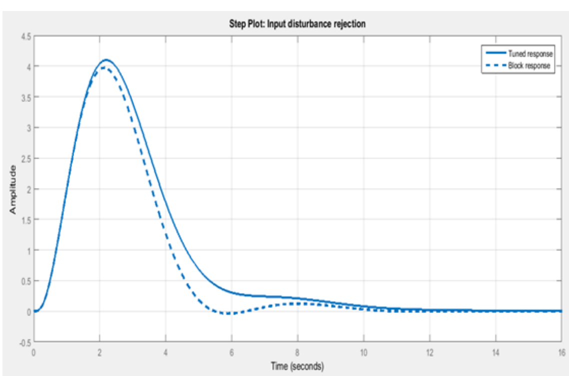

Fig. 11: Input disturbance rejection

XII. NON-LINEAR SIMULATION RESULT

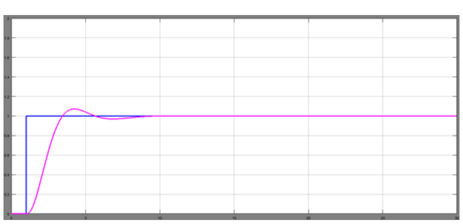

Fig. 12: Step response plot for the non-linear loop

A more refined plot is obtained with improved response and good stability. This is evidenced in the acceptable percent overshoot achieved. The percent overshoot should not be more than 10%.

CONCLUSION

The performance of the Controller is in its ability to reject disturbances generated within the system, as well as those from external sources, and still retain stability. Mathematical models can be used in solving real life problem.

REFERENCES

[1] Control.com, "Relationship between Power factor and Exciter field current". February, 2014.

[2] ENG-TIPs.com, "Generator Excitation and Power Factor". Intelligent Work Forums For Engineering Professionals, 2016.

[3] Dhiya Ali Al-Nimma and Majid Salim Matti, "Reactive Power Control of an Alternator with Static Excitation System Connected to a Network." Vol.18, No.3, June 2010

[4] Vivek Kumar Bhatt & Sandeep Bhongade, “Design of PID Controller in Automatic Voltage Regulator (AVR) System using PSO Technique”. International Journal of Engineering Research, Vol. 3, issue 4, July-Aug, 2013, pp. 1480-1485.

[5] V.K. Metha & Rohit Metha, “Principles of Power System”.4th Edition, 2008.