International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS)
Volume IX, Issue XI, November 2020 | ISSN 2278-2540

Performance Response Improvement of Automatic Voltage Regulator Using Linear Quadratic Gaussian Tuned Controller

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***Abstract*: This paper has presented performance response improvement of Automatic Voltage Regulator (AVR) using Linear Quadratic Gaussian Tuned Controller (LQGTC). The controller was designed using the Control and Estimation Tools Manager (CETM) LQG controller design method of the automatic tuning of the MATLAB/Simulink. The developed simulation model was completely designed as a single input single output (SISO) system for the two possible scenario of operation of an AVR closed loop system. The simulation results indicated that the introduction of the LQGTC was able to improve the time domain performance parameters for transient as well as steady state response, and generally reduced deviation error with effective tracking of desired terminal voltage. For the first case scenario called AVR_sys1, the improvements achieved with the LQGTC were: rise time by 20%, the time to peak overshoot by 21%, percentage overshoot by 86%, and settling time by 60%. The second case scenario called AVR_sys2 showed improvement in rise time by 26%, time to peak overshoot by 30%, percentage overshoot by 51%, and settling time by 62%. In order to validate the effectiveness of the LQGTC, different desired terminal voltage values were considered and the results obtained were the same as those from unit step input, which validated the capability of the proposed controller to provide improved, robust and effective contol for an AVR system.**

***Keywords-:* AVR system, LQGTC, SISO, Terminal voltage**

I. INTRODUCTION

Steady and reliable voltage supply is essential for efficient working of electrical equipment. This is can be achieved using Automatic Voltage Regulators (AVRs). Thus a constant voltage level is sustained by AVR to electrical equipment loads that need a steady and reliable voltage supply. The application of AVR in electrical power systems ensures that the terminal voltage of a synchronous generator is kept at a constant level. This is achieved by using the AVR to control the exciter voltage of the synchronous generator.

Since variations in voltage are regulated by AVR to ensure specific and reliable power supply, its absence in electrical power system can cause voltage drop, spike or surge and thereby damaging electrical devices. Also, choosing appropriate AVR ensures that optimal voltage regulation, low impedance, compatibility with specified load, reliable and accurate voltage level is achieved. Optimal voltage control is achieved for voltage level equivalent to all electrical equipment loads. Achieving low impedance is an object of AVR as this will make it avoids the problem of low voltage, harmonic distortion and voltage unbalance that is by the interaction between load current and generator impedance. The operation of AVR must be well-matched with the specified load to guarantee its operation and to prevent interfering the working of the other loads connected to the same generator.

With changing load and field winding inductance of generator, there may be an undesirable effect on the regulator response [1]. Hence, additional control measure may be required in order to guarantee stable, fast and effective response to transient disturbances in the terminal voltages. One of such control techniques is the conventional Proportional Integral Derivate (PID) controller which has been well deployed in control processes because of its ease of design, simple structure and application. An AVR control system using double derivative PID controller (PIDD) has been proposed by [1] to provide dead-beat response but generally make the response faster with reduced rise and settling times than conventional PID controller. However, the PIDD can produce high peak overshoots in the transient part such that a pre-filter was added to the loop to address this effect. Application of optimal tuning based on Continuous Firefly Algorithm (CFA) has been proposed by Bendjeghaba [2]. Other optimization algorithms that have been proposed and used to tune PID controller are Anarchic Society Optimization [3], Particle Swarm Optimization (PSO) [4, 5], modified evolutionary PSO (MEPSO) [6], Bat Algorithm (BA) [7], teaching Learning Based Optimization (TLBO) [8]. However, these proposed algorithms were not shown to have been tested on varying AVR parameters to ascertain the individual robustness and effectiveness.

This paper has presented an AVR control system that provides robust regulation of terminal voltage. The main goal and contribution of this paper is to minimize deviation from the desired terminal voltage by using a Linear Quadratic Gaussian (LQG) method to design a controller that will provide robust performance for different value range of operational parameters of AVR system.

II. DESCRIPTION AND MODELLING OF AVR SYSTEM

A voltage regulator is a device for changing the voltage of a circuit or for automatically sustaining it at or near a specified value [9]. Hence, the function of an AVR will basically be to maintain the magnitude of the terminal voltage of a synchronous generator at a prescribed value. Figure 1 is a typical circuit diagram of AVR connected to the output terminals of a diesel engine type synchronous generator. The operation is such that the terminal voltage of the generator is sampled through the transformer and rectification performed on it by simple circuit and the bridge rectifier [9].

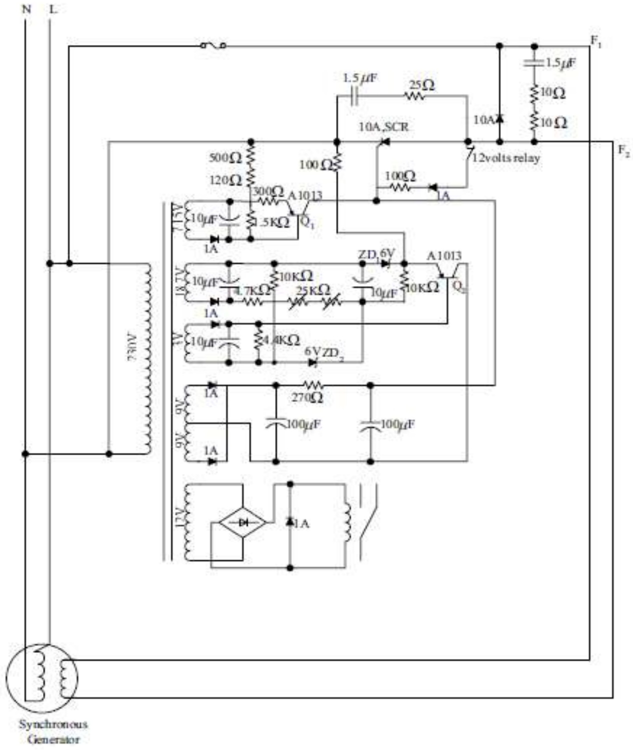

Fig. 1 Circuit diagram of AVR for Diesel Engine type synchronous generator [9]

Since the concern of this paper is to develop a control algorithm to enhance the performance an AVR, the focus will generally be on the main components that determine the voltage regulation capabilities. There are basically four components of interest in designing a control system for AVR, and are: amplifier, exciter, generator, and sensor as shown in the closed loop control structure in Fig. 2. The figure shows that amplifier, exciter and generator are all in the forward path while the sensor is in the feedback path.

As shown in Fig. 2, the first input to the summer is the reference voltage $V_{ref}(s)$, the desired voltage at which the terminal or generator output voltage $\boldsymbol{V_t(s)}$, is expected to run for reliable and steady load equipment voltage operation. The second input $V_S(s)$, is the feedback or measurement signal, and represents the current terminal voltage of the generator captured by the feedback sensor. The difference between these two inputs is the voltage error signal $E(s)$, which is fed to the amplifier such that the size of error signal is magnified and fed to the exciter for subsequent control of the synchronous generator.

The mathematical models of amplifier, exciter, and generator are given as follows:

Amplifier model: The excitation system amplifier may be a magnetic amplifier, rotating amplifier, or contemporary electronic amplifier [1]. The transfer function of the amplifier is represented by a gain K_a, and a time constant τ_a and is given by:

$$\frac{V_a(s)}{E(s)} = \frac{K_a}{1+\tau_a s} \tag{1}$$

where the gain and the time constant of the amplifier are in the limits of $10 \le K_a \le 40$; and $0.02 \le \tau_a \le 0.1$ [1][3][4]. The Transfer functions of amplifier system for simulation purpose are given by:

$$\frac{\boldsymbol{V_a(s)}}{\boldsymbol{E(s)}} = \begin{cases} \dfrac{10}{1+0.02\boldsymbol{s}} \\ \\ \dfrac{10}{1+0.05\boldsymbol{s}} \end{cases} \tag{2}$$

Exciter model: Though different types of excitation systems exist, modern ones use alternating current (ac) power source through solid rectifiers such as silicon control rectifier (SCR) [1]. The exciter output voltage is a nonlinear function of the field voltage due to the saturation effect of the magnetic circuit. Hence, no direct relationship between the terminal voltage and the exciter field voltage. However, a linearized model is established for modern exciter that takes into consideration the time constant while neglecting the saturation or other nonlinearities. The transfer function of the exciter with gain K_e, and time constant τ_e, in the limits of $1.0 \le K_e \le 10$, and $0.4 \le \boldsymbol{\tau_e} \le 1.0$ [1]. The transfer functions for the different values selected are given by:

$$\frac{\boldsymbol{V_f(s)}}{\boldsymbol{V_a(s)}} = \frac{\boldsymbol{K_e}}{1+\boldsymbol{\tau_e s}} \tag{3}$$

$$\frac{\boldsymbol{V_f(s)}}{\boldsymbol{V_a(s)}} = \begin{cases} \dfrac{1}{1+0.4\boldsymbol{s}} \\ \\ \dfrac{1}{1+\boldsymbol{s}} \end{cases} \tag{4}$$

Generator model: The generated electromotive force (emf) of the synchronous generator is a function of the machine magnetization curve [1]. The first order linearized transform function model relates the generator terminal voltage to exciter field voltage and can be represented with gain K_g, and time constant τ_g, whose limits are: $0.7 \le K_g \le 1.0$, and $1.0 \le \tau_g \le 2.0$ [1, 4].

$$\frac{\boldsymbol{V_t(s)}}{\boldsymbol{V_f(s)}} = \frac{\boldsymbol{K_g}}{1+\boldsymbol{\tau_g s}} \tag{5}$$

$$\frac{\boldsymbol{V_t(s)}}{\boldsymbol{V_f(s)}} = \begin{cases} \dfrac{0.7}{1+\boldsymbol{s}} \\ \\ \dfrac{1}{1+\boldsymbol{s}} \end{cases} \tag{6}$$

Sensor model: The terminal voltage is sensed by a potential transformer and is rectified by a bridge rectifier [1]. The mathematical model of the sensor with gain K_s, and time constant τ_s, whose limits are: $K_s = 1.0$, and $0.001 \le \tau_s \le 0.06$ [1, 4] is given by:

$$\frac{\boldsymbol{V_s(s)}}{\boldsymbol{V_t(s)}} = \frac{\boldsymbol{K_s}}{1+\boldsymbol{\tau_s s}} \tag{7}$$

$$\frac{\boldsymbol{V_s(s)}}{\boldsymbol{V_t(s)}} = \frac{1}{1+0.001\boldsymbol{s}} \tag{8}$$

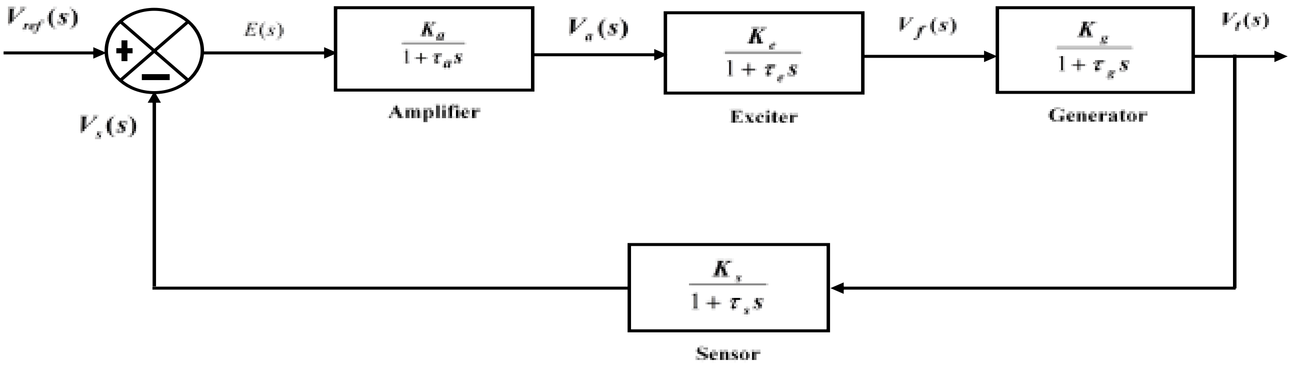

Fig. 2 Closed loop block diagram of AVR system

III. DESIGN OF CONTROLLER

The control system toolbox (CST) of the MATLAB/Simulink offers industrial algorithms and applications for systematically analysing, designing, and tuning linear control system [10]. Using CST requires that a system be represented either as a transfer function, state-space, zero-pole-gain, or frequency-response model. The characteristic performance of the system as step response plot, impulse response plot, and Bode plot can easily be visualized and studied in time domain or frequency domain.

Designing a compensator requires its parameters to be tuned using graphical tuning such as root locus, Bode loop shaping, Ziegler-Nichols, or using automated tuning such as optimization based tuning, proportional integral (PI)/PID tuning, internal model control (IMC) tuning, and linear quadratic Gaussian (LQG) tuning method. Hence, this section presents the design of AVR system in Control and Estimation Tools Manager (CETM). The design flowchart of the proposed LQG tuned controller (LQGTC) is shown in Fig. 3. The developed simulation model that was completely designed as a single input single output (SISO) system for the two conditions of operation considered in this paper as shown in Fig. 4 and 5. The designed compensator is given in Eq. (9).

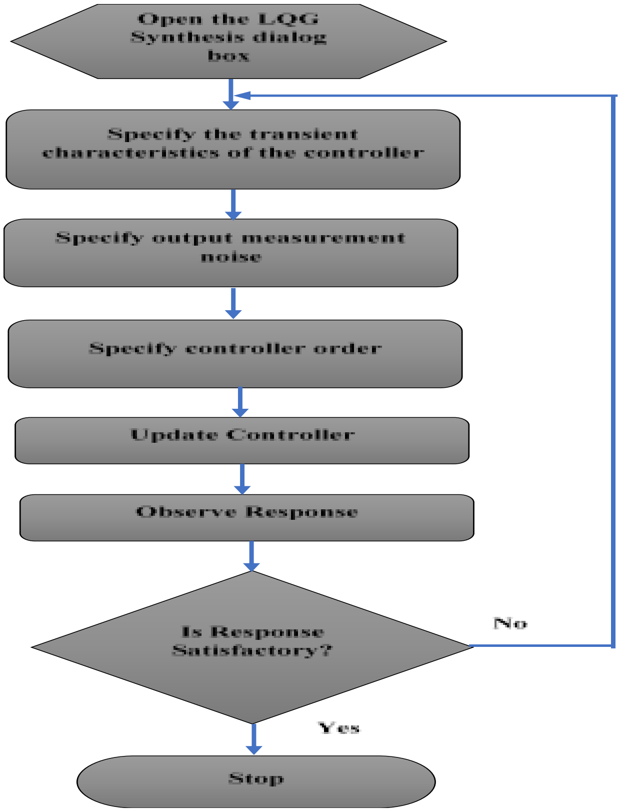

Fig. 3 Flowchart of the controller design process

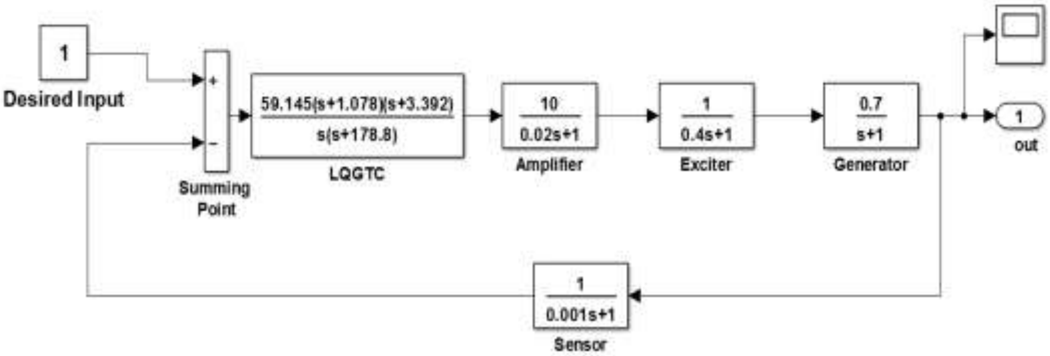

Fig. 4 Simulink model of AVR system (sys1)

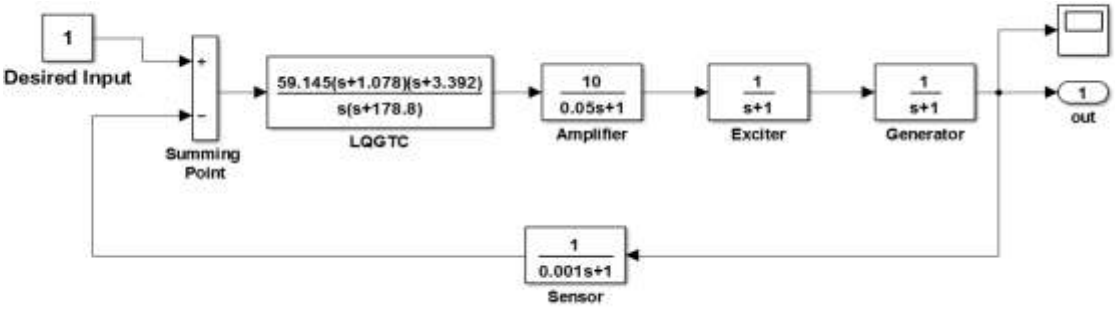

Fig. 5 Simulink model of AVR system (sys2)

$$C(s) = \frac{59.145(s+1.078)(s+3.392)}{s(s+178.8)} \qquad (9)$$

IV. SIMULATION RESULTS ANDDISCUSSION

The results of the simulations carried out in MATLAB/Simulink environment are presented in this section. Performance analysis of each result is performed and subsequently discussion is presented with respect to the time domain characteristics responses of the simulation plots for AVR systems 1&2. Analysis in terms of improvement is based on the approach used in [11].

A. *Simulation Results*

The various simulation results obtained are presented in Fig. 6 to 9. Figures 6 and 7 are the step response plots of AVR system 1&2 without and with the integration of Linear Quadratic Gaussian Tuned Controller (LQGTC) into the AVR closed loops as shown in Fig. 4 and 5 respectively. Figures 8 is the step response plots for the performance comparison of the LQGTC in both AVR closed loop compensated systems. In order to validate the efficiency of the designed LQGTC simulation was conducted for different values of desired terminal voltage, 5V, 9V, and 12V and the Simulink scope graphs are shown in Fig. 9.

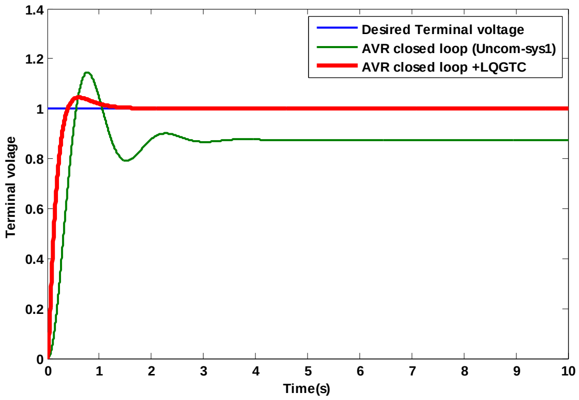

Fig. 6 Step response for AVR system1 terminal voltage

The time domain performance parameters obtained from AVR system1 step response of Fig. 6 are shown in Table 1.

Table 1 Time domain characteristics performance of AVR system 1

AVR Closed loop	Rise time	Time to peak	overshoot	Settling time
Uncomp_sys1	0.31s	0.77 s	30.89 %	2.49 s
LQGTC	0.25 s	0.61 s	4.50 %	1.01 s

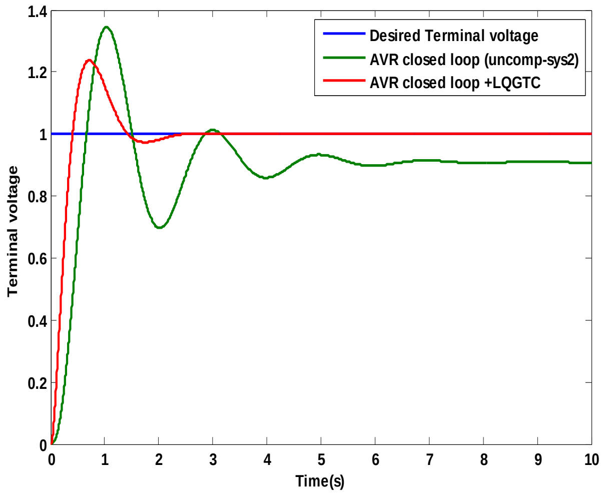

Fig. 7 Step response for AVR system2 terminal voltage

The analysis of the time domain parameters of the step response of AVR system2 is presented in Table 2.

Table 2 Time domain characteristics performance of AVR system 2

AVR Closed loop	Rise time	Time to peak	overshoot	Settling time
Uncomp_sys2	0.38 s	1.03 s	48.10 %	5.22s
LQGTC	0.28 s	0.72 s	23.76%	1.97 s

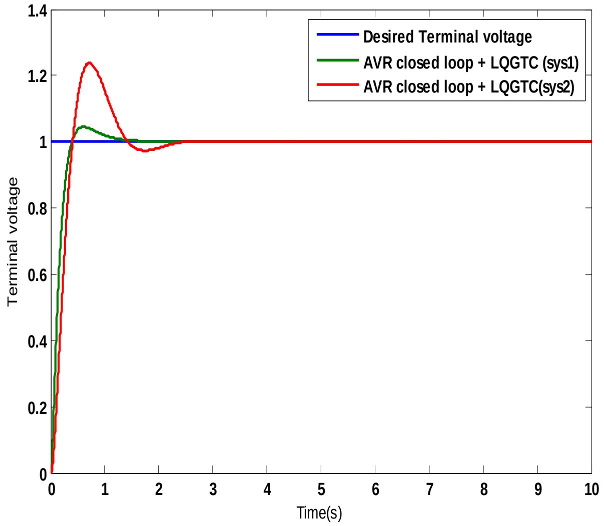

Fig. 8 Performance comparison of LQGTC in AVR system 1&2

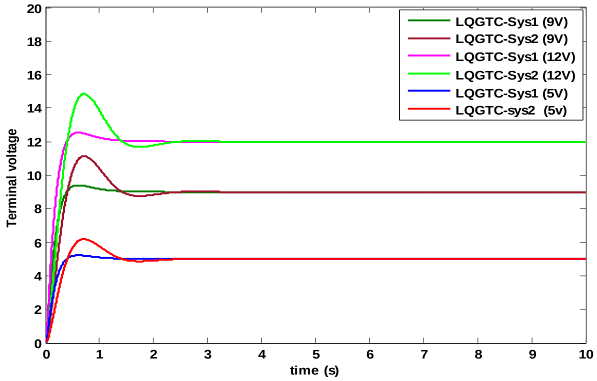

Fig. 9 Validation plots of LQGTC

The time domain performance parameters of the LQGTC compensated AVR system 1&2 for different desired terminal voltage operated points are shown in Table 3.

Table 3: Time domain performance parameter for varying desired terminal voltage

LQGTC_AVR system	Rise time	Time to peak	Overshoot	Settling time
LQGTC_sys1 (5V)	0.25 s	0.61 s	4.50%	1.01 s
LQGTC_sys2 (5V)	0.28 s	0.72 s	23.77 %	1.97 s
LQGTC_sys1 (9V)	0.25 s	0.61 s	4.50 %	1.01 s
LQGTC_sys2 (9V)	0.28 s	0.72 s	23.77 %	1.97 s
LQGTC_sys1 (12V)	0.25 s	0.61 s	4.50 %	1.01 s
LQGTC_sys2 (12V)	0.28	0.72s	23.77 %	1.97 s

B. Discussion

As can be seen in Table 1, the rise time was 0.31 s before the introduction of LQGTC into the system but changed to 0.25 s when the LQGTC was introduced. This indicates an improvement of 20% on AVR system1 rise time due to the addition of LQGTC into the system. The time to peak overshoot was 0.77 s when the system was in uncompensated (Uncomp_sys1) that is without LQGTC, and reduced to 0.61 s when LQGTC was added which is an improvement of 21% with respect to time to peak overshoot. The percentage overshoot was initially 30.89% without LQGTC but reduced to 4.50% as a result of the introduction of LQGTC, which is 86% improvement as far as percentage overshoot is concerned. Also, the settling time was 2.49 s as at the time the system was without LQGTC but reduced to 1.01 s when the controller was introduced. This signifies time domain performance improvement of 60% with regard to settling time.

As shown in Table 2, the analysis of the time domain parameters of Fig. 7 reveals that the rise time was 0.38 before the introduction of LQGTC into the system, which then reduced to 0.28 with the proposed controller in the loop. This shows a remarkable improvement of 26% with respect to rise time. Without the introduction of LQGTC, the time to peak overshoot was 1.03 s but changed to 0.72s on addition of the controller, which is an improvement of 30% as far as time to peak overshoot is concerned. The percentage peak overshoot was initially 48.10% without the controller but reduced to 23.76% with the introduction of LQGTC, which means an improvement of 51% regarding peak overshoot performance. Similarly, the settling time changed from 5.22 s for the AVR system 2 (uncompensated) to 1.97 s with LQGTC (compensated) indicating 62% improvement in settling time.

From Table 3, it can be deduced that designed controller achieved steady and robust performance irrespective of the value of desired terminal voltage and was able to track and maintain this value as shown in Fig. 9. This validates the effectiveness of the proposed controller to aid and enhanced AVR system to provide and maintain steady voltage output under varying load voltage.

Generally, it can be deduced from the simulation results that incorporation of the LQGTC provided better transient and steady states response because of the lower value of the time domain characteristics performance of AVR closed loop plus LQGTC system.

V. CONCLUSION

The paper has designed a Linear Quadratic Gaussian Tuned Controller (LQGTC) for an Automatic Voltage Regulation (AVR). The designed controller was applied to a typical AVR system and the effectiveness successfully verified by simulations conducted in MATLAB/Simulink in environment. The transient response of the compensated system was compared with the uncompensated AVR closed system. Suffice it to say that the LQGTC provided a more robust and improved transient and steady state response.

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