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# Using a Reduced Order Robust Control Approach to Damp Subsynchronous Resonance in Power Systems

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**Abstract**
***This work focuses on the use of the Linear Quadratic Gaussian (LQG) technique to construct a reliable Static VAr Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), and Excitation System controller for damping Subsynchronous Resonance ( SSR ) in a power system. There is only one quantifiable feedback signal used by the controller (generator speed deviation). It is also possible to purchase this controller in a reduced-order form. The findings of the robust control are contrasted with those of the "idealistic" full state optimal control. The LQG damping controller's regulator robustness is then strengthened by the application of Loop Transfer Recovery (LTR). Nonlinear power system simulation is used to confirm the resilience of the planned controller and demonstrates how well the regulator dampens power system oscillations. The approach dampens all torsional oscillatory modes quickly while maintaining appropriate control actions, according to simulation results.***

**KEYWORDS: Flexible AC Transmission Systems, FACTS, Linear Quadratic Gaussian, LQG Control, Loop Transfer Recovery, LTR method, Power System Oscillation Damping.**

## I. INTRODUCTION

Three factors, namely voltage, impedance, and phase difference, affect the amount of power that is transmitted over a power system network. Flexible AC transmission systems are the result of high voltage and high current power semiconductor device development (FACTS). FACTS devices are power electronics-based systems and other stationary machinery that regulate one or more AC transmission system parameters [1]. In order to adapt changes in operating circumstances of an electric transmission system while maintaining enough steady-state and transient stability margins, series compensator and static VAr systems (SVC) are utilized as the FACTS devices in power systems. The issue of subsynchronous resonance (SSR), which has two unique impacts, namely the induction generator effect and torsional interactions effect, is caused by the series compensation of a transmission line. The Turbine-Generator (T-G) set's shaft is susceptible to breaking due to torsional vibrations, which could have disastrous effects [2]. In order to investigate the subsynchronous torsional interaction between the thyristor controlled series compensation (TCSC) and the turbine generator shaft and to assess the control interactions between the TCSC and other power system components like the SVC (static VAr compensation) and excitation systems, H.R. Liang; A.V. Prokhorov and H. Mokhlis, [3] developed an analytical model of the TCSC. However, data revealed that die interarea mode is less damped when uncertain load factors are present. H. Ghorbani; D. E. Moghadam; A. L.and J. I. Candela [4] proposed the resilient adjustment of SVC. There are no controllers or schemes that can successfully dampen all SSR modes at various levels of series compensation, over extremely light load to overload conditions, for various types of severe faults, according to a thorough review of the literature (without considering the natural damping of the system) [5–9].

In order to dampen the inertial and torsional modes of T-G sets, a reliable control method is presented in this study. Generator speed deviation is the controller's input, and three control signals are its outputs. The Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR) is the foundation of the controller. This technique's primary benefit is its ability to deliver strong performance with just one output feedback. Additionally, the designed controller is reduced. For evaluation purposes, the LQG/performance LTR's is contrasted with that of the full state feedback optimum control. The system depicted in Fig. 1 is the subject of the investigation.

## II. System Models

### A. Power System

The system under discussion consists of a 200MVA steam turbine synchronous generator (type TVV-200) connected to the infinite bus through a long transmission line with TCSC and SVC fixed capacitors and an inductor whose inductance is variable by modifying the conduction angle of the thyristor in response to terminal voltage change, as illustrated in Fig.1. The high-pressure turbine (HP), mid-pressure turbine (MP), low-pressure turbine (LP), generator rotor (Gen), and exciter are the five masses that make up the T-G set's shaft system (Exc). At frequencies of 125 rad/sec, 174 rad/sec, 191 rad/sec, and 407 rad/sec, the shaft system has four torsional modes. For systems lacking TCSC and SVC, the first torsional mode is unstable at 60% level compensation while the second and third modes are just slightly stable. The mathematical depiction of the shaft system makes use of a spring-mass concept. The electrical system for generators is represented using the Park's two axes model. One damper winding, one field winding, and one damper winding on the d-axis and q-axis, respectively, are used to represent the rotor circuits. The comparable lumped parameters of the transmission lines and step-up transformer serve as representations. In appendix I, the system's electro-mechanical data are listed.

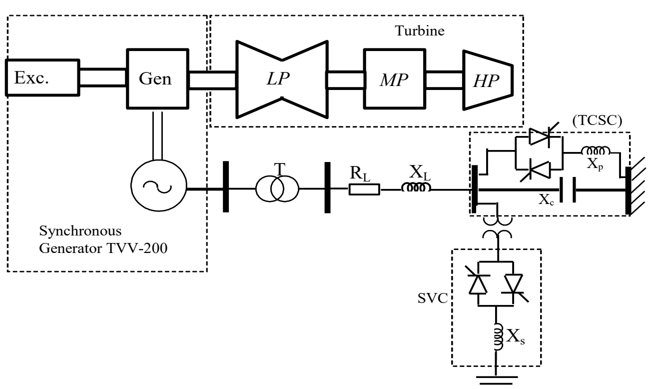



Fig.1. Schematic diagram of the system under study.

### B. Excitation System

The excitation system utilized for the investigations is depicted in Fig. 2. The terminal voltage error (Ve) serves as the primary input to the excitation system. (Ve) is supplemented by the supplementary stabilizing signal (Usf) to reduce the inertial and torsional oscillation modes.

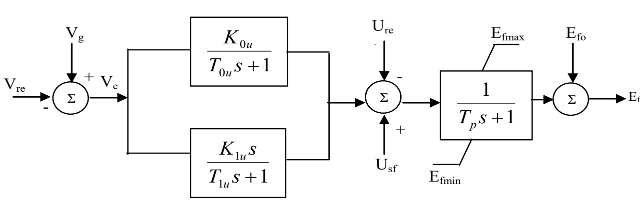



Fig. 2. Excitation system used in the study.

### C. Static VAr Compensator (SVC)

The studies employ a thyristor-controlled reactor (TCR) as the SVC. The corresponding model of the SVC and its control system is shown in Fig. 3. A controllable voltage source concealed behind a set reactance is how the controlled reactor is depicted [10-19]. According to Fig. 1, the SVC unit is attached to the capacitor terminal. Reactive power control and system voltage stabilization are the SVC's two main tasks. To reduce the inertial and torsional modes, the auxiliary stabilizing signal (Usr) is supplied to the main input of the SVC controller.

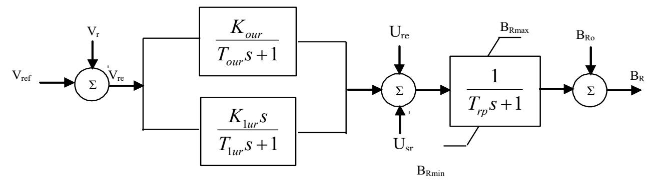



Fig.3. Modeling for Static VAr Compensator (SVC).

### D. Thyristor Controlled Series Compensation TCSC

The TCSC, which enables quick and continuous changes to the transmission line impedance, is one crucial FACTS component. Under a variety of operating conditions, active power flows over the compensated transmission line can be kept at a given value. A TCSC module is shown schematically in Fig. 4 and consists of a series capacitor bank parallel to a Thyristor-controlled reactor (TCR). Fig. 4 illustrates the equivalent TCSC model. The primary input to the TCSC is the terminal voltage across the fixed capacitor error. In order to reduce the inertial and torsional oscillation modes of (Vec), the auxiliary stabilizing signal (Usc) is applied.

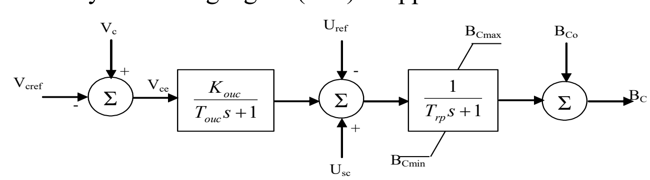



Fig.4 Modeling for TCSC.

## III. The Robust the LQG/LTR Controls

Typically, a notional model of the plant to be controlled serves as the foundation for a control system's design. The design process frequently involves the typical simplifications, such as linearization around an operating point or lumped parameter approximation, and it frequently ignores the effects of unmolded dynamics, sensor/actuator noise, and undesirable external disturbances on various system components. The end result is an approximation plant, or uncertain plant as it is sometimes referred as. Therefore, the controller's effectiveness in assisting the real plant in achieving the intended goals must be a concern for the controller's designer, as well as the viability of designing a controller that addresses more than just the aforementioned concerns. This results in the development of robust control, as it is known today. When presented with models that have large uncertainties, the robust control problem is the challenge of analyzing and creating an accurate control system.

For the robust control problem, numerous strategies have been created, and others are currently being investigated. However, the Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR) methodology is especially alluring because of how effectively it handles plant uncertainties in a systematic and easy-to-understand manner [20–24].

A block schematic of the system with the robust controller is shown in Fig. 5. All of the subsystems seen in Figs. 1, 2, 3, and 4 are represented by the block referred to as "system." The objective is to build a reliable controller that generates three control signals to account for differences in speed ($U_{Sf}$, $U_{Sr}$ and $U_{sc}$). While the signal Usr and Usc are intended to help the SVC and TCSC by damping torsional modes, the signal Usf is intended to help the power system stabilizer (PSS) by damping electromechanical hunting modes [23]. This setup is appealing because it is simple and affordable to implement with actual systems, which should be the end goal, and needs minimal information (just the output).

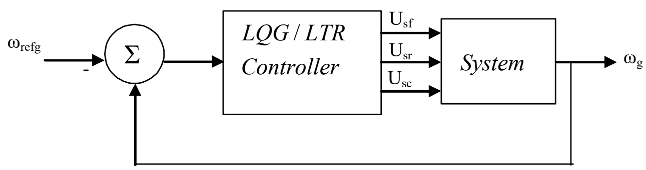



Fig. 5. System with robust controller.

There are two steps in the design process. A filter design makes up the first, while a controller design makes up the second. The LQG/fundamental LTR's tenet is to treat the unstructured uncertainties on the plant as noises in the processes and measurements. In this scenario, a "fictitious" filter created to exclude these disturbances effectively eliminates the consequences of uncertainties. The Kalman filter is used to create a target feedback loop (TFL) with the required loop shape in the first design step. This loop acts as the point of convergence for the controlled system. In the second step, the Linear Quadratic Regulator (LQR) is mostly used to regain the target loop shape.

### A. Kalman Filter Design

A linear model's state space representation is:

$$\frac{dx}{dt} = Ax + Bu + \Gamma\omega \quad (1)$$

$$y = Cx + Du + v \quad (2)$$

where w and v are zero-mean white-noise Gaussian processes with $Q_f$ and $R_f$, respectively, covariance's. Here, will be used as design parameters in the LQG/LTR technique to create a compensator that satisfies the required requirements. The state estimation, error, and gain equations for the Kalman filter are

$$\frac{d\hat{x}}{dt} = A\hat{x} + K_f[y - C\hat{x}] + Bu \quad (3)$$

$$\frac{de}{dt} = [A - K_f C]e + \Gamma\omega + K_f^v \quad (4)$$

$$K_f = P_f C^T R_f^{-1} \quad (5)$$

where $K_f$ stands for gain Kalman filter and e is the error in state estimation. The Riccati equation's positive-semidefinite solution is $P_f$.

$$P_f A^T + AP_f - P_f C^T R_f^{-1} C P_f + \Gamma Q_f \Gamma^T = 0 \quad (6)$$

By adjusting the filter gain, $K_f$, the Target Feedback Loop (TFL), GKF, has to be constructed in this design step. This approach is frequently known as the (LQG) approach. It is important to note that this filter also avoids torsional interference, which prevents negative damping of torsional oscillations [18].

### B. Controller Design

An optimal control problem exists in this stage. In order to restore the TFL, we must use the optimal control technique to solve for the full state feedback regulator gains Kc. The metric for performance is provided by

$$J = \int_0^\infty [qy^T cy + u^T R_c u]\, dt \quad (7)$$

Where Qc and Rc are positive definite matrices that penalize the states and controls, respectively, and q > 0 is a scalar design parameter. In equation (7), y is the system's output and is the input vector [Usf, Usr, Usc]. The best control law can be found in:

$$u = -K_c x \quad (8)$$

$$K_c = R_c^{-1} B^T P_c \quad (9)$$

where $Pc$ satisfies another algebraic Riccati equation:

$$A^T P_c + P_c A - P_c B R_c^{-1} B^T P_c + qC^T Q_c C = 0 \quad (10)$$

If one is able to create a Kc and tweak $K_f$ so that GKF(S) has the desired loop shape over the frequency range relevant to our performance and robustness concerns, then K(s) is a robust compensator.

Given that the plant is stabilizable, detectable, has a minimum phase, and has fewer outputs than inputs, there is such a compensator, and the closed-loop system is internally stable [12]. Fig. 6 depicts the configuration of the dynamic robust controller K(s) that was created through the aforementioned procedures.

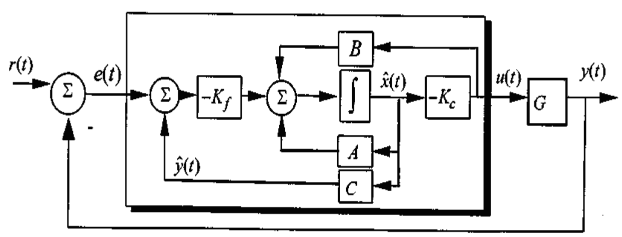



Fig. 6. Dynamics of the LQG/LTR controller.

## IV. Model Order Reduction

The control design techniques, like LQG or $H_\infty$, result in controllers that are at least as ordered as the plant, and typically higher due to the incorporation of the necessary additional weights. To reduce the complexity of the final controller and simplify the design process, model order reduction is necessary. For proper control design, the reduced plant that was employed in the design had to be a close approximation of the full order counterpart. Thus, the following is the main issue raised.

Determine a low-order approximation Gr(s) such that the infinity norm of their difference $||G - G_r||_\infty$ is sufficiently small given a high-order linear model G(s).

The controller reduction approach uses the same concept. Based on the Schur balanced model reduction process [15], our approach involves model and controller reduction. In this instance, the reduction goal is described as follows.

$k^{th}$ -order reduced model computation From an $n^{th}$-order complete model, $G_r(s) = C_r(sI - A_r)^{-1}B_r + D_r$ such that $G(s) = C\,(sI - A)^{-1}\,B + D$

$$\|G - G_r\|_\infty \le 2\sum_{i=k+1}^{n}\sigma_i \tag{11}$$

where $\sigma_i$ denotes the Hankel singular values of $G(j\omega)$, i.e., the square roots of the eigenvalues of their controllability and observability grammians

$$\sigma_i = \sqrt{\lambda_i(PQ)} \tag{12}$$

where $\lambda_i(PQ)$ is the $i$th largest eigenvalue of $PQ$ and $P$, $Q$ are the solutions of the following Lyapunov equalities:

$$PA^T + AP + BB^T = 0 \quad \text{(controllability grammian)} \tag{13}$$

$$QA + ATQ + CTC = 0 \quad \text{(absorbability grammian)} \tag{14}$$

Note that whereas Ar, Br, Cr, and Dr are the state space matrices of the reduced-order model A, B, C, and D are those of the full order model G(s). The use of numerical techniques, such as the Krylov subspace-based technique, may be necessary in situations where there are many state variables (i.e., more than 1000), as the analytical techniques by themselves will not be sufficient [22].

For the purpose of designing controllers, a lower order model is obtained using the best Hankel norm approximation technique. It provides the best reduced order model for the given order [16–18] by minimizing the difference between the nominal and reduced order models' frequency responses. Given that it is numerically efficient and that the provided error bound can be used as a criterion to set the order of the reduction, it meshes nicely with the LQG design.

## V. Centralized Control Method

### A. Application of LTR

The LTR technique for q = 1, 5, 10, 100, and 1000 is shown in Fig.7 and (10). To illustrate the qualities of high-quality sensor equipment, the measurement noise covariance is chosen to be quite low [22]. For the sake of suitable comparison, the controller that produced the results in Fig. 7 is the full 29th order. For the remainder of the design, q was fixed at 10, resulting in a sufficient recovery within the interest frequency range and a quicker roll-off at high frequencies than q=1000.

### B. LQG Controller Reduction

The complete order controller in this system is of $29^{th}$ order. The planned LQG controller is of the $14^{th}$ order, which is equivalent to the order of the design (reduced) plant, and its transfer function is shown in equation (15). The controller size should be further minimized while still meeting the necessary damping ratios for the torsional modes for the entire power network model. The Schur balanced reduction approach, which is covered in Section IV [15], is used for the reduction process.

$$K_{lqg} = \begin{bmatrix} A_r - B_rK_c - K_fC_r & K_f \\ -K_c & 0 \end{bmatrix} \tag{15}$$

where Ar, Br, and Cr are the reduced-order plant's state space matrices for the design (Dr = 0). In comparison to the original $29^{th}$-order designed controller, Fig. 8 shows the singular value plot for a range of decreased size controller options. For a variety of reduced size controller options, Fig. 9 also shows the error bound (the infinity norm of the difference between full and reduced controller).

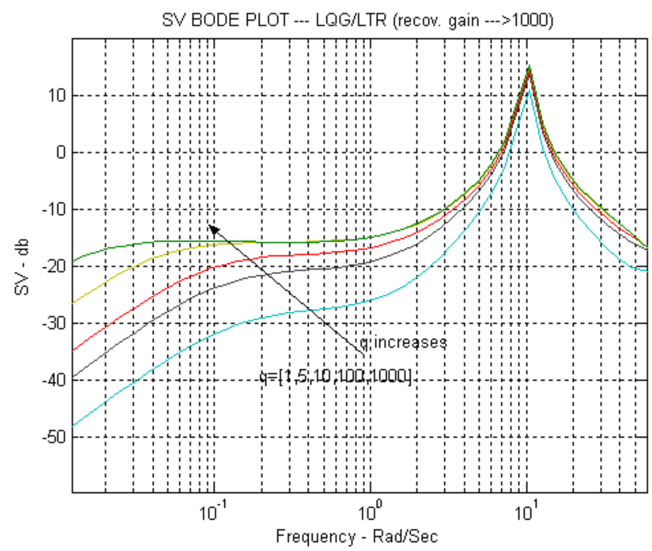



Fig.7. LTR method at plant input for various q parameter values.

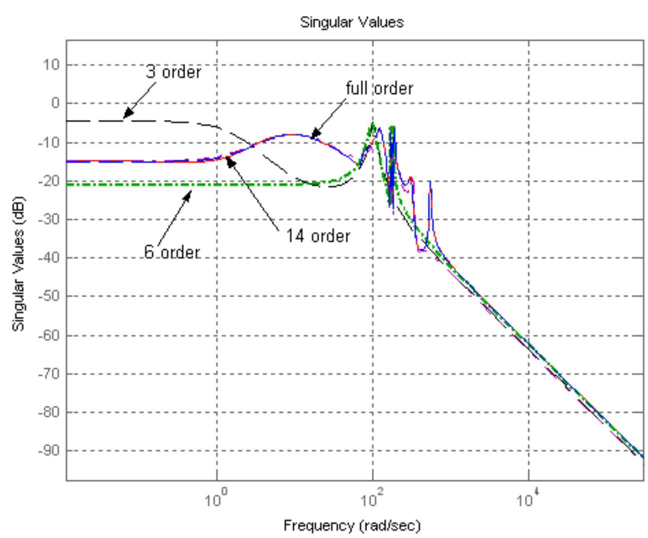



Fig.8. Singular value plot of controller approximation.

The $14^{th}$ order controller is nearly indistinguishable from the original $29^{th}$order (full order), as can be seen in Fig. 8, while deterioration begins to occur as the order is further reduced. This is further supported by Fig. 9, which demonstrates how the error bound significantly increases after selecting the 14th order controller. From Fig. 9, it can be inferred that the 14th order reduced order model is a wise decision that doesn't introduce a lot of mistake. The error bound at the 14$^{th}$ reduced order is equal.

$$\|G(j\omega) - G_r(j\omega)\| = 0.026964$$

The "ideal" eigenvalues for the closed-loop system based on the reduced-order system with LQR state feedback are presented in Table I. The eigenvalue for the open loop system demonstrates that all modes are only marginally stable because the system is open loop without any additional signal to the excitation system, TCSC and SVC.

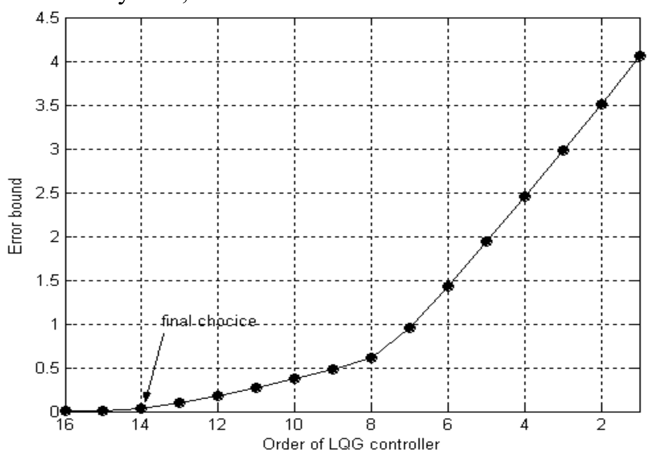



Fig.9. Controller reduction error bound.

TABLE I
EIGENVALUE OF OPEN LOOP AND CLOSED LOOP FOR REDUCED ORDER REGULATOR

| | **Mode 1 @125 rad/sec** | **Mode 2 @174 rad/sec** | **Mode 3 @191 rad/sec** |
|---|---|---|---|
| **Open loop** | **-0.06733** | **-0.02514** | -0.020288 |
| **Closed loop with Full order 29 th** | **-7.2484** | **-0.6856** | -1.4146 |
| **Closed loop with Order 14 th** | **-6.9585** | **-0.66597** | -1.3661 |
| **Closed loop with Order 12 th** | **-5.3898** | **-0.5286** | -1.1234 |
| **Closed loop with Order 9 th** | **-4.2458** | **-0.40775** | -0.81285 |
| **Closed loop with Order 6 th** | **-1.3449** | **-0.12783** | -0.33268 |
| **Closed loop with Order 3 rd** | -1. 2074 | -0.058126 | -0.073612 |

## VI. Study Results

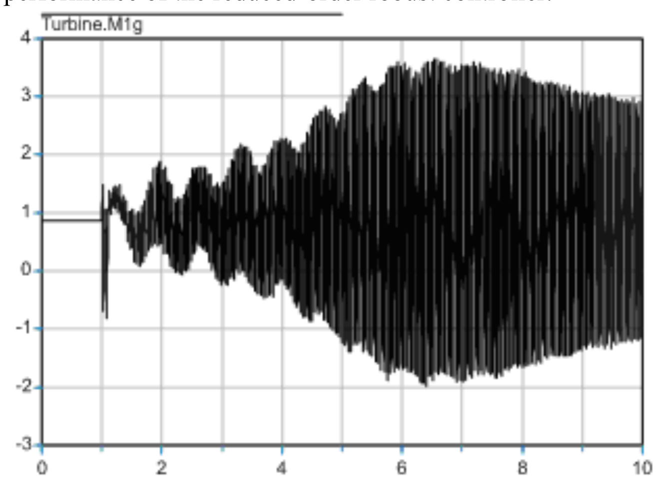
Full-order robust control and reduced order robust control are the two control strategies that have been studied. Here is the simulated scenario. Up to the time t = 1 second, the system is in a steady state. At time t = 1 seconds, a three phase short circuit is injected at the generator terminal for 0.1 seconds, and the controller is not in operation. The controller is activated when t = 3 seconds.

The system response for a three-phase short circuit occurring at time = 1 second is shown in Fig. 10. The torque between the low-pressure turbine and the generator ($\Delta T_{lg}$) is shown in Figs. 10(a,b), without and with a full order LQG controller for the 29th, respectively, and the electromechanical torque ($\Delta T_e$) is shown in Figs. 11 (a, b)

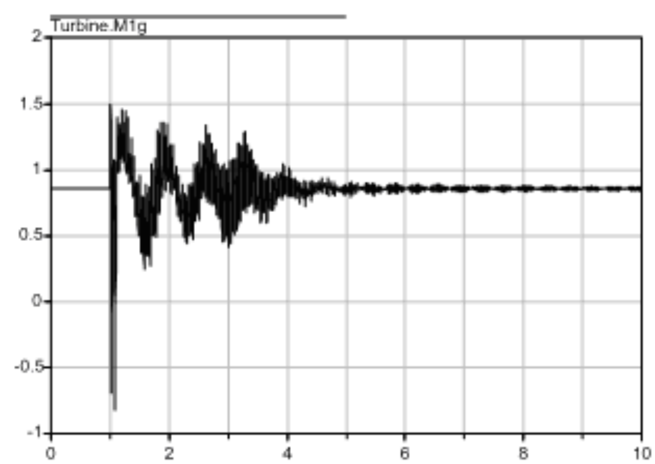
Figs. 12a and 12b depict the torque between the low-pressure turbine and the generator ($\Delta T_{lg}$) when the order of the LQG controller is reduced to third and fourteenth, respectively, and the electromechanical torque (ΔTe) is shown in Figs. 13 (a, b)

The controller ends up having the same order as the open-loop system because it is based on full state feedback (during the design phase, not the implementation phase). The LQG belongs to order 29. A controller decrease is feasible in many situations. To achieve a balanced state-space realization, the controller state-space model can be normalized via a similarity transformation [13–15].

In order to lower the model's order, states that can be eliminated are indicated by the balanced realization. The complete order controller in this system is of 29th order. As a result, the controller's order can be lowered from 29 to just 14 with negligible performance loss. Fig.14 display the performance of the reduced-order robust controller.

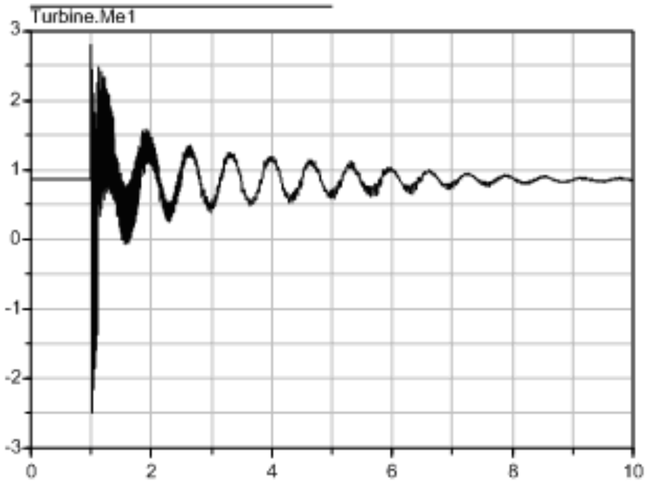



(a) Without controller.

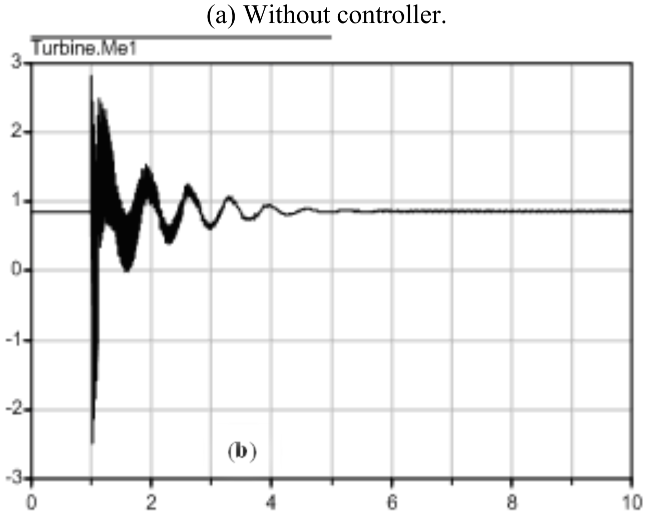



(b) With full order controller.

Fig.10: Torque between the low-pressure turbine and the generator (ΔTlg) at 3-phase short circuit.

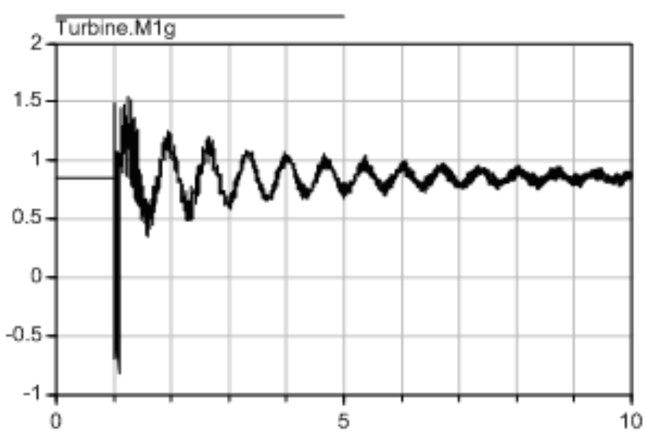



(a) Without controller.

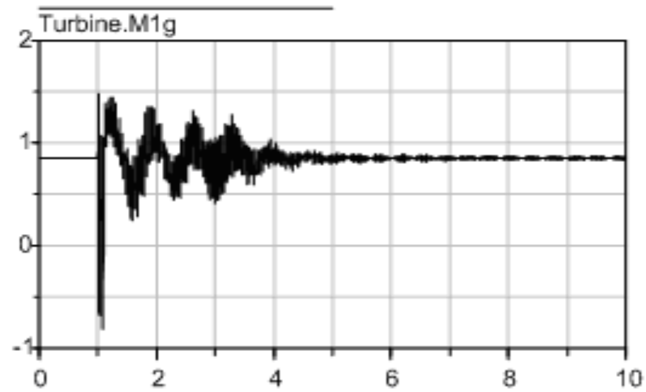



(b) With full order controller.

Fig. 11: Electromechanical torque (ΔTe) at 3-phase short circuit.

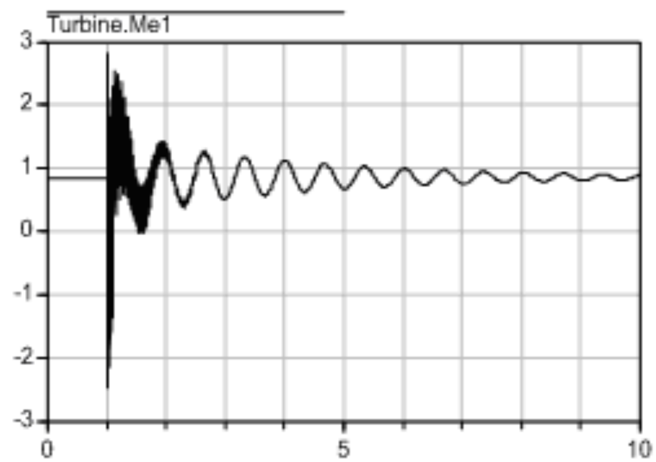



(a) With a 3th decrease order controller.

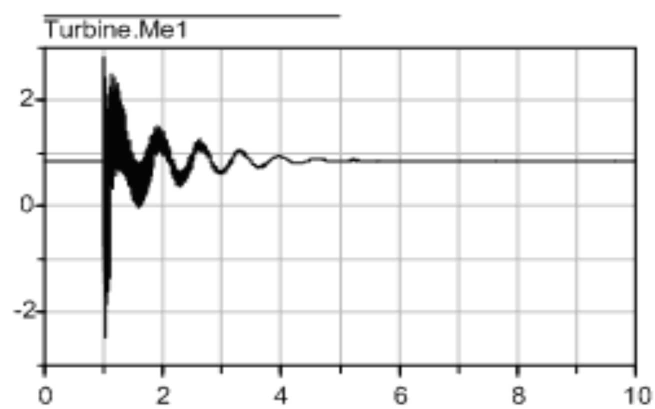



(b) With a 14th decrease order controller.

Fig.12: The Low-pressure turbine to generator torque (ΔTlg) at three-phase short.

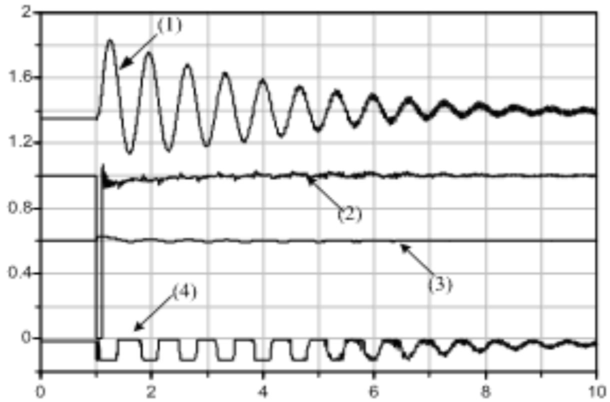



(a) With a $3^{th}$ decrease order controller.

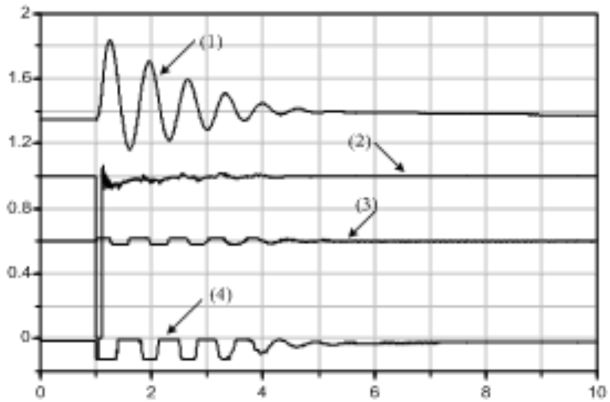



(b) With a $14^{th}$ decrease order controller.

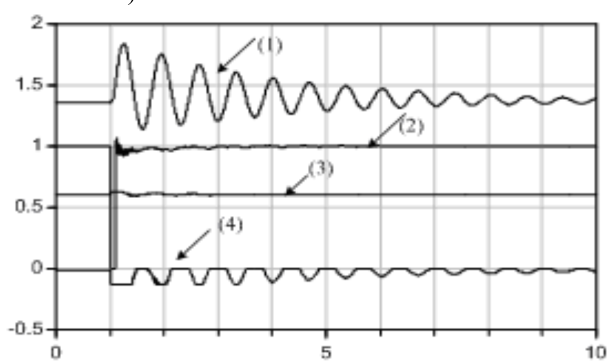
Fig.13: Electromechanical torque (ΔTe) at three-phase short.



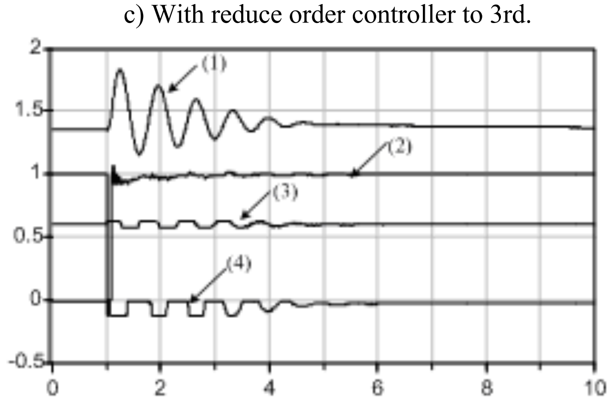

a) Without controller.




b) With full order controller for 29th




c) With reduce order controller to 3rd.




d) With reduce order controller to 14th.

Fig. 14: (1). Rotor angle oscillations, (2). Terminal voltage generator, (3). Level compensation, and (4). SVC susceptance. At three phase short circuit.

This 14th reduced order LQG/LTR controller is capable of efficiently dampening all SSR modes at varying amounts of series compensation, ranging from 30% to 90%. Rotor angle oscillations, level compensation, and SVC susceptibility were presented in Fig. 15 for three different levels of level compensation.

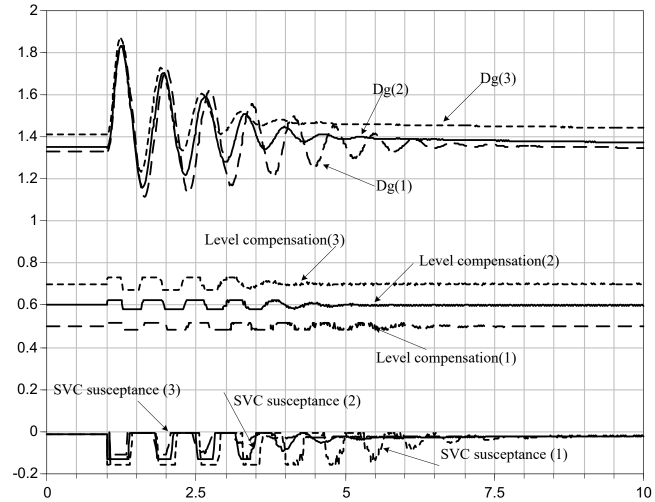



Fig.15: System response for three phase short circuit 0.1sec at time t=1sec, with reduce order controller to 14th. Rotor angle oscillations, level compensation, and SVC susceptance for three cases according the following
1-for level compensation = 50%
2- for level compensation = 60%
3- for level compensation = 70%

## VII. Conclusion

In order to dampen subsynchronous resonance oscillations, this study outlines a design process for LQG control of VSC, TCSC, and excitation system. One feedback signal (angular speed deviation) and three control signals, each of which is capable of dampening all undesired oscillations, are used to create a robust control utilizing LQG. This setup uses a quantity that can be measured, making it both easy to use and practical. The 14th order version of the full-order robust controller displayed the same high performance.

## Appendix I

***Generator data***

$X_d$=1.869, $X_q$=1.869, $X_s$=0.194, $X'_d$=0.3016, $X''_d$=0.2337, $X'_q$=0.2337, $R_a$=0.0022, $Rr$=904e-6, $R_{1d}$=3.688e-3, $R_{1q}$=0.00108,

***Transformer data***

$Rt$=0.005, $Xt$=0.12.

***Excitation system data***

$K_{ou}$=-15, $K_{1u}$=-7.2, $T_{ou}$=0.09, $T_{1u}$=0.039, $T_p$=0.07,

***Transmission line data***

$R_L$=0.025, $X_L$=0.5

***SVC data***

$K_{our}$=-15, $K_{1ur}$=-10, $T_{our}$=0.09, $T_{1ur}$=0.39, $T_{pr}$=0.001, $BLo$=-0.01, $BLmax$=-0.0001, $BLmin$=-0.25;

***TCSC data***

$K_{ouc}=-0.5$, $T_{ouc}=0.039$, $T_{pc}=0.001$, $Bco=3.333$; $Bcmax=1000$, $Bcmin=2$.

***Generator as five-mass units***

| Mass | Shaft | Inertia (H) s | K(p.u.torque/rad) |
|---|---|---|---|
| HP | | 0.079 | |
| | HP-IP | | 64.478 |
| IP | | 0.336 | |
| | IP-LP | | 67.52 |
| LP | | 1.4425 | |
| | LP-GEN | | 85.8 |
| GEN | | 1.15 | |
| | GEN-EXC | | 11.44 |
| EXC | | 0.063 | |

## Conflict of Interest

The authors have no conflict of relevant interest to this article.

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