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Matlab/Simulink Simulation Small Signal Stability of Single-Machine Infinite Bus Using Optimal Control Based on Load Cluster Patterns

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***Abstract*—Matlab/Simulink is sophisticated software that has been facilitated by MathWorks Inc. This device is increasingly being used in various fields of research. Likewise, it has great potential in the field of power system simulation. This paper presents a simulation of the optimal performance of the power generation system due to changes in load consumption. Small signal stability due to changes in electrical power usage at the load center is overcome by applying a load cluster pattern. The main objective of this research is to achieve control in a power generation system that is responsive and able to maintain stability in all operating conditions at the load center. Simulation results show the performance of optimal control of the power generation system in each load cluster. Contributions to improve the stability of the power plant system performance by 28.03 percent for frequency (F), 23.03 percent for voltage (V), and 29.5 percent for electric power (P).**

***Keywords*—electrical load, forecasting, load clusters, optimal control, SMIB**

I. Introduction

Effort to maintain the stability of the generating system due to minor disturbance is a dynamic stability study [1]. Electricity system stability is defined as the ability of an electric power system or its component parts in maintaining synchronization and balance in the system. Stability can mean that the power generation system will be stable if there is a balance between the mechanical input power of the prime mover and the electrical power output (electrical load) on the system. This happens if every increase and decrease in load must be followed by changes in mechanical input power in the prime mover of generators. If mechanical input power does not quickly follow changes in load and system losses, the generator rotor speed (frequency stability) and voltage will deviate from normal conditions. This instantaneous condition results in a large difference between the mechanical input power and the electrical output power of the generator. Excess mechanical power to electrical power results in acceleration of the rotor generator rotation or vice versa. If the disturbance is not eliminated immediately then the acceleration and deceleration of the rotor generator rotation will result in loss of synchronization in the system [2].

Recent studies that have been carried out in maintaining the stability of the power generation until 2019 include research that identifies the impact of high PV penetration that has an impact on the stability of the small signal from the generating system [3]. Research on improving the stability of small signals from ac three-phase interface systems by applying d-q frame impedance measurements and Nyquist stability criteria [4]. As for other studies in 2016, one of the main findings is penetration of a combination of renewable energy, solar and wind. The results of this study are able to increase the stability of frequency modes between areas, with minimal impact on damping [5]. The small signal stability evaluation technique based on eigenvalues is used to allow / deny interconnect microgrids. Thus, a microgrid will undergo a significant transformation in its structure when combined with one or more adjacent microgrids [6]. Inverter-based distributed generators (DGs) based on renewable sources are widely used in microgrids. But this renewable energy supply problem is stability. The modified droop control is proposed to improve transient response and margin stability in this study [7]. This research in 2018 proposes a generic modeling framework based on a modular DC Multilevel converter (MMC) based for small signal stability studies. The time-domain simulation shows the frequency oscillation stability and good attenuation control based on the eigenvalue [8]. Other researchers have developed a probabilistic analysis method based on a combination of cumulants and Gram-Charlier expansion techniques. The proposed method provides accurate results in less computational time compared to conventional techniques. This method is able to minimize the errors in the PV forecast which have an impact on the stability of the electric power system [9]. In the same year, a small signal modeling method for a modular multilevel converter (MMC) was simulated based on the harmonic state-space (HSS) method. The small signal model is validated by comparing step responses with simulations built in Simulink/MATLAB [10]

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The Matlab/Simulink application has been carried out by several researchers. Modeling and Simulation is very helpful and makes it easy for modeling, analysis, and simulation of various dynamic systems. Simulink provides a graphical user interface for building block diagram models using 'drag and drop' operations [11]. The system is configured in terms of block diagram representation from standard component libraries. Simulink is very useful for studying nonlinear effects on system behavior and is able to represent problems found in the real world. In this paper we have shown a simplified but efficient approach to studying the stability performance of small signal power generation systems. The simulation is done by applying several load criteria in the form of optimal load clusters with Simulink as a tool. We hope that this effort will add some more practical information in important domains and is still being carried out until now.

II. Research Methods

A. Proposed Model

In the operation of the generating system must always be endeavored so that the power generated is equal to the demand for power in the system. Actually, load fluctuations cause changes in frequency and voltage values on the generator side so that the stability of the system will be disrupted. Descriptions that are close to the real condition of electricity consumption are needed to help make decisions and policies on the use of electricity that are more efficient and can maintain reliable system stability.

In the study of the dynamic stability of the power plant system, the activity of channeling electric power to the load contains a series of continuous data that can form the pattern of load characteristics. Changes in electricity load form a continuous pattern or are time series. To ensure dynamic stability, an optimal control is designed that has a fast response to any load changes

This study designed the optimal control of multilevel generating systems. This design refers to the pattern of load consumption which has the same tendency at certain hours and times. This multilevel pattern approach applies a cluster method based on a descriptive analytic approach. Through a quantitative approach the time series data from forecasting and training results is used as a reference for optimal control cluster analysis. The identification of changes in load consumption at any time is illustrated through the proposal submitted in Fig. 1 below.

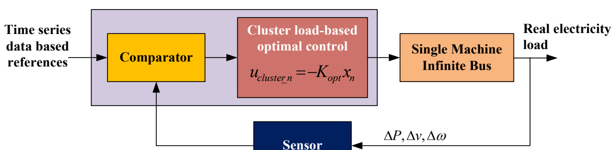

Fig. 1. The proposed load-based optimal control-cluster

In principle, future load changes have been predicted and have also been tested based on the time series analysis approach. Through a descriptive analytic approach we are able to identify states (x_n) based on load cluster pattern and design an optimal control (K_{opt}) for each cluster. As an illustration of this paper proposal, the control has input data based on forecasting results based on time series analysis. Changes in load at any time due to usage will be responded to sensor equipment to identify the amount of electric power, voltage and changes in rotor angle speed. This data series comparison will supply the controller state based on the desired load cluster. This identification modeling is very dependent on the results of load forecasting validation that has been done before.

B. Modeling the System

The complete system has been represented in terms of Simulink blocks in the overall model. The mathematical models given below provide full support of simulation modeling. One of the most important features of the model in Simulink is its extraordinary interactive capacity. It makes the signal display at every point available; all you have to do is add a scope or plot block. Giving feedback signals is also as easy as drawing a line. Parameters in any block can be controlled from the MATLAB command line or through the m-file program. This is very useful for stability studies because power system configurations differ before, during and after errors. And it is very easy to analyze.

C. Mathematical Modelling

The stability of small signals is analyzed through the approach of a single machine connected to an infinite bus (SMIB). The Park's-based SMIB model, with the criteria: stator resistance is ignored, system conditions are considered to be balanced and core saturation at the generator is ignored, and the load is considered a static load [12]. This model refers to the synchronous machine model that has been introduced by De Mello and Concordia [13]. Furthermore, this engine model was developed by Hamdy A.M. Moussa and Y.N. Yu became a multi-machine model [14].

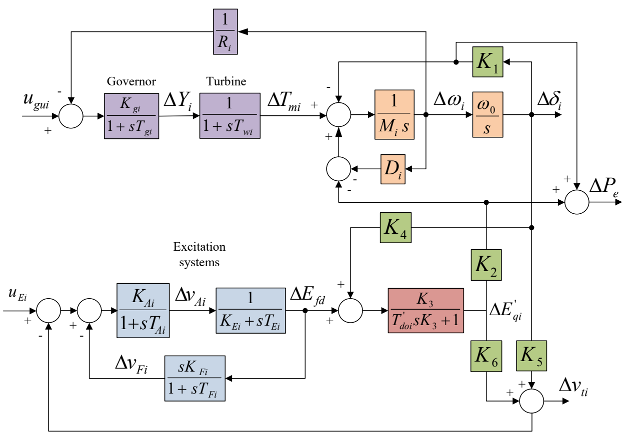

Fig. 2. Single-machne to connected to an infinite bus

Fig. 2 represents the Matlab/Simulink simulation program of the SMIB model. Completion of small signal stability of power systems due to changes in load through the concept of the state space [12]:

$$\dot{x} = Ax + Bu \qquad (1)$$
$$y = Cx \qquad (2)$$

The variables in the overall block diagram in Fig. 2 can be formed into the state space equation, as follows:

equation changes in valve height and mechanical torque on the turbine:

$$\Delta\dot{Y}_i = \frac{K_{gui}\,\Delta u_{gui}}{T_{gui}} - \frac{K_{gui}\,\Delta\omega_i}{T_{gui}\,R_i} - \frac{\Delta Y_i}{T_{wi}} \qquad (3)$$

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$$\Delta\dot{T}_m = \frac{\Delta Y_i}{T_{tu}} - \frac{\Delta T_m}{T_{tu}} \quad (4)$$

single machine dynamic equations:

$$\Delta\delta_i = \frac{\omega_0}{s}\,\Delta\omega_i \quad (5)$$

$$\Delta\omega_i = -\frac{\Delta T_e}{s\,M} \quad (6)$$

$$\Delta E'_{qi} = \frac{K_3}{1 + s\,T'_{doi}}\,(\Delta v_{Fi} - K_4\,\Delta\delta_i) \quad (7)$$

$$\Delta v_F = -\frac{K_A}{1 + s\,T_A}\,(\Delta v_{ti} - u_{Ei}) \quad (8)$$

$$\Delta v_{ti} = K_5\,\Delta\delta_i + K_6\,\Delta E'_{qi} \quad (9)$$

$$\Delta T_{ei} = K_1\,\Delta\delta_i + K_2\,\Delta E'_{qi} \quad (10)$$

for the output variable state of the equation that satisfies:

$$\Delta P_e = K_1\,\Delta\delta_i + K_2\,\Delta E'_{qi} + D\,\Delta\omega_i \quad (11)$$

With the elimination of ΔT_{ei} and Δv_{ti} it will be obtained in the form of the state space equation, with the state variable x defined as $x = [\Delta Y_i \quad \Delta T_m \quad \Delta\delta_i \quad \Delta\omega_i \quad \Delta E'_{qi} \quad \Delta v_{Fi}]^T$ and output as $y = [\Delta Y_i \quad \Delta T_m \quad \Delta P \quad \Delta\omega_i \quad \Delta v_{ti} \quad \Delta v_{Fi}]^T$.

D. Load Cluster Based Optimal Control

The optimal control design is to obtain the K matrix through the optimal input signal generated by the system in the form of [15]:

$$u = -Kx \quad (12)$$

Optimal control with a performance index is called a Linear Quadratic Regulator. The optimal control law $u(x,t)$ is used to move the system from the initial state to the final state which provides an optimal performance index. Quadratic performance index based on the criteria of minimum-deviation error of the state variables and the minimum energy input variable.

$$J = \int_{t_0}^{t_1} (x^T(t)\,Q\,x(t) + u^T(t)\,R\,u(t)dt) \quad (13)$$

To solve this equation the following Lagrange multifier method is used:

$$(x,\lambda,u,t) = (x^T\,Q\,x + u^T\,R\,u) + \lambda^T\,(Ax + Bu - x) \quad (14)$$

By equating the partial derivatives equal to zero obtained following Riccati algebraic equation:

$$pA + A^Tp + Q - pBR^{-1}B^Tp = 0 \quad (15)$$

If the p matrix is constant, the completion of the p matrix is constant, then the K value in the equation is:

$$K = R^{-1}\,B^T\,p \quad (16)$$

With the K feedback equation, the state variable becomes:

$$\dot{x}(t) = (A - B\,K)\,x(t) \quad (17)$$

This system will have the characteristic roots of the following equation:

$$|sI - (A - B\,K)| = 0 \quad (18)$$

Cluster analysis conducted in this research refers to the statistical description analysis technique. Descriptive statistics are methods relating to the collection and presentation of a group of data so as to provide useful information [16]. This data processing analysis becomes information which contains a set of data characteristics that can be concluded numerically (for example, calculating the average or standard deviation) or graphically (both in the form of tables and graphs).

This description analysis includes several things, namely: Frequency distribution as data arrangement according to certain basic or categories in a systematic compiled list; Central Tendency Measurement is a statistical analysis that specifically describes representative scores such as mode, median, and mean or mean average count; and Measurement of variability is a measurement of the degree of spread of variable values usually by calculating range, mean deviation or standard deviation of data [17].

Changes in electricity load at any time that contain a series of data with time series characteristics can be resolved through the formation of a load cluster pattern based on the characteristics or groups of data variable distribution. So the model proposed in this research is the K_{opt-n} pattern as the development of Fig. 2.

$$\dot{x}_1(t) = (A_1 - B_1K_1)\,x_1(t) \qquad \text{Cluster 1}$$
$$\dot{x}_2(t) = (A_2 - B_2K_2)\,x_2(t) \qquad \text{Cluster 2}$$
$$\vdots$$
$$\dot{x}_n(t) = (A_n - B_nK_n)\,x_n(t) \qquad \text{Cluster-}n$$

The stages of optimal control design based on load clusters are obtained from the identification of predicted load conditions. Data forecasting results are analyzed through descriptive analytic methods to obtain data grouping based on the characteristics of the load.

III. SIMULINK MODELS

A. Classical System Model

A single machine model with a complete infinite bus is shown in Fig. 2, has been simulated as a single integral model in Simulink. Mathematical models represent the transfer function of power plant components from different blocks. Fig. 3 represents the classical system of small signal stability studies in the Matlab/Simulink model.

B. Model Identification Parameters

The identification parameter is done to fulfill the representative system; linearity and measurable system. Identification techniques using the error prediction (PEM) approach in Matlab [18]. The results of the identification of parameters in the form of order matrix 3. Fig. 4 shows the simulation comparison of the identification model and the real parameters of the generator system in Simulink.

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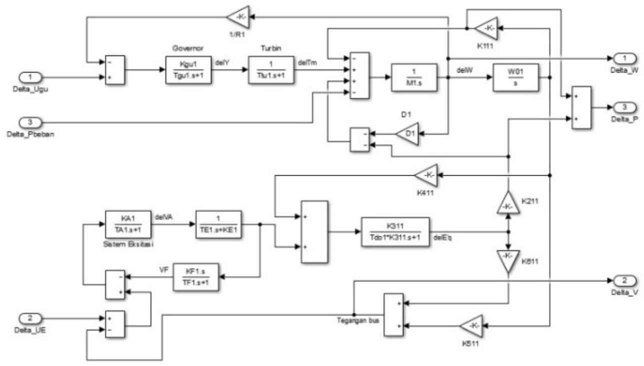

Fig. 3. Matlab/Simulink model power generation

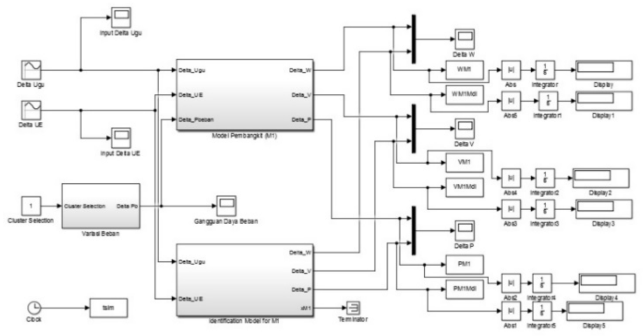

Fig. 4. Validation model

C. Modeling Of Optimal Control Based On Load Cluster

The results of parameter identification in the 3rd order discrete approach determined the optimal control linear Linear Quadratic Regulator gain value for each load cluster. The optimal control model versus the uncontrolled system is shown in Figure 5 in Simulink.

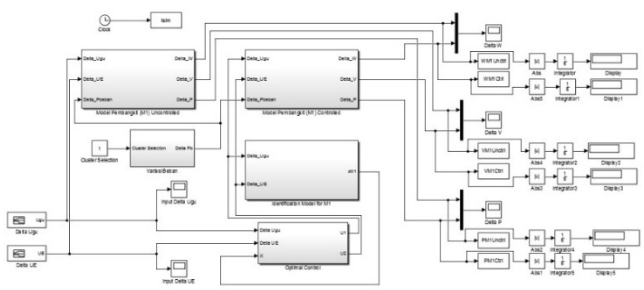

Fig. 5. Representative optimal control model

Fig. 5 shows that the system works based on cluster load tunning in the form of cluster selection models. This model also facilitates simulation parameter choices, such as start and stop times, step size, tolerance, output options, simulation parameters for load cluster patterns and initialization blocks. The model can be run either directly or from the MATLAB command line or from the m-file program. In this study, the error clearing time, the initialization time of the generator system parameters, identification matrix, and the optimal gain matrix are controlled through the m-file program in MATLAB.

IV. Result and Discussions

A. Cluster Modeling

Cluster modeling in this study uses a descriptive analytic statistical model with a distribution pattern approach as previously done [19]. The range of intervals between the minimum values predicted, quartile 1, middle values, quartiles 3, and maximum values are used as a cluster model for each load condition. Cluster load simulation is represented in the form of sinusoidal wave equations and is equivalent in pu units.

Cluster 1 $\Rightarrow Pb = (0{,}125\ sin(0{,}5\ t) + 0{,}125)$
Cluster 2 $\Rightarrow Pb = (0{,}125\ sin(0{,}5\ t) + 0{,}375)$
Cluster 3 $\Rightarrow Pb = (0{,}125\ sin(0{,}5\ t) + 0{,}625)$
Cluster 4 $\Rightarrow Pb = (0{,}125\ sin(0{,}5\ t) + 0{,}875)$

B. Model Identification

Identification is done to get a linear model that represents each operating condition. Cluster load variation is defined as interference that occurs in the system due to changes in electrical power at the load center. While the input from the turbine u_{gu} and excitation u_E side is fixed.

These models are each represented by a signal:

Input (u):

$\Delta\, u_{gu}$ = 0,5 sin (0,1t) + 0,5 (in 1unit pu)
$\Delta\, u_E$ = 0,5 sin (0,2t) + 0,5 (in 1 unit pu)

Output (y):

$\Delta\, \omega$ (frequency in 1unit pu)
$\Delta\, v$ (bus voltage in 1unit pu)
$\Delta\, P$ (electrical power in 1 unit pu)

For all identification processes use 0.1 second sampling intervals. The identification process uses the MATLAB Identification Toolbox, PEM Black Box. The identification results in the third order equation. Identification of the state matrices A, B, and C are shown section by section as below.

Cluster	**Matrix A** (3×3)
1	$\begin{bmatrix} 1.0006 & 0.4699 & -0.0567 \\ -0.0562 & 0.8521 & 0.0317 \\ -0.02208 & 0.1863 & 0.9662 \end{bmatrix}$
2	$\begin{bmatrix} 0.9499 & 0.6371 & -0.0459 \\ -0.0397 & 0.8488 & -0.0070 \\ 0.0234 & -0.3796 & 0.9921 \end{bmatrix}$
3	$\begin{bmatrix} 1.0513 & 0.5022 & 0.2361 \\ -0.0662 & 0.8710 & -0.0124 \\ 0.0251 & -0.1192 & 0.8908 \end{bmatrix}$
4	$\begin{bmatrix} 0.8189 & -1.1845 & -0.5249 \\ 0.0910 & 1.3565 & 0.2761 \\ -0.1205 & -0.4570 & 0.5857 \end{bmatrix}$
Cluster	**Matrix B** (3×2)
1	$\begin{bmatrix} -1.1014 & -0.4644 \\ 0.0906 & -0.8310 \\ -0.5709 & -0.7381 \end{bmatrix}$
2	$\begin{bmatrix} -0.6493 & -0.4438 \\ 0.0823 & -0.9872 \\ 0.4765 & 0.6902 \end{bmatrix}$
3	$\begin{bmatrix} 0.1099 & -0.9611 \\ -0.2356 & -0.6486 \\ 0.5362 & 0.5751 \end{bmatrix}$
4	$\begin{bmatrix} 0.1141 & 2.4466 \\ -0.1583 & 0.7748 \\ 0.2317 & -1.7243 \end{bmatrix}$
Cluster	**Matrix C** (3×3)

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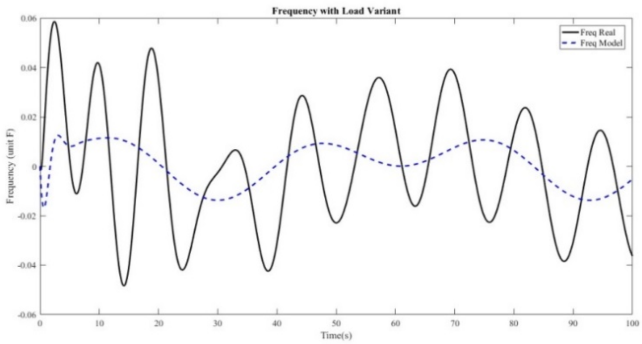
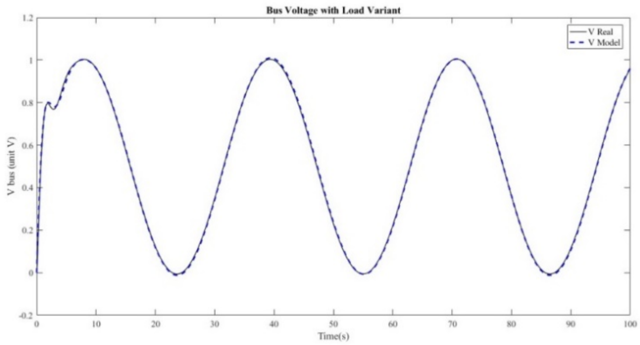
Cluster	Matrix
1	$\begin{bmatrix} -0.0333 & -0.0208 & 0.0594 \\ -0.0179 & -0.1015 & -0.0531 \\ 0.2325 & 0.5239 & -0.4321 \end{bmatrix}$
2	$\begin{bmatrix} -0.0056 & 0.0043 & -0.0084 \\ -0.0246 & -0.1114 & 0.0185 \\ 0.1572 & 0.3463 & 0.2393 \end{bmatrix}$
3	$\begin{bmatrix} 0.0022 & 0.0125 & 0.0049 \\ -0.0735 & -0.1159 & -0.0107 \\ 0.0960 & 0.4697 & 0.2131 \end{bmatrix}$
4	$\begin{bmatrix} -0.0188 & -0.1593 & -0.1006 \\ 0.0151 & 0.0293 & -0.0686 \\ 0.0310 & -0.2124 & -0.1050 \end{bmatrix}$

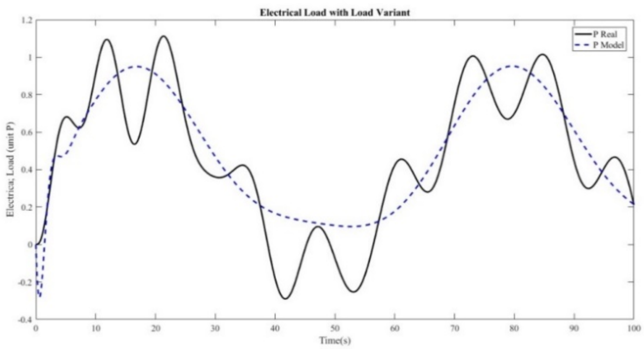
Figure 6 is a model of identifying the generator parameters in the first cluster.



(a)



(b)



(c)

Fig. 6. Results of cluster 1 simulation results, (a) frequency, (b) bus voltage, (c) electrical power

The mathematical equation of the power generation is identified and validated in the state model of each cluster condition. Based on the average data comparison between IAE output real and IAE output identification model, the model approach is significantly able to represent power generation with better measurement error in Table 1

TABLE I. COMPARISON OF IAE

Cluster	**IAE Output real**			**IAE Output model identification**		
	F	**V**	**P**	**F**	**V**	**P**
1	2.046	51.32	51.49	0.7489	51.27	50.54
2	1.856	51.32	35.81	0.3652	51.55	30.8
3	1.909	51.31	31.17	0.4764	51.46	17.48
4	2.184	51.3	37.7	0.4927	51.45	20.72
average	1.999	51.313	39.043	0.5208	51,433	29.885

C. *Gain Optimal LQR*

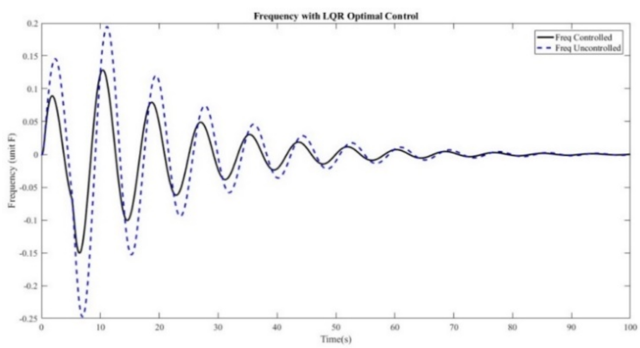
The optimal gain is determined based on the optimal linear quadratic regulator. The results of calculating the optimal LQR gain consist of the Q, R and K-opt matrices that are described in each cluster section by section below.

Cluster	**Matrix R** (2×2)
1	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
2	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
3	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
4	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

Cluster	**Matrix Q** (3×3)
1	$\begin{bmatrix} 0.0555 & 0.1243 & -0.1015 \\ 0.1243 & 0.2853 & -0.2223 \\ -0.1015 & -0.2223 & 0.1931 \end{bmatrix}$
2	$\begin{bmatrix} 0.0253 & 0.0572 & 0.0372 \\ 0.0572 & 0.1324 & 0.0808 \\ 0.0372 & 0.0808 & 0.0577 \end{bmatrix}$
3	$\begin{bmatrix} 0.0146 & 0.0536 & 0.0212 \\ 0.0536 & 0.2342 & 0.1014 \\ 0.0212 & 0.1014 & 0.0456 \end{bmatrix}$
4	$\begin{bmatrix} 0.0015 & -0.0031 & -0.0024 \\ -0.0031 & 0.0714 & 0.0363 \\ -0.0024 & 0.0363 & 0.0258 \end{bmatrix}$

Cluster	**Matrix** K_{opt} (2×3)
1	$\begin{bmatrix} 0.0887 & 0.1188 & -0.2005 \\ -0.0461 & -0.2176 & 0.0694 \end{bmatrix}$
2	$\begin{bmatrix} 0.0458 & 0.0390 & 0.0835 \\ -0.0360 & -0.1838 & -0.0425 \end{bmatrix}$
3	$\begin{bmatrix} -0.0046 & 0.0187 & 0.0179 \\ -0.0665 & -0.2969 & -0.1252 \end{bmatrix}$
4	$\begin{bmatrix} -0.0066 & -0.0816 & -0.0398 \\ 0.0481 & 0.1954 & 0.0837 \end{bmatrix}$

Below is shown the simulation results of power generation with optimal control compared uncontrolled control. Figure 7 is the optimal control model of the generator in the first cluster. The results of cluster 2, 3 and 4 simulation are included in the following table 2.



(a)

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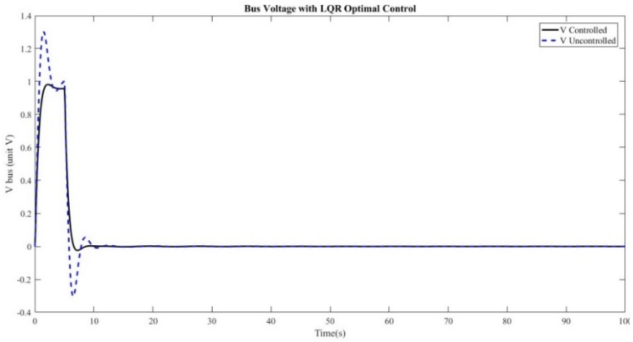

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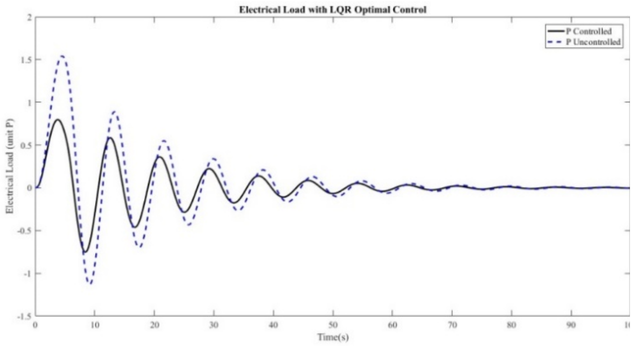

(c)

Fig. 7. Simulation results of optimal and uncontrolled control signals in cluster 1, (a) frequency, (b) bus voltage, (c) electrical power

TABLE II. COMPARISON OF IAE

Cluster	IAE Output uncontrolled control			IAE Output optimal control		
	F	V	P	F	V	P
1	3.457	5.786	19.97	2.168	4.878	12.11
2	2.485	5.773	14.34	1.593	4.593	9.019
3	1.574	5.762	8.996	1.033	4.443	5.807
4	0.9378	5.752	4.977	1.29	3.615	7.108
Average	2.1135	5.768	12.071	1.521	4.3823	8.511

IV. CONCLUSION

A complete model for the small-signal stability study of a power plant system based on a single-machine infinite bus model was developed using Simulink. This is basically a transfer function and block diagram representation of the system equation. Various component blocks are available in various Simulink libraries and also in other compatible toolboxes such as Power System Blockset, Controls Toolbox, Neural Networks Blockset, etc. As such, the Simulink model is not only best suited for typical power system network analytic studies. , but can also combine sophisticated tools for detailed study and parameter optimization. The Simulink model is very user friendly, with exceptional interactive capacity and unlimited hierarchical structure. For small-signal stability studies facilitating a fast and precise solution of nonlinear differential equations namely parameter identification. Every parameter in any model block or subsystem can be easily modified through a simple MATLAB command to adjust to changes in the original power system network due to errors or corrective actions. In this study Simulink's representation was very instrumental and gave support in improving the performance of the controller that had been tested.

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