Mugla Journal of Science and Technology

THE EFFECTS OF DYNAMIC MODELS USED IN SYNCHRONOUS GENERATOR ON SMALL SIGNAL STABILITY

M. Kenan DÖŞOĞLU*, Electrical Electronics Engineering Department, Faculty of Engineering, Duzce University, Turkey, kenandosoglu@duzce.edu.tr
https://orcid.org/ 0000-0001-8804-7070
Enes KAYMAZ, Electrical Electronics Engineering Department, Faculty of Engineering, Duzce University, Turkey, eneskaymaz@duzce.edu.tr
https://orcid.org/ 0000-0002-4774-0773

Received: 26.03.2024, Accepted: 17.06.2024 Research Article
*Corresponding author DOI: 10.22531/muglajsci.1458879

Abstract

Generators used in multi-machine power systems are very affected by transient situations such as malfunctions and line breaks. In transient situations, the system becomes unstable, and oscillations increase. In particular, order modeling of synchronous generators effectively eliminates transient stability situations. To analyze this in the best way, a small signal stability analysis is performed. This study was carried out in the MATLAB-based Power Systems Analysis Program (PSAT), using the 2nd-order and 5th-order models of the synchronous generator for small signal stability analysis in a 3-machine 9-bus power system. While the 2nd-order model is used as the traditional model in synchronous generators, the 5th-order model has been developed as a dynamic order model. Especially in the 5th-order model, it was developed based on a sub-temporal model for better damping of the system. In the comparisons made in both order models, the real and imaginary values and participation factors are shown in figures, while the eigenvalues, damping percentage, frequency, dominant values, and operating modes are presented in tables. By using both order models in the synchronous generator, the number of eigenvalues of the system was determined. The results obtained showed that the 5th-order model gave better results in small signal stability analysis.

Keywords: Synchronous generator, Order models, Small signal stability, PSAT

SENKRON GENARATÖRDE KULLANILAN DİNAMİK MODELLERİN KÜÇÜK SİNYAL KARARLILIĞI ÜZERİNDEKİ ETKİLERİ

Özet

Çok makineli güç sistemlerinde kullanılan generatörler arıza ve hat kopmaları gibi geçici durumlardan çok etkilenmektedir. Geçici durumlarda, sistem kararsız olmakta ve salınımlar artmaktadır. Özellikle, senkron generatörlerin dinamik modellemesi geçici kararlılık durumlarını etkili bir şekilde ortadan kaldırmaktadır. Bunu en iyi şekilde analiz etmek için küçük sinyal kararlılığı analizi yapılmaktadır. Yapılan bu çalışma, 3-makineli 9-baralı güç sisteminde küçük sinyal kararlılığı analizi için senkron generatörün 2. derece ve 5. derece modelleri kullanılarak MATLAB tabanlı olarak çalışan Güç Sistemleri Analizi Programı (PSAT)'da gerçekleştirilmiştir. Senkron generatörlerde 2. derece modeli geleneksel model olarak kullanılırken, 5. derece modeli dinamik derece modeli olarak geliştirilmiştir. Özellikle de 5. derece modelinde sistemin daha iyi sönümlenmesi için alt geçici model tabanlı olarak geliştirilmiştir. Her iki derece modelinde yapılan karşılaştırmalarda gerçek ile sanal değerler ve katılım faktörleri şekiller ile gösterilirken, özdeğerler, sönümleme yüzdesi, frekans, baskın değerler ve çalışma modları tablolar halinde sunulmuştur. Her iki derece modelinin senkron generatörde kullanılması ile sistemin özdeğerlerinin sayısı belirlenmiştir. Elde edilen sonuçlar, küçük sinyal kararlılığı analizinde 5. derece modelinin daha iyi sonuçlar verdiğini göstermiştir.

Anahtar Kelimeler: Senkron generatör, Derece modeller, Küçük sinyal kararlılığı, PSAT

Cite

Döşoğlu, M. K., Kaymaz, E., (2024). "The Effects of Dynamic Models Used in Synchronous Generator on Small Signal Stability", Mugla Journal of Science and Technology, 10(1), 113-119.

1. Introduction

Multi-machine power systems are highly affected by various transient stability states. For this purpose, various analyses are made in power systems. One of the most effective of these is the improved models used in synchronous generators. Small signal stability analyses are performed with these developed models. There are many studies in the literature regarding these. Power systems often suffer from low frequency oscillations. This may cause instability when left in the system for a long time. To reduce these oscillations, power system stabilizers through excitation control are used [1,2]. Due to the integration of wind turbines from renewable energy sources into power systems, certain operating limits need to be set in terms of small signal stability in transient stability situations in large systems. In this regard, various developments are being made in power system stabilization models [3-5]. One of the models that is successful in eliminating transient stability situations in synchronous generators in a short time is the automatic voltage regulator. Effective results have been obtained in small signal stability analysis by using automatic voltage stability in synchronous generators. In addition, the automatic voltage regulator plays an important role in improving low-frequency oscillations by using it together with the power system stabilizer model [6-9]. With the expansion of energy production, low oscillation frequency problems have begun to emerge due to the increase in energy demand. Power electronics-based Flexible AC Transmission System (FACTS) devices are used to eliminate such problems. Among the FACTS devices, Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC), and Unified Power Flow Control (UPFC) are widely used for small signal stability analysis in multi-machine power systems. is used [10-14]. In recent years, grid integration of wind power plants, one of the renewable energy sources, has been one of the most popular topics. Detailed analyses are carried out, especially for instability situations that occur during grid connection. One of these is small signal stability analysis [6,15].

In the studies given in the literature, power system stabilizer models, automatic voltage regulator models, and FACTS devices, which are generally used in synchronous generators, and small signal stability analyses in multi-bus power systems have been examined in detail. In this study, unlike literature studies, the effects of dynamic models used in synchronous generators on small signal stability are examined in detail. Eigenvalue analyses, polar representations, and participation factors of each order model were examined in detail. The results obtained were interpreted in detail.

In the article, synchronous generator order models are discussed in section 2 and small signal stability is discussed in section 3. While simulation study is included in section 4, the simulation study result is examined in section 5. The conclusion is detailed in the last section.

2. Synchronous Generator Order Models

In this study, 2nd and 5th-order models were used in synchronous generator models. In the 2nd-order model, all d and q-axis electromagnetic circuits are neglected. The 2nd-order model is defined by three variables. These are angle, angular speed, and q-axis transient voltage source. Angle and angular speed changes are shown in Equation (1) and Equation (2).

$$\delta = f_b(\omega - 1) \tag{1}$$

$$\omega = (P_m - P_e - D(\omega - 1)) / M \tag{2}$$

The 5th-degree model is obtained by adding one circuit to the d-axis and two circuits to the q-axis. It consists of five variables: angle, angular speed, q-axis transient voltage source, d-axis transient voltage source, and q-axis sub-transient voltage source. In the 5th-order model, the q-axis sub-transient voltage is neglected. The equations used to obtain the 5th-order model are given between Equation (3) and Equation (7).

$$\delta = f_b(\omega - 1) \tag{3}$$

$$\omega = (P_m - P_e - D(\omega - 1)) / M \tag{4}$$

$$e_q^{'} = -e_q^{'} - \left(x_d - x_d^{'} - \frac{T_{d0}^{"}}{T_{d0}^{'}} \frac{x_d^{"}}{x_d^{'}} \left(x_d - x_d^{'} \right) \right) i_d + \frac{(1 - T_{AA} / T_{d0}^{'}) v_f^{*}}{T_{d0}^{'}} \tag{5}$$

$$e_d^{'} = \left(-f_s(e_d^{'}) + \left(x_q - x_q^{'} - \frac{T_{q0}^{"}}{T_{q0}^{'}} \frac{x_q^{"}}{x_q^{'}} \left(x_q - x_q^{'} \right) \right) i_q \right) / T_{q0}^{'} \tag{6}$$

$$\omega = (P_m - P_e - D(\omega - 1)) / M \tag{7}$$

Where, f_b is the base frequency, P_m is the mechanical power, M is the torque, D is the damping coefficient x_d and x_q d-q axis synchronous reactances, x'_d and x'_q are the d-q axis synchronous transient reactances, x''_d and x''_q *d-q* axis synchronous sub- transient reactances, T'_{d0} and T'_{q0} *d-q* axis open circuit transient time constant, T''_{d0} and T''_{q0} *d-q* axis open circuit sub-transient time constant, T_{AA} *d-q* axis additional leakage time constant, i_d and i_q *s the d-q* axis current, δ is the rotor angle, w is the rotor speed, v_f is the field voltage, e'_d and e'_q *d-q* axis transient voltage source, e''_d and e''_q is *d-q* axis sub-transient voltage source [16].

3. Small Signal Stability

In small signal stability analysis, the eigenvalue calculation method is primarily used. When the power system is at equilibrium point, non-linearity is expressed in the eigenvalue calculation. Nonlinear state expressions are shown in Equation (8) and Equation (9) [17,18].

$$\dot{x}_0 = f\left(x_0, u_0\right) = 0 \tag{8}$$

$$y_0 = g\left(x_0, u_0\right) \tag{9}$$

where x_0 and u_0 indicate the equilibrium state and entry at point u. y_0 shows the output at the equilibrium point. The x value is represented as the difference in the state variable x_0. The differential equation of the expression x is shown in Equation (10).

$$\dot{x} = \dot{x}_0 + \Delta\dot{x} \tag{10}$$

where, Δx is defined as the change in state x_0 when the disturbance occurs. This equality can be shown in Equation (11).

$$\dot{x} = f\left[\left(x_0 + \Delta x\right), \left(u_0 + \Delta u\right)\right] \tag{11}$$

If the disturbance is small, the Taylor series is expanded. The equations obtained by expanding Equation (11) are shown between Equation (12) and Equation (16).

$$\dot{x}_n = \dot{x}_{n-0} + \Delta\dot{x}_n \tag{12}$$

$$= f_n\left[(x_0 + \Delta x),(u_0 + \Delta u)\right] \tag{13}$$

$$= f_n(x_0, u_0) + \frac{\partial f_n}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_n}{\partial x_m}\Delta x_m + \frac{\partial f_n}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_n}{\partial u_q}\Delta u_q \tag{14}$$

$$\dot{x}_n = \Delta\dot{x}_n \tag{15}$$

$$= \frac{\partial f_n}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_n}{\partial x_m}\Delta x_m + \frac{\partial f_n}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_n}{\partial u_q}\Delta u_q \tag{16}$$

The output expression can be obtained similarly, and shown as in Equation (17).

$$\Delta y_m = \frac{\partial g_m}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial g_m}{\partial x_m}\Delta x_m + \frac{\partial g_m}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial g_m}{\partial u_q}\Delta u_q \tag{17}$$

Equations (16) and (17) can be shown as Equations (18) and (19).

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{18}$$

$$\Delta\dot{y} = C\Delta x + D\Delta u \tag{19}$$

The A, B, C, and D parameter Equations used in Equation (18) and Equation (19) are shown in Equation (20) and Equation (21) [17,18].

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_m} \\ \vdots & & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_m} \end{bmatrix}, B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_q} \\ \vdots & & \vdots \\ \frac{\partial f_m}{\partial u_1} & \cdots & \frac{\partial f_m}{\partial u_q} \end{bmatrix} \tag{20}$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_m} \\ \vdots & & \vdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_m} \end{bmatrix}, D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_q} \\ \vdots & & \vdots \\ \frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_q} \end{bmatrix} \tag{21}$$

During the calculation process, linearization operations need to be performed around small disturbances in the power system. For this purpose, the small signal stability calculation is discussed after this stage [17,18].

Small signal stability analysis is very important for the operating modes of electromechanical oscillations in multi-machine power systems. The oscillation states of the generators are controlled when they work individually or when they work in groups. To ensure small signal stability, operating modes must be optimally selected. Damping processes of controllers used in synchronous generators occur depending on their operating modes. Eigenvalues are used to evaluate this. The eigenvalue expression used in calculating the damping expression is shown in Equation (22).

$$\lambda = \sigma \pm j\omega \tag{22}$$

Eigenvalues consist of two parts. While the first part shows the real part damping condition; The second part shows the imaginary part damping condition. In addition, oscillation frequency and damping ratios are also taken into account in the eigenvalue calculation. The expressions for oscillation frequency *(ϕ)* and damping ratio (ζ) are shown in Equation (23) and Equation (24).

$$\phi = \frac{\omega}{2\pi} \tag{23}$$

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{24}$$

Another important expression used in eigenvalue calculation is the participation factor. The participation factor is used to determine the operating modes of the system according to frequency. It shows the contribution of the eigenvectors used in the system, especially in local area and inter-regional operating modes [7,19].

4. Simulation Study

An examination of the order models used in the synchronous generator in a 3-machine, 9-bus power system was carried out [20]. The analyzed system is shown in Fig.1. In this test system, bus number 1 was used as the slack bus, while buses 2 and 3 were used as the generator bus. In addition, buses numbered 4, 5, 6, 7, 8, and 9 were used as load buses. In the system, automatic voltage regulators work connected to synchronous generators. Transformers were used between buses 2 and 7 and between buses 3 and 9 in the system. Transient stability analysis was carried out in this system by disabling the breaker used between buses 5 and 7 for a certain period of time and then reactivating it. Two different situations were analyzed in the simulation study. In the first case, comparisons were made for the situation where the 2nd-order model was used in synchronous generators. In the other analysis, comparisons were made when the 5th-order model was used in synchronous generators. In synchronous generators, automatic voltage regulators model 2 and power system stabilizer model 3 are preferred. The analyses were examined in detail.

4.1 Simulation Study Results

In the first analysis of this study, the second-order model was preferred for synchronous generators used in a 3-machine 9-bus system. Using the 2nd-order model, synchronous generator angular speed change, eigenvalue analysis results of the system, and participation factors results are shown in Fig. 2, while eigenvalue values, damping percentage, frequency, dominant parameters, and operating modes are shown in Table 1.

Table 1. Small signal stability results in the 2nd-order model.

Eigenvalue (λ)	Damping percentage	Frequency	Dominant parameters	Operating modes
-0.08701 ±12.1773	0.714	1.9381	delta2, omega 2	Local area
-0.0365 ±7.8943	0.462	1.22564	SG delta 1, SG omega1	Local area

In the results obtained, Fig.2.a shows the region where the system parameters are stable in real and imaginary values; Fig.2.b shows the situations where all parameters are stable and unstable in real and imaginary values. Fig. 2.c shows the angular speed changes of synchronous generators when the order model is used. When the angular speed changes in the 2nd order model of the synchronous generators used in the test system are examined in terms of oscillation, the minimum and maximum values are in the range of 0.9995-1.00065. Fig 2.d shows the relationship between eigenvalues, situation variables, and participation factors. It can be seen that 2 of the 6 state variables are on the real axis, 2 are on the zero axis and 2 are on the imaginary axis. It is seen that the system becomes stable in the angular speed changes of the synchronous generator in a late period. In the other analysis made in this study, the 5th-order model was preferred in the synchronous generators used in the system.

With the use of the 5th order model in synchronous generators, the system eigenvalue analysis results, synchronous generator angular speed change, and participation factors results are given in detail in Fig. 3, while the system eigenvalue analysis results are given in detail in Fig. 3 values, damping percentage, frequency, dominant values and operating modes of the system are presented in detail in Table 2.

Table 2. Small signal stability results in the 5th-order model.

Eigenvalue (λ)	Damping percentage	Frequency	Dominant parameters	Operating modes
-0.77171 ±11.6309	6.62	1.8511	delta 2, omega 2	Local area
-0.20749 ±7.5749	2.738	1.206	delta 1, omega 1	Local area

In the use of the 5th-order model in the synchronous generator, Fig.3.a gives the region on the left where the system parameters are stable in real and imaginary values; Fig.3.b gives the situations where all parameters are stable or unstable in real values and imaginary values on the left and right. Fig. 3.c shows the angular speed changes when the 5th-order model is used in a synchronous generator. Fig. 3.d shows the eigenvalues, state variables, and participation factors in detail in the 5th-order model used in the synchronous generator. It can be seen that 11 of the 15 variables in total are on the imaginary axis. It can be seen that 2 values are on the real axis and 2 variables are on the zero axis. It is seen that the system becomes stable in a short time in case of synchronous generator angular speed changes. By using the 5th order model in the synchronous generator, the oscillations in angular velocity changes are in the range of 0.9996-1.00063.

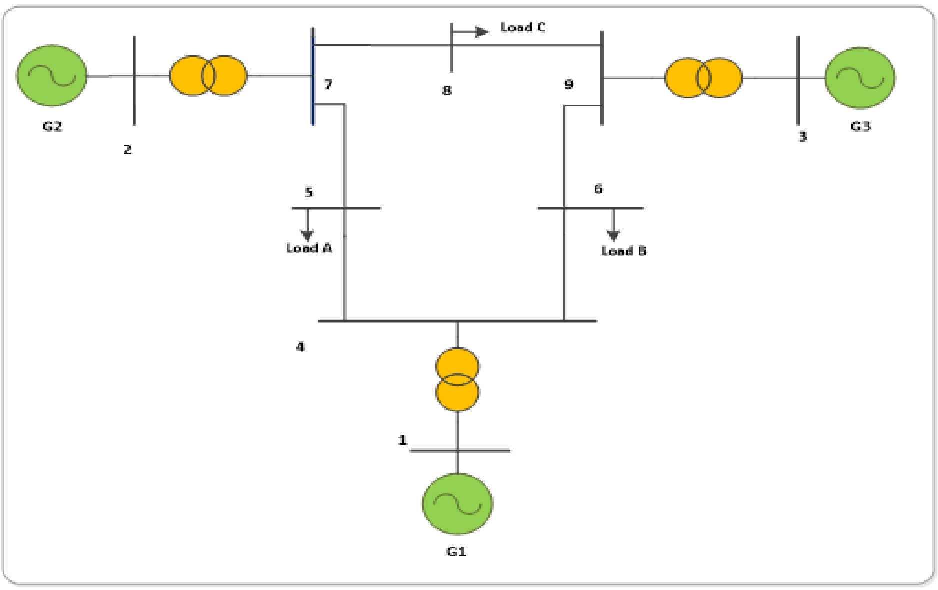

Figure 1. 3-machine 9-bus power system.

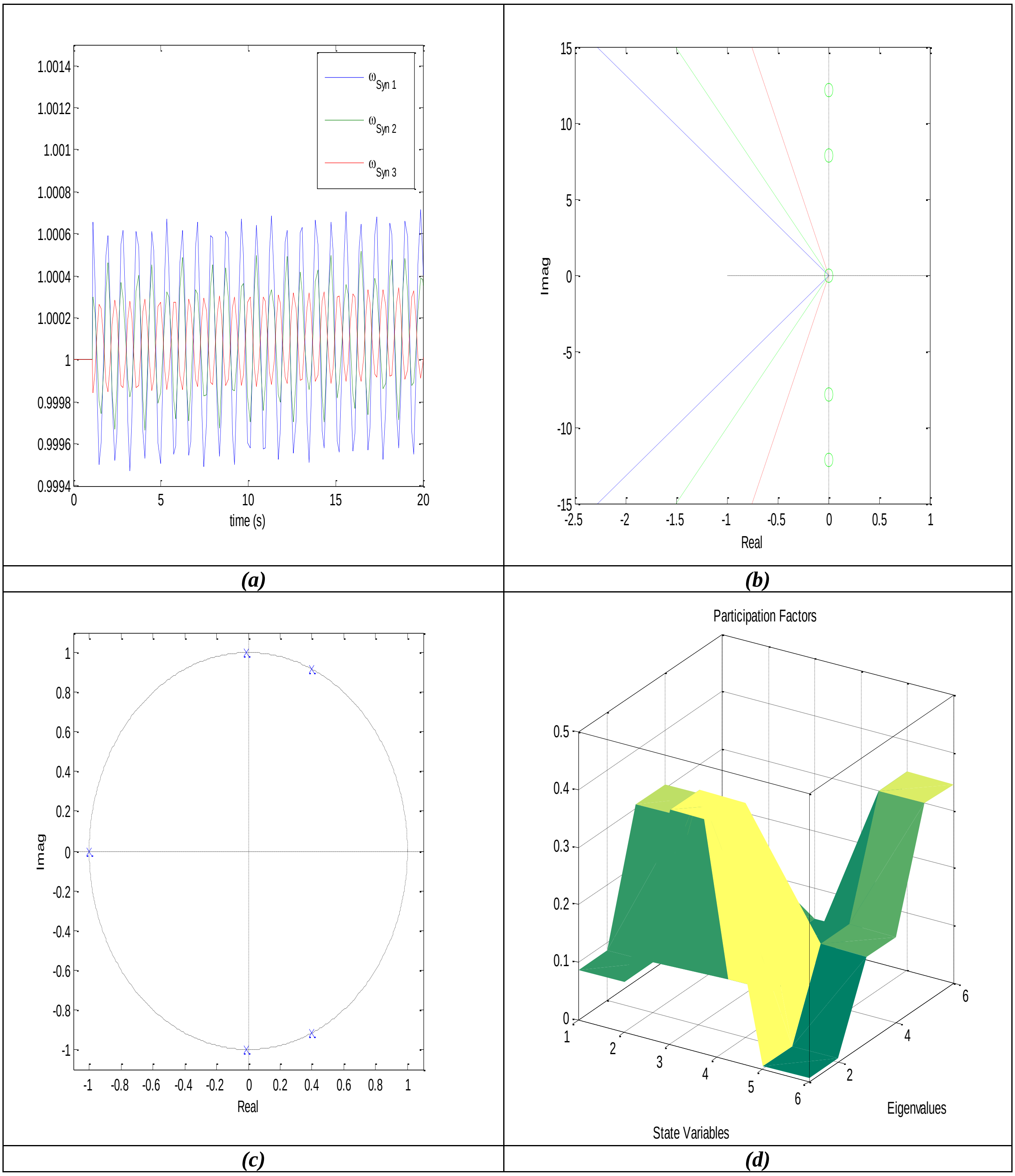

Figure 2. Results obtained with the 2nd order model.

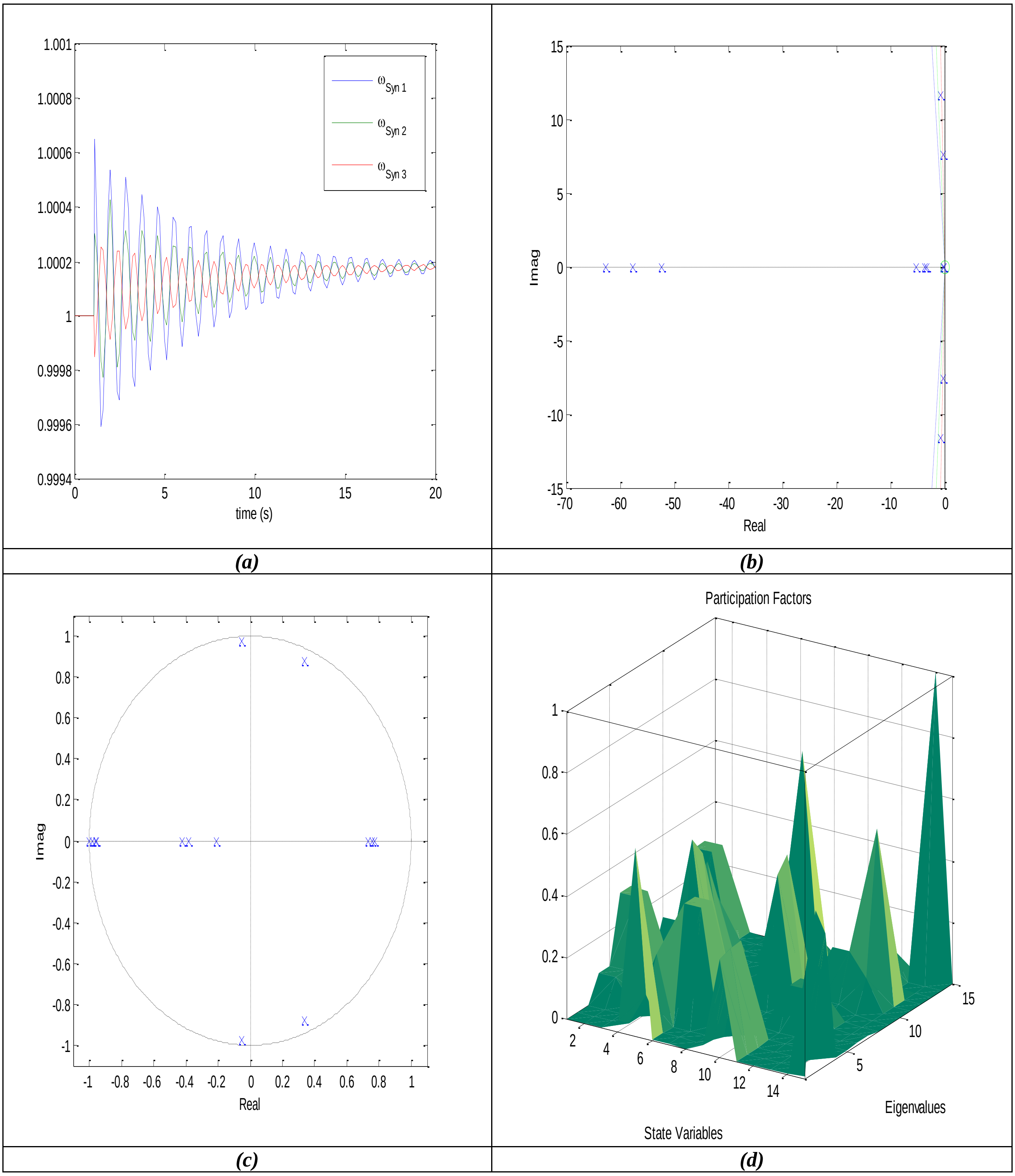

Figure 3. Results obtained with the 5th-order model

5. Conclusion

The effects of synchronous generators in multi-machine power systems in transient stability situations were examined by using different-order modeling. For this study, eigenvalue analyses, damping percentage, frequency, dominant machines, and operating modes were examined in detail. The angular speed change in the synchronous generator was chosen as the reference to control system oscillations. With the use of the 2nd order model, it was observed that the oscillations in the system were high and the system was unstable, while with the use of the 5th order model, it was determined that the oscillations in the system decreased and the system became stable. When the order models are compared in terms of small signal stability, it is seen that in the 5th-order model, most of the parameters are on the left side, that is, in the stable region, while in the 2nd-order model, the parameters are distributed equally to the sides. In addition, the 5th order model used in synchronous generators gives better results in oscillation damping. This study will pave the way for ensuring the coordination of controllers used in synchronous generators in multi-machine power systems and for performing small signal stability analyses with different scenarios.

6. References

[1] Elliott, R. T., Arabshahi, P., and Kirschen, D. S. "A Generalized PSS Architecture for Balancing Transient and Small-Signal Response", *IEEE Transactions on Power Systems*, Vol. 35 No.2, 1446-1456, 2019.

[2] Dey, P., Bhattacharya, A., and Das, P., "Tuning of Power System Stabilizer for Small Signal Stability Improvement of Interconnected Power System", *Applied Computing and Informatics*, Vol.16 No.1/2, 3-28, 2017.

[3] He, P., Ma, T., Li, Z., Chen, J., and Fang, Q., "Small-Signal Stability Analysis of Wind Power Integrated System with Different PSS Models*", 5th Asia Conference on Power and Electrical Engineering (ACPEE),* 2020, 721-726.

[4] He, P., Zheng, M., Jin, H., Gong, Z., and Dong, J. "Introducing MRAC-PSS-VI to Increase Small-Signal Stability of the Power System After Wind Power Integration", *International Transactions on Electrical Energy Systems*, Vol.2022, 1-12, 2022.

[5] Talha, A. and Qureshi, I. S. "Small Signal Stability Analysis of Power System with Wind Generation Using Optimized Wind PSS", *Saudi Arabia Smart Grid (SASG), IEEE*, 2015, 1-5.

[6] Mehta, B., Bhatt, P., and Pandya, V., "Small Signal Stability Analysis of Power Systems with DFIG based Wind Power Penetration", *International Journal of Electrical Power & Energy Systems*, Vol. 58, 64-74, 2014.

[7] Essallah, S., Bouallegue, A., and Khedher, A. "Integration of Automatic Voltage Regulator and Power System Stabilizer: Small-Signal Stability in DFIG-Based Wind Farms", *Journal of Modern Power Systems and Clean Energy*, Vol. 7 No. 5, 1115-1128, 2019.

[8] Bhukya, J., and Mahajan, V."Integration Of DFIG Based Wind Turbine Generator On Small Signal Stability Of Power Systems", *Innovations in Power and Advanced Computing Technologies*, IEEE, 2017, 1-6.

[9] Barot, S. B., Jain, M. V., Mehta, C. R., and Vora, S. C. "Small Signal Stability Analysis of DFIG Penetrated Multi-machine Power System with Synthetic Inertia Control", *20th National Power Systems Conference , IEEE,*2018, 1-6.

[10] Abido, M. A., "Analysis and Assessment of STATCOM-based Damping Stabilizers for Power System Stability Enhancement", *Electric Power Systems Research*, Vol.73 No.2, 177-185, 2005.

[11] Mondal, D., Chakrabarti, A., and Sengupta, A., "Optimal Placement and Parameter Setting of SVC and TCSC using PSO to Mitigate Small Signal Stability Problem", *International Journal of Electrical Power & Energy Systems*, Vol. 42 No.1, 334-340,2012.

[12] Castro, M. S., Ayres, H. M., Da Costa, V. F., and Da Silva, L. C. P., "Impacts of the SSSC Control Modes on Small-Signal and Transient Stability of A Power System", *Electric Power Systems Research*, Vol.77 No. 1, 1-9, 2007.

[13] Seo, J. C., Moon, S. I., Park, J. K., and Choe, J. W. "Design of A Robust UPFC Controller for Enhancing the Small Signal Stability in the Multi-Machine Power Systems", *In 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings*, 2021, 1197-1202.

[14] Abido, M. A., "Power System Stability Enhancement Using FACTS Controllers: A Review", *The Arabian Journal for Science and Engineering*, Vol. 34 No.1B, 153-172, 2009.

[15] Nkosi, N. R., Bansal, R. C., Adefarati, T., Naidoo, R. M., and Bansal, S. K. "A Review of Small-Signal Stability Analysis of DFIG-based Wind Power System", *International Journal of Modelling and Simulation*, Vol.43 No.3, 153-170, 2023.

[16] F.Milano,Available:http://www.Power.uwaterloo.ca /-fmilano/archive/psat-1.3.4.pdf. Documentation for PSAT version 1. 3. 4. 2005.

[17] Kundur, P. and Wang, L. "Small Signal Stability Analysis: Experiences, Achievements, and Challenges". *International Conference on Power System Technology* Vol.1, 6-12, 2002.

[18] Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., and Vittal, V. "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions", *IEEE transactions on Power Systems,* Vol.19 No.3, 1387-1401,2004.

[19] Kundur P., *Power System Stability and Control*. McGraw Hill, New York, 1994.

[20] Milano F. "An Open Source Power System Analysis Toolbox ", *IEEE Transaction on Power System,* Vol. 20 No.3, 1199-1206, 2005.