

Synchronous Generator Modeling Using a MATLAB-Based dq Method for Dynamic Characteristic Analysis

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ABSTRACT

This study analyzes the dynamic characteristics of a synchronous generator using a MATLAB-based direct-quadrature (dq) model. The dq model simplifies the analysis by transforming three-phase electrical quantities into direct and quadrature rotating axes. The simulation evaluates the effect of stator-resistance variations on stator current, electromagnetic torque, rotor speed, rise time, and settling time. The results show that a lower stator resistance produces higher current and torque and a faster response, but also causes larger transient oscillations. In contrast, a higher stator resistance improves damping and stability, although it reduces generator performance. These findings confirm a trade-off between dynamic performance and operating stability, so the stator-resistance value should be selected according to the system's operating requirements.

Keywords: dq model; synchronous generator; stator resistance; dynamic response; MATLAB simulation

1. INTRODUCTION

A synchronous generator is one of the primary components of an electric power system because it converts mechanical energy into electrical energy. Its reliability and performance strongly influence system stability and the continuity of electricity supply to consumers. Under practical operating conditions, synchronous generators frequently experience load changes and system disturbances that produce complex, nonlinear dynamic responses. Analyzing these dynamic characteristics is therefore essential for maintaining stable and efficient power-system operation.

The direct-quadrature (dq) transformation is widely used to analyze synchronous-generator behavior. The dq model transforms a three-phase system into two rotating coordinate axes, namely the direct (d) and quadrature (q) axes, which simplifies the analysis of electrical and mechanical variables. Through this transformation, sinusoidal quantities in a three-phase system can be represented more simply under steady-state conditions, facilitating the analysis of stator current, electromagnetic torque, and rotor-speed dynamics [1].

Previous studies have applied dq models to investigate the transient and dynamic characteristics of synchronous machines. MATLAB-based simulation is commonly used because it offers flexibility and accuracy in representing generator behavior under different operating conditions [2]. In addition, system parameters such as stator resistance significantly affect generator performance and stability. Variations in stator resistance influence stator-current magnitude, electromagnetic torque, damping characteristics, and the dynamic rotor response [3].

Stator resistance is particularly relevant because it appears directly in the stator-voltage equations and determines the resistive voltage drop associated with the d- and q-axis currents. Although its numerical value is normally small compared with other machine parameters, a resistance change can alter the magnitude and decay of a transient response. The present study therefore isolates R_s as the principal test variable. The objective is not to design a controller or estimate parameters from field measurements, but to identify how three resistance settings modify the simulated response while the remaining model structure is maintained consistently.

A low stator-resistance value generally produces higher current and torque, resulting in a faster system response. However, this condition can also generate larger oscillations and reduce system stability. Conversely, a higher stator resistance increases the damping effect and improves stability, although

generator performance decreases because the resulting current and torque are lower. Selecting an appropriate stator-resistance value is therefore an important consideration in synchronous-generator design and operation.

Based on this background, this study analyzes the effect of stator-resistance variation on the dynamic characteristics of a synchronous generator using a MATLAB-based dq simulation model. The evaluated responses include stator current, electromagnetic torque, rotor speed, rise time, and settling time. The analysis is intended to clarify the relationship between stator resistance and dynamic generator performance and to identify the trade-off between system performance and operating stability.

2. RESEARCH METHOD

This study uses simulation and mathematical modeling to analyze the dynamic characteristics of a synchronous generator. The model applies the direct-quadrature (dq) method and is implemented in MATLAB. The dq method was selected because it transforms a three-phase system into the direct (d) and quadrature (q) rotating axes, making the generator's dynamic characteristics easier and more efficient to analyze.

2.1 Synchronous Generator dq Model

The dq model represents the relationships among voltage, current, flux linkage, and rotor speed in a synchronous generator. Through the dq transformation, sinusoidal three-phase electrical quantities are converted into simpler variables in a rotating reference frame. The fundamental voltage equations for the d and q axes are expressed as follows:

$$V_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega \lambda_q$$

$$V_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega \lambda_d$$

where:

- V_d and V_q are the d- and q-axis voltages,
- R_s is the stator resistance,
- i_d and i_q are the d- and q-axis stator currents,
- λ_d and λ_q are the d- and q-axis flux linkages, and
- ω is the rotor angular speed.

The electromagnetic torque of the synchronous generator is expressed as follows:

$$T_e = \frac{3}{2} \frac{P}{2} (\lambda_d i_q - \lambda_q i_d)$$

where T_e is the electromagnetic torque and P is the number of machine poles.

Electromagnetic torque provides the connection between the electrical dq variables and the mechanical motion of the rotor. A difference between electromagnetic torque and the opposing mechanical load produces angular acceleration, whereas a balanced torque condition corresponds to constant rotor speed. In this model, the effect of stator resistance is therefore transmitted from the electrical subsystem to the mechanical subsystem through the current and flux-linkage terms. This relationship explains why the resistance variations can be observed not only in stator current but also in torque and rotor-speed curves.

2.2 Simulation Parameters

The simulation varies the stator resistance (R_s) to evaluate its effect on the dynamic characteristics of the synchronous generator. The resistance values are 0.2, 0.4, and 0.8. These variations are used to compare the system response under different operating conditions.

For a controlled comparison, each simulation uses the same model configuration, observation interval, and initial operating assumptions; only the selected stator-resistance value is changed. This one-factor-at-a-time approach makes the direction of the resistance effect easier to identify. The three cases represent a low, intermediate, and high resistance condition within the scope of the model. The resulting curves are evaluated comparatively rather than treated as universal machine limits, because their absolute values remain dependent on the complete set of generator and load parameters.

The observed simulation parameters are:

- stator current,
- electromagnetic torque,
- rotor speed,
- rise time, and
- settling time.

2.3 Simulation Procedure

The study begins by formulating a mathematical model of the synchronous generator based on the dq transformation. The model is then implemented in MATLAB to obtain the system's dynamic response. After the model is successfully executed, the predefined stator-resistance variations are applied.

The simulation results are compared to determine how changes in stator resistance affect synchronous-generator performance. The analysis considers changes in current, electromagnetic torque, rotor speed, and overall system stability for each simulation condition. This procedure clarifies the relationship between stator resistance and the dynamic characteristics of the synchronous generator.

2.4 Dynamic Response Evaluation

The evaluation separates the response into transient and steady-state regions. The transient region begins when the simulation is initiated and includes the initial rise, overshoot or undershoot, and oscillatory decay. The steady-state region is identified when the response remains within a narrow range and no longer exhibits a material change in amplitude. This distinction is applied consistently to the current, torque, and rotor-speed curves so that the influence of R_s can be discussed using the same response criteria.

Rise time is interpreted as the relative time required for a response to approach its final operating level, while settling time describes how long the oscillations require to decay to an acceptably stable region. Because the study emphasizes graphical comparison, these indicators are assessed from the curve shapes and relative timing rather than reported as instrument-grade measurements. Peak magnitude, oscillation amplitude, decay rate, and final level are also considered. Together, these indicators provide a broader interpretation than a comparison based only on the maximum value of each curve.

3. RESULTS AND DISCUSSION

The simulation results show that variations in stator resistance (R_s) significantly affect the dynamic characteristics of the synchronous generator. At the beginning of each simulation, all conditions exhibit an oscillatory transient response before reaching steady state. The stator-resistance value affects current magnitude, electromagnetic torque, rotor speed, and overall system stability. The MATLAB simulation results are presented in the following figures.

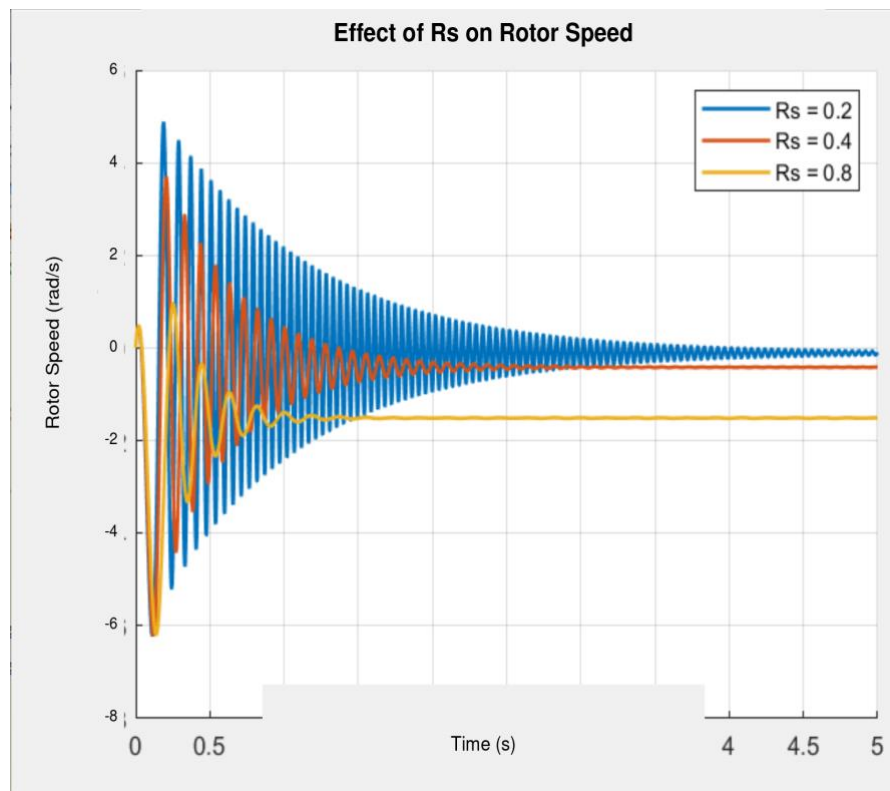


Figure 1. Effect of Stator Resistance on Rotor Speed

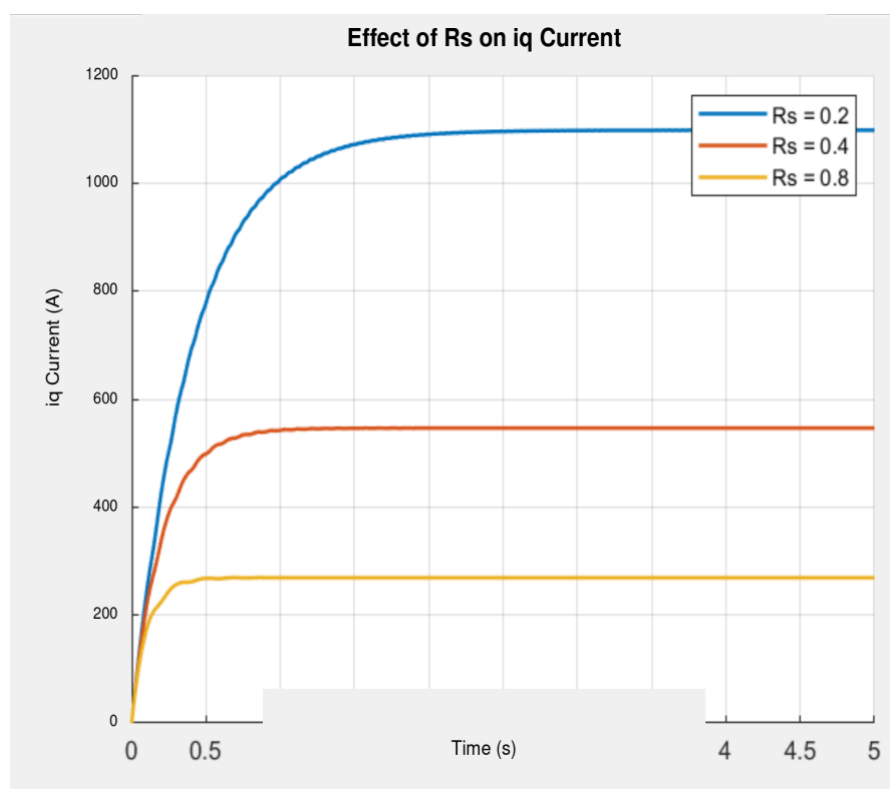


Figure 2. Effect of Stator Resistance on iq Current

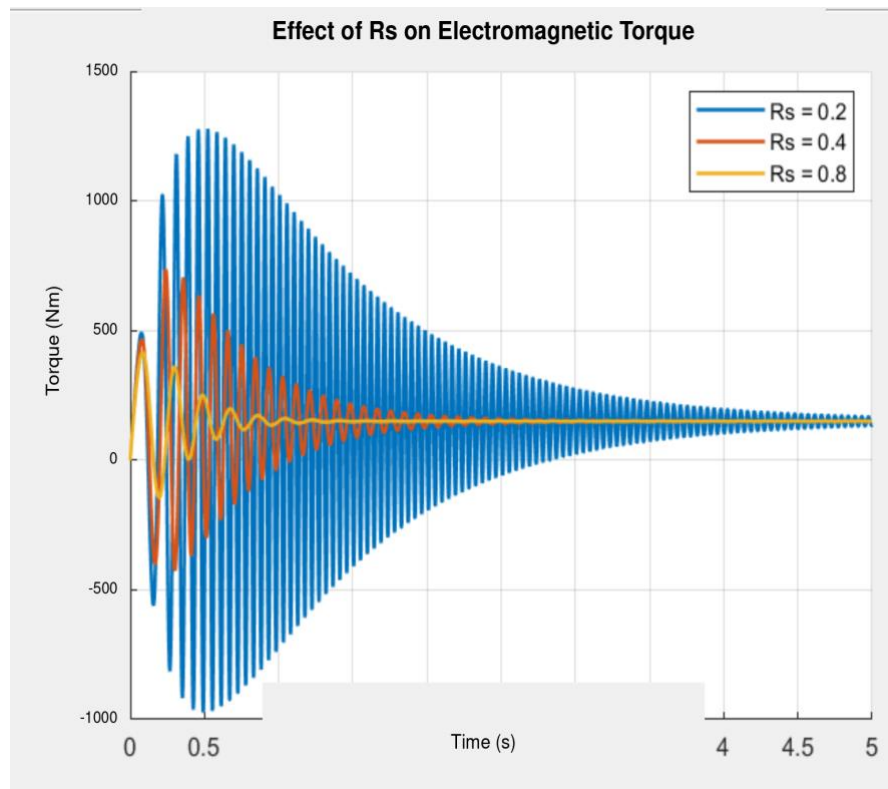


Figure 3. Effect of Stator Resistance on Electromagnetic Torque

3.1 Effect of Stator Resistance on Stator Current

The results show that a lower stator resistance produces a higher stator current. At $R_s = 0.2$, the stator current increases substantially because the stator-circuit resistance is relatively small. The larger current produces a faster system response, but it also causes pronounced oscillations during the initial transient.

At $R_s = 0.8$, the higher stator resistance reduces the generated current. This current reduction slows the system response, but it also suppresses oscillations and makes the system more stable. The intermediate value, $R_s = 0.4$, provides a more balanced response between speed and stability.

Figure 2 reinforces this relationship by showing a clear separation among the three i_q -current trajectories. The low-resistance case reaches the largest final current, the intermediate case produces a moderate value, and the high-resistance case produces the smallest value. The trajectories do not cross after the early transient, indicating that the relative ordering is maintained throughout the simulated interval. From an engineering perspective, a larger current may support stronger torque production, but it also implies greater electrical loading and potentially higher thermal stress if the condition is sustained in a physical machine.

3.2 Effect of Stator Resistance on Electromagnetic Torque

Changes in stator resistance also affect the electromagnetic torque generated by the synchronous generator. Electromagnetic torque is directly influenced by stator current; therefore, a low resistance produces a higher torque. At $R_s = 0.2$, the generator develops the highest electromagnetic torque among the evaluated conditions, which accelerates the rotor more rapidly.

However, the increased torque at low resistance also produces larger response fluctuations. At higher resistance values, electromagnetic torque decreases because the stator current is lower. Although generator performance is reduced, the system exhibits better damping and a more stable response.

The torque envelopes in Figure 3 also reveal that damping should be considered together with peak output. At $R_s = 0.2$, the large positive and negative excursions persist for a longer portion of the

observation window. Increasing R_s reduces the envelope more rapidly and limits the transient peaks. The steady-state torque values become closer after the oscillations decay, but the paths taken to reach that region remain substantially different. This result demonstrates that two operating cases may approach a stable condition while imposing very different transient mechanical stresses on the shaft and connected equipment.

3.3 Effect of Stator Resistance on Rotor Speed

Rotor speed exhibits different characteristics for each stator-resistance value. At low resistance, the rotor reaches steady state more quickly because the generated electromagnetic torque is higher. However, the rotor-speed response also undergoes substantial oscillations before stabilizing.

At higher stator resistance, rotor acceleration is slower because the generated electromagnetic torque is lower. Nevertheless, the system is more stable, and the transient oscillations decay more rapidly because of the increased damping effect.

Figure 1 shows that the resistance variation also changes the final rotor-speed level in the simulated model. The three curves remain separated after the dominant oscillations have decayed, with the largest resistance producing the greatest deviation from the reference level. This behavior indicates that additional damping does not automatically produce the most desirable operating point. A resistance value must therefore be judged using both transient stability and the final speed requirement. An operating condition that suppresses oscillation effectively may still require corrective control or parameter adjustment to achieve the intended steady-state speed.

3.4 System Response Characteristics

Response characteristics such as rise time and settling time illustrate the relationship between performance and stability in the synchronous-generator system. A low stator resistance produces a shorter rise time because the system responds quickly to changes. However, the large transient oscillations increase the time required for the response to settle.

Conversely, a high stator resistance produces a longer rise time but a shorter settling time because the oscillations decay more rapidly. This behavior demonstrates the important role of stator resistance in determining system damping.

Overall, the results indicate a trade-off between performance and stability. Low stator resistance provides a rapid response and high output, whereas higher resistance improves system stability but reduces generator performance. The optimum stator-resistance value should therefore be selected according to the operating requirements of the power system.

The graphical results also show why rise time and settling time should not be interpreted as interchangeable measures. A response can approach its final level quickly and still require a long period for its oscillations to disappear. Conversely, a more heavily damped response may develop more slowly but remain easier to control once it approaches steady state. No separate numerical table of rise time and settling time is available in the present simulation output; therefore, the conclusions regarding these indicators are comparative and are based on the visible response envelopes.

3.5 Practical Implications and Model Limitations

The results provide a useful design insight, but they should not be interpreted as a recommendation to increase physical stator resistance without further evaluation. Additional resistance may improve the damping observed in the model, yet it also increases resistive losses and can reduce efficiency. In an actual generator, thermal limits, conductor dimensions, excitation control, protection settings, and the connected load must be considered together. The intermediate case in this study illustrates a compromise, but the optimum value for a real installation can only be established after the machine parameters and operating objectives are defined.

The model also has several limitations. The study varies only stator resistance and does not independently evaluate changes in d- and q-axis inductances, rotor inertia, load torque, excitation voltage, magnetic saturation, temperature, or controller dynamics. Harmonics, measurement noise, and unbalanced operating conditions are not represented in the reported figures. These simplifications are appropriate for isolating the resistance effect, but they limit the extent to which the numerical magnitudes can be transferred directly to a physical generator.

Future work should validate the simulated trends using measured generator data or a laboratory-scale synchronous machine. A broader sensitivity analysis could vary resistance together with inductance,

inertia, excitation, and load torque to identify parameter interactions. Additional operating scenarios, including sudden load changes, voltage disturbances, and different initial conditions, would provide a more complete stability assessment. Reporting numerical peak values, rise time, settling time, steady-state error, and energy losses would also strengthen the quantitative comparison and support objective parameter selection.

4. CONCLUSION

The simulation and analysis demonstrate that stator resistance (R_s) significantly affects the dynamic characteristics of a synchronous generator. Changes in stator resistance influence stator-current magnitude, electromagnetic torque, rotor speed, and the manner in which the system reaches steady state.

A low stator resistance produces larger stator current and electromagnetic torque, enabling a faster system response. However, it also creates larger oscillations and reduces stability. A higher stator resistance provides better damping, resulting in a more stable system with faster attenuation of transient oscillations, although generator performance declines because the current and torque are lower.

The results therefore confirm a trade-off between synchronous-generator performance and stability. Selecting an optimum stator resistance requires consideration of the intended operating priority, whether a faster response or greater stability is required. The findings can support the analysis and design of dq-model-based synchronous generators to achieve stable and effective operation.

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