**Study of the Mode of Deep Consumption of Reactive Power by a Synchronous Compensator with Longitudinal-Transverse Excitation**

Nurali Pirmatov1 , Allabergen Bekishev1 , a ) , Gulzoda Mustafakulova2 , Najmiddin Kurbanov3 Usman Norkulov3 , Munisakhon Kurbonova3

1 Tashkent state technical university named after Islam Karimov , Tashkent, Uzbekistan

*2Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan*

3 Karshi state technical university, Karshi , Uzbekistan

a) Corresponding author: [allabergenbekisev@gmail.com](mailto:allabergenbekisev@gmail.com)

**Abstract.** This article examines the deep reactive power consumption mode of a synchronous compensator with longitudinal-transverse excitation. We analyze existing research and regulatory documents in accordance with GOST standards, construct a d – q model of the synchronous machine taking into account magnetic core saturation and cross-inductances, and propose a methodology for modeling transient processes and assessing stability. The results obtained allow us to determine the dynamic and steady-state characteristics of the compensator in deep underexcitation mode and formulate recommendations for adjusting the excitation and protection systems.

**INTRODUCTION**

Modern power systems face challenges with voltage stability and dynamics, especially with a high share of renewable energy sources (RES) and weak grids. Synchronous compensators provide reactive power support and inertial response, which is critical for HVAC connections and grid stability. However, when operating in high-reactive power mode, the compensator effectively absorbs Q from the grid, which can lead to overloads and loss of synchronization.

The aim of the article is to study the dynamics and stability of a synchronous compensator with longitudinal-transverse excitation under deep reactive power consumption modes, to develop a mathematical model and analysis methodology, and to formulate recommendations for machine control and protection.

Research objectives:

- conduct a review of modern literature and regulatory documents according to GOST;

- develop a d – q model of a synchronous compensator taking into account the dual - excited rotor;

- and investigate transient processes and stability in the deep consumption mode Q;

- propose a method for optimizing the operation of automatic excitation control and protection systems;

- compare the results of modeling with the requirements of GOST and practical recommendations.

Synchronous compensators are widely used to maintain voltage, compensate reactive power, and improve the stability of power systems. Modern research [1–3] emphasizes the importance of choosing the correct excitation strategy and initial state of the compensator:

**-** Teleke S. et al. [1] compared the dynamic behavior of a synchronous compensator and static compensating devices (SVC) under three-phase faults. The results showed that the synchronous compensator provides more stable reactive support and faster voltage recovery.

**-** Zican Tao et al. [2] investigated the optimization of reactive power input and output of synchronous compensator in HVDC systems, demonstrating the significant impact of excitation control strategy on the dynamic performance of the network.

**-** Zhang D. et al. [3] analyzed the development and dynamics of a synchronous compensator in electrical networks , noting the need to model underexcitation and deep consumption modes of Q.

Q consumption is characterized by negative reactive power absorbed from the grid and an increase in stator current. The literature identifies the following key consequences of this mode [2, 4]:

**-** increase in the amplitudes of currents i \_ d and i \_ q;

**-** reduction of voltage on buses;

**-** increasing the influence of magnetic circuit saturation;

**-** possible loss of stability when the critical excitation current is exceeded.

Optimization of operation of automatic excitation control and setting of minimum excitation current limits I*f,min* allow you to control the machine's entry into deep consumption mode and prevent overloads.

**Longitudinal-transverse (dual) excitation.** Longitudinal-transverse excitation (dual - excited) increases the controllability of the machine by allowing the flow component to be distributed between the d- and q- axes. As noted in [5–6]:

- dual - excited synchronous compensator can flexibly compensate reactive loads;

- reduces the amplitude of transient processes with a sharp decrease in excitation;

- requires coordination of two channels of excitation and protection.

Direct experimental studies of the deep consumption mode specifically for dual - excited SC are still limited, which underlines the relevance of this dissertation.

**MODELING AND ANALYSIS METHODS**

To simulate the dynamics of a synchronous compensator, **a rotating coordinate system d – q is used**, associated with the rotor:

- id, iq – stator currents along the d and q axes;

- vd, vq​ – voltages at the stator terminals;

- ψd, ψq – stator flux linkage;

- i*fd*, i*fq*​​ – excitation currents of the longitudinal and transverse rotor systems (dual - excited);

- ω m – mechanical frequency of the rotor;

- Tm, Te​ – mechanical and electrical moments.

**Electrical part. Stator equations of a** synchronous compensator in d – q coordinates taking into account the rotating system:

(1)

where R s is the stator resistance, ω s is the synchronous frequency.

**Relationship between flux linkage and currents.** Taking into account cross-inductances and saturation of the magnetic circuit [11-15]:

(2)

Where:

Ld, Lq​ – nonlinear inductances taking into account saturation;

Lmd, Lmq – mutual inductances of the stator and rotor for the longitudinal and transverse axes.

**Note:** Saturation is taken into account as a function of current , allowing deep Q consumption to be modeled .

**Mechanical dynamics of the rotor.**

(3)

Where:

*J* – moment of inertia of the rotor;

*D* – mechanical damping coefficient;

*p* – number of pole pairs.

**Active and reactive power.**

(4)

Where is Q? < 0 corresponds to the mode of deep consumption of reactive power.

**Excitation system (automatic excitation control) for dual - excited**

For the longitudinal-transverse excitation scheme, two control channels are used:

(5)

where U *ref* is the set voltage, U *term* is the voltage at the terminals.

The automatic excitation control system is implemented as a PI / PID controller with anti- windup and limitations:

allows you to manage reactive power, preventing deep consumption beyond permissible limits.

**Features of modeling deep consumption Q**

1. i *f* decreases below the critical level, Q becomes negative.
2. The stator current increases , which can lead to overheating of the windings.
3. Nonlinearities are taken into account: saturation of the magnetic circuit, cross-inductances, delays, automatic excitation control.
4. The model allows us to study the influence of dual - excitation on dynamics: oscillation softening, flow control, and overload minimization.

**Time equations for simulation.** For simulation in MATLAB, differential equations are used [16-22]:

(6)

where T *fd* , T *fq*​​ are the excitation time constants of the longitudinal and transverse systems.

**Dual - excited synchronous compensator control circuit (text description)**:

* the longitudinal axis (d) forms the basic reactive power;
* the transverse axis (q) compensates for sudden voltage fluctuations;
* Automatic excitation control regulates two channels in real time;
* Current and voltage limiters prevent dangerous conditions from occurring.

**Statement of the modeling problem.** The model of a synchronous compensator with longitudinal-transverse excitation was implemented in **MATLAB**.

**TABLE 1.** Main parameters of the machine:

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Designation** | **Meaning** |
| Nominal voltage | U n | 10 kV |
| Nominal power | S n | 25 MVA |
| Resistance stator | R s | 0.02 Ω |
| d- axis inductance | L d | 0.15 H |
| Inductance of the q- axis | L q | 0.12 H |
| Moment inertia | J | 5.0 kg m² |
| Number polar steam | p | 2 |
| Constant time excitement | T *fd* , T *fq* | 0.25 s |

**The purpose of the simulation is** to investigate the U -shaped characteristic of a synchronous compensator with longitudinal-transverse excitation, the data of which are given in Table 1. In Figure 1, based on the Matlab script, the U-shaped characteristic of a two-axis synchronous compensator is simulated, the parameters of which are given in Table 1.

|  |
| --- |
|  |
| **FIGURE 1.** U- shaped characteristic and mode of deep consumption of reactive power by a synchronous compensator with longitudinal-transverse excitation |

**RESEARCH RESULTS**

- Dual - excited excitation effectively softens transient processes in the deep Q consumption mode;

- Limitation on the minimum excitation current I*f,min* prevents critical voltage drop and overheating of the windings;

- The established model allows us to predict the dynamics under various scenarios, including short circuits and sudden load changes;

- The classical form of the reactive characteristic is observed: negative values of Q are associated with an increase in i \_ d and a drop in voltage, which is consistent with the theory [1–3, 8–10].

**Conclusion of the simulation:**

**-** the mode of deep consumption of reactive power is accompanied by negative values of Q and an increase in the stator current;

- dual - excited excitation reduces the negative consequences of transient processes;

- the model allows you to set limits on the minimum excitation current, which is important for compliance with GOST 21558-2018;

- the obtained data correspond to the results described in [1–6].

**MAIN RESULTS OF THE WORK**

1. The analysis of the mode of deep consumption of reactive power by a synchronous compensator with longitudinal-transverse (dual) excitation was carried out.
2. A mathematical d – q model of a synchronous compensator has been developed taking into account the saturation of the magnetic circuit, cross-inductances and nonlinearities of the windings.
3. Matlab was created a model of a synchronous compensator that allows one to study the dynamics of currents id, iq, terminal voltage and reactive power Q under various operating scenarios, including deep consumption of Q.
4. It has been found that dual - excited arousal provides:

- mitigation of transient processes;

- reduction of negative Q peaks;

- improving voltage stability with a sharp decrease in excitation current.

1. The consequences of deep Q consumption, including stator growth, voltage drop and potential loss of stability, are analyzed, which is confirmed by the regulatory requirements of GOST 21558-2018 and GOST 609-84.

**CONCLUSION AND RECOMMENDATIONS**

**Recommendations for operation and further research:**

1. When operating a synchronous compensator, it is necessary to maintain the excitation current above the critical I*f,min* to prevent deep consumption of Q .
2. It is recommended to implement dual - channelAutomatic excitation control for flexible control of reactive power and mitigation of transient processes.

For further research it is suggested:

- experimental verification of the model on a real synchronous compensator;

- expansion of the model taking into account losses, nonlinear load characteristics and short circuits;

- analysis of the influence of phase shifts and asymmetric loads on the stability of the deep consumption mode Q.

The study confirmed that dual - excitedA synchronous compensator can effectively manage reactive power, minimize the negative effects of deep consumption, and ensure dynamic stability of the power system. The proposed models and methods can be used for scientific and practical purposes, including the design, operation, and modernization of excitation systems.

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