Abstract
Based on the novel rotor speed control, the complete AC/DC/AC synchronous machine drive system is integrated. It consists of AC grid, rectifier, inverter and synchronous machine with its excitation system. All power components as well as complete control system are modeled. The sequences of machine starting, voltage control and reactive power control are then accomplished. Short circuit studies are also provided; one with IGBT- and the other with thyristor-based rectifier. Despite the system complexity, all control functions are successfully fulfilled.

1. Introduction
Global warming and climate change pose an unprecedented threat to humanity. Technological innovation and development is vital to reconciling the expanding energy services with environmental protection. In this context, governments provide huge amounts of incentives for renewable energy generation and support the related investments in many countries.

Most renewable energy sources are intermittent and it is often a challenge to match the production with the demand. Especially wind energy brings new challenges for the power system operation. There is therefore, a need to be able to store energy in the systems that contain a substantial fraction of renewable energy, such as wind and solar energy.

Pumped storage is a good alternative for long-term storage of large amounts of energy, while batteries and flywheels are better alternatives for short-time intervals, as well as significantly lower capacities.

There are many services and contributions of pumped storage to the power system:
- Load leveling and reducing transmission congestion;
- Reduced environmental emissions;
- Primary and secondary frequency control;
- Spinning and non-spinning reserve;
- Integration of variable energy resources;
- Load following;
- Voltage support;
- Improved dynamic stability;
- Black start capability;
- Generating capacity.

To achieve its full potential the pump storage has to be built as adjustable speed system. Regarding the electrical solution for adjustable speed system, two main concepts [1] have been developed:
- Full-rated frequency converter system;
- Doubly-fed induction machine system.

Full-rated converter system consists of a full rated converter connected to the stator of the synchronous machine (SM). It is simple, but due to higher prices of high-power semi-conductors, its use is today limited to power ratings below 200 MVA.

Doubly-fed system consists of a partially rated frequency converter connected to the rotor of the induction machine. This topology seems to be more economic but it brings many new demands on the machine design. It is used by fewer manufacturers and mostly for higher power applications up to 500 MVA.

KEYWORDS
AC/DC/AC converter, synchronous machine, system integration, variable speed operation

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Due to its simplicity in design, implementation and maintenance full-rated converter configuration is used in this work.

This work is an extension of the novel rotor speed control studies [2], [3], [4], [5]. In [5] the control system has been modeled only for DC/AC (inverter) part of the system. Also, the excitation system voltage has been considered constant.

To simulate the pump storage electrical system, the integration of the complete AC/DC/AC voltage source inverter drive has been performed. Apart from the inverter, it also includes AC/DC (rectifier) and excitation system modeling and control.

The state-of-the-art production of this type of drive system gives two major topologies. The first one with IGBT/IGCT-based rectifiers, and the second one with thyristor-based ones. Due to the switching advantages of transistors, for the inverter part of the drive modern topologies use IGBT, IGCT, GTO or similar components. In this work IGBT bridge inverter has been considered.

The paper is organized so as to give the complete SM drive system description, followed by the study of starting with sequences of voltage and reactive power control. To review the major drive topologies, a short circuit study for each of them has also been accomplished: the first one with IGBT- and the second with thyristor-based rectifier.

2. System Description

The simplified scheme of simulated system is given in Figure 1. Its modeling is done by MATLAB Simulink. The used power system components are standard Simulink blocks. For example: SM is of the sixth order, excitation model is according to the IEEE type 1, rectifier and inverter are universal bridges, etc.

Apart from the non-linear speed controller [5], it contains linear DC voltage and linear excitation system control. DC voltage is controlled by a simple PI controller, while the excitation system includes stator voltage and also the reactive power PI controller.

The space vector pulse width modulation is used. The sampling time of the entire control system is 12 kHz which is well within the range of the modern digital signal processors.

2.1 Parameters

For practical reasons, small power SM has been chosen. SM nominal values of power, voltage, frequency, pole pairs and inertia constant are:

\[ S_n = 8.1 \text{ kVA}, \ U_n = 400 \text{ V}, f_n = 50 \text{ Hz}, p = 2, \ H = 0.1406 \text{ s}. \]

Stator winding (p.u.) values are: \( r_s = 0.082, L_s = 0.072, L_{md} = 1.728, L_{mq} = 0.823. \)

Excitation winding (p.u.) values are: \( r_f = 0.0612, L_{sf} = 0.18, U_{fn} = 2.0. \)

Damper winding (p.u.) values are: \( r_D = 0.159, L_{sd} = 0.117, r_Q = 0.242, L_{sq} = 0.162. \)

DC link capacitor value is: \( C = 200 \text{ mF}. \)

DC voltage controller values are: \( P = 1, I = 2. \)

Reactive power controller values are: \( P = 0.5, I = 1. \)


\[
\begin{align*}
\mathbf{\varphi} = \begin{bmatrix} \varphi_D \\ \varphi_Q \end{bmatrix} = \begin{bmatrix} c_1 i + c_2 j + c_3 \varphi_D \\ f_1 i + f_2 \varphi_Q \end{bmatrix}
\end{align*}
\]

the reactive power could be obtained as given in (2):

\[ Q = (i_d \varphi_D + i_q \varphi_Q) \]
The first part of the sequence is machine starting that lasts until the end of the 1st second. At 1.5th second the reactive power control is turned on and it lasts until the end of the 3rd second.

Rotor speed (Figure 2) error is below one percent during the entire dynamics. The excitation voltage comes to its nominal value at the end of the starting and retains it (Figure 3) until the beginning of the reactive power control. The stator voltage is also successfully controlled as given in Figure 4. After 1.5th second the reactive power control is started. By the end of the third second the reactive power is reduced to zero (Figure 5). DC voltage is controlled fast and precisely (Figure 6) during the dynamics. Also, the stator current waveform (Figure 7) is not distorted.

4. Short circuit with IGBT and thyristor rectifier

The grid side short circuits are simulated in this simulation, firstly for the IGBT bridge in rectifier part of the drive and secondly for the thyristor bridge rectifier.

This simulation is done by IGBT-based bridges in both rectifier and inverter.

where:

\begin{align*}
i_{d} & \quad \text{stator d-axis current,} \\
i_{q} & \quad \text{stator q-axis current,} \\
\phi_{D} & \quad \text{damper d-axis flux,}
\phi_{Q} & \quad \text{damper q-axis flux,} \\
\omega & \quad \text{rotor speed.}
\end{align*}
the space vector modulation. In the thyristor bridge control, only classical pulse with modulation could be used. At 1.4th second the short circuit occurs and it lasts until 1.5th second.

4.1 IGBT Rectifier

During the short circuit, the rotor speed drops to about 50 percent of the nominal speed (Figure 8) but it recovers to its nominal value. The electromagnetic torque acts very fast (Figure 9) while DC voltage drops to zero (Figure 10) during the short circuit. To obtain nominal conditions, the excitation voltage reacts significantly as given in Figure 11.

4.2 Thyristor Rectifier

In case of thyristor-based rectifier topology, the rotor speed dip is significantly lower (Figure 12). This is due to the thyristor commutation principle that prevents DC voltage dip. But because of the use of classical modulation method, DC voltage oscillations are higher (Figure 13). For the same reason the electromagnetic torque oscillations are also higher (Figure 14). The excitation reaction (Figure 15) is reduced in this case.

5. Conclusion

This paper presents the simulation studies of synchronous machine AC/DC/AC drive system. The rotor speed, stator voltage, reactive power and DC voltage controls are obtained through complete system integration. Short circuit analysis has been performed for two rectifier topologies: IGBT-based rectifier and thyristor-based one. The advantages and disadvantages of each instance have been discussed.

The obtained results show that all control advantages of the given drive systems could be easily achieved.

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6. References


Biography

Marijo Šundrica graduated at the Faculty of Electrical Engineering and Computing, University of Zagreb. Since 2006 he has been working as a design and development engineer in Končar Power Plant and Electric Traction Engineering. He is pursuing his PhD degree in the field of synchronous machine dynamics, modelling and control. He has been author of many scientific and professional papers. He is a member of HRO CIGRE and SEER CIGRE WG 4.

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