Stabilized Series Compensation of Induction Machines in Motor Operation fed by Voltage Source Inverter

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Abstract

Series capacitors are proposed to overcome the reduction of torque with increasing speed in the field-weakening range of induction motors. The operational behavior is studied, example applications are given and a control concept, based on state-space and field-oriented control, is proposed to stabilize the system in motor operation.

Introduction

Since the invention of power electronic converters, the asynchronous induction machine (IM) was established for many applications as variable speed drive.

One particular application is the use as railway traction drive, where a maximum of power or tractive-effort for a wide frequency range has to be achieved. The rating of such a traction drive has to be geared to two main design-steps:

The maximum output voltage of the converter is given from the system conditions, e.g. input voltage. At the low frequency range the converter output voltage is increased proportionally to the frequency until the maximum voltage is reached. From this point the voltage stays constant even if the frequency or speed of the IM is increased. This results in a linear decrease of flux and a quadratic decreasing of utilizable torque. This leads to the second design-step, the maximally utilizable torque at maximum speed. The outcome is a set of design-parameters of the induction motor such as size, number of winding turns, reactance etc.

It is necessary, especially for fast-running railway vehicles, to achieve high torque at high speed, leading to low inductances of the IM. This design has several disadvantages for the use at low frequencies, since the switching of the converter leads to current-ripple and pulsating torque causing noise and additional stress on the traction system.

It would be ideal to have an IM, which has high inductance at low speed and low inductance at high speed. In principle, this can be realized by switching additionally reactors (chokes) between the converter and the IM in the lower frequency-range.

Another possibility, which is described in this paper, is to design the IM with high inductances and to compensate these using series-connected capacitors in the higher frequency-range. This is the so called Series-Compensation (SC). A motor-design with higher leakage inductance, e.g. by choosing a larger number of winding-turns, leads to non-compliance with the torque-requirements at high frequencies. This non-compliance can be overcome by means of increasing the terminal voltage of the induction machine causing a higher utilizable torque. This increase of the terminal voltage beyond the maximum converter output voltage is possible by means of connecting capacitors in series with the induction machine. The SC is switched off at low frequencies and switched on in the upper frequency range, where the pullout torque would be lower than the required torque, if the terminal voltage would not be increased. All three capacitors can be shunted by standard contactors or a circuit-breaker. Fig. 1 shows the variable speed drive with SC IM.

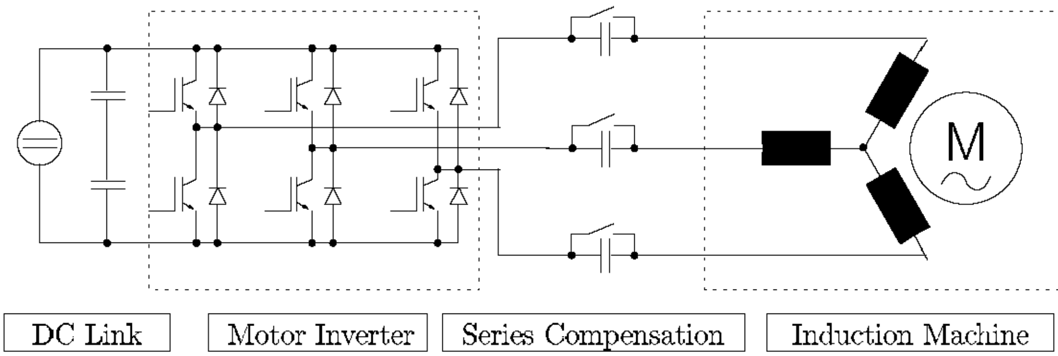

Fig. 1: Series compensated induction motor drive fed by a voltage source inverter.

SC provides several benefits: the design with high inductance leads to a high number of winding-turns, causing a lower effective current at the same armature ampere conductors. Additionally, the current-peaks are reduced. The major benefit from this design is that the converter can become smaller due to lower currents at low frequencies. Further advantages are lower torque ripple and also less noise-production from the drive-system. The capacitors are smaller, lighter and less expensive than accordant reactors.

Performance of the Series Compensation

To analyze the effects of the series capacitor on the steady state behavior of the induction machine, the equivalent circuit diagram, presented in Fig. 2, is considered. The model of the induction machine is well known and derived in literature, e.g. [1].

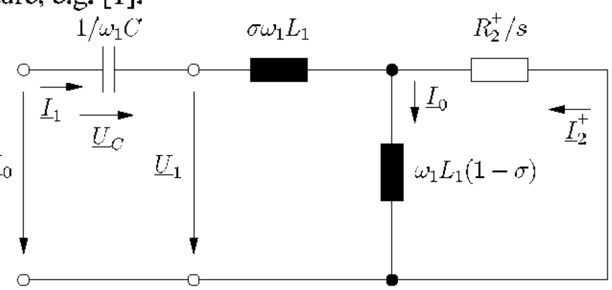

Fig. 2: Equivalent circuit diagram of the series compensated induction motor.

Using the definition of the total leakage factor $1-\sigma = 1/(1+\sigma_1)(1+\sigma_2)$ and the rotor time constant $T_2 = L_2'/R_2'$, the input impedance of the induction machine as a function of stator frequency ω_1 yields

$$\underline{Z}_1 = \frac{\underline{U}_1}{\underline{I}_1} = j \cdot \omega_1 L_1 \left(\sigma + \frac{(1-\sigma)}{1 + j\omega_1 s T_2} \right) . \qquad (1)$$

The ratio of the inverter voltage $\underline{U}_0$ and the terminal voltage $\underline{U}_1$ is defined as:

$$k_{u0}(\omega_1) = \left|\frac{\underline{U}_0}{\underline{U}_1}\right| = \left|1 + \frac{\underline{I}_1}{j\omega C \cdot \underline{U}_1}\right| . \tag{2}$$

Substituting the expressions for the impedance yields the relative voltage

$$k_{u0}(\omega_1) = \left|1 - \frac{1}{\omega_1^2 \cdot L_1 C \cdot \left(\sigma + \dfrac{(1-\sigma)}{1 + j\omega_1 s T_2}\right)}\right| . \tag{3}$$

For a standard traction drive, three different regions in the speed range can be classified: In the base speed range, the torque is limited by the current not exceeding its nominal value. (approx. $1500\,\mathrm{min}^{-1}$ in Fig. 3.) The maximum torque is constant being equal to nominal torque. The adjacent operational area is the field-weakening range. It begins at the nominal point of operation. Starting at this point, torque decreases with $1/n$, resulting in constant power operation. At one point in the field-weakening range (approx. $2750\,\mathrm{min}^{-1}$ in Fig. 3), torque is equal to the pullout torque. Starting at this point, torque is limited by the pullout torque at this voltage, which decreases with $1/n^2$ and is proportional to U_1^2.

Fig. 3 shows the torque of the original machine (Morig), which is considered the required torque for a certain application. If the inductance of the machine is increased, or only a lower input voltage is available, the machine is not capable of delivering the required torque through out the entire speed range (Mred).

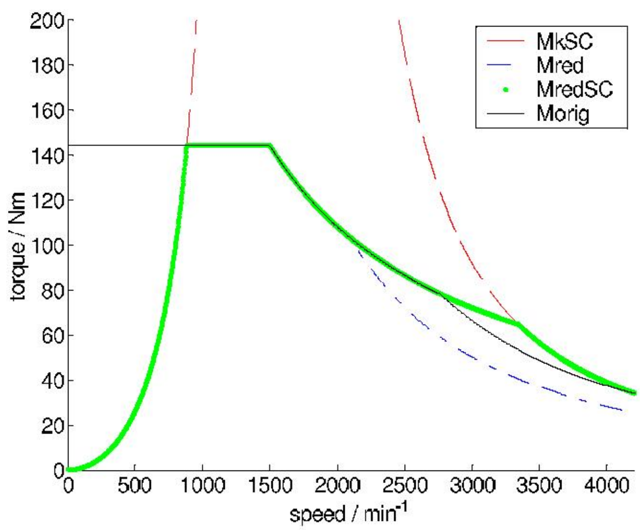

Fig. 3: Operational characteristic of the series compensated induction motor drive.

If SC is applied, the required torque can even be delivered by the machine with increased winding turns. Since pullout torque is proportional to the square of the terminal voltage, the pullout torque with SC (MkSC) is inversely proportional to the square of the relative voltage $k_{u0}(\omega_1)$. As it can be seen from Fig. 3, the SC increases the maximum torque at high frequencies, and decreases it at low frequencies. Thus, the SC is not applied at low frequencies, but it is switched on as required, (approx. $2200\,\mathrm{min}^{-1}$ in this example). The torque of the modified machine achievable with the capacitors switched on, is shown in Fig. 3 (MredSC). It can be seen, that at high speeds the maximum achievable torque exceeds the required torque.

Dimensioning of the Capacitors

The computation of the optimal capacitance is started at the maximum frequency, called ω_b. The factor, by which the inductance is increased, or the DC link voltage is decreased is called ν. Since the reduction due to ν, has to be compensated by the SC at ω_b, the voltage ratio at this frequency is

$$k_{u0}(\omega_b) = \nu \ . \qquad (4)$$

The frequency ω_a, at which the SC has to be switched on, is determined by the intersection of the required or original torque with the pullout torque of the modified machine.

Due to $\left(\sigma + \frac{(1-\sigma)}{1+j\omega_1 s T_2}\right) << 1$ for practical machines, equation (3) can approximated by

$$k_{u0}(\omega_1) = \left| 1 - \frac{1}{\omega_1^2 \cdot L_1 C} \right| \ . \qquad (5)$$

Assuming that ω_b is larger than the resonance frequency $1/\sqrt{L_1 C}$, and solving for C yields

$$C = 1 - \frac{1}{\omega_b^2 \cdot L_1 (1-\nu)} \ . \qquad (6)$$

The next design step is to check, whether it is possible to meet the torque requirement at ω_a. That is, the initially proposed voltage ratio ν can be compensated for, if

$$k_{u0}(\omega_a) \leq 1 \ . \qquad (7)$$

The performance of the SC is evaluated by repeating this procedure for different values of ν. Fig. 4 shows the voltage ratio ν, and the winding turn ratio as a function of capacitance, respectively.

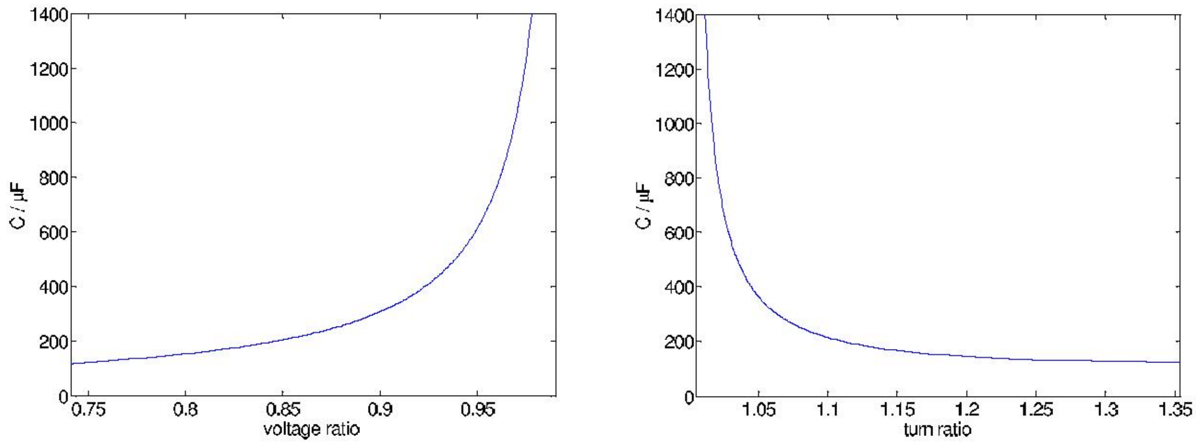

Fig. 4: Voltage ratio $k_{u0}(\omega_1)$ and turn ratio versus capacitance.

These diagrams show, for example, that choosing three 200μF capacitors, the SC can be operated with 15% less voltage. Alternatively, the number of winding turns can be increased by 10%, increasing the inductance of the machine according to the square of the turn ratio. The boundary of the diagrams (voltage ratio = 0.75 and turn ratio = 1.35) represents the limit, up to which it is possible to find a suitable capacitor and to obtain the required torque.

Control of the Series Compensation

Controlling the SC IM involves two major tasks: The first is the control of the transient and steady state operation of the SC, and the second is to switch on and off the SC according to the stator frequency. Oppose its advantages; the SC has one major disadvantage: The additional capacitor adds another energy-storage to the system, and the SC IM may become to operate unstable under certain conditions. Therefore, it is necessary to analyze the stability of the system and to find a stabilizing control scheme if required.

State-Space and Stability Analysis

To perform the analyses, the stator and rotor voltage equations of the squirrel cage IM

$$\begin{pmatrix} u_{d1} \\ u_{q1} \end{pmatrix} = R_1 \begin{pmatrix} i_{d1} \\ i_{q1} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \psi_{d1} \\ \psi_{q1} \end{pmatrix} + \omega_1 \begin{pmatrix} -\psi_{q1} \\ \psi_{d1} \end{pmatrix}, \tag{8}$$

$$\begin{pmatrix} 0 \\ 0 \end{pmatrix} = R_2 \begin{pmatrix} i_{d2} \\ i_{q2} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \psi_{d2} \\ \psi_{q2} \end{pmatrix} + (\omega - \omega_1) \begin{pmatrix} -\psi_{q2} \\ \psi_{d2} \end{pmatrix}, \tag{9}$$

and the capacitor's system equation

$$\frac{d}{dt}\begin{pmatrix} u_{dC} \\ u_{qC} \end{pmatrix} = \frac{1}{C}\begin{pmatrix} i_{d1} \\ i_{q1} \end{pmatrix} + \omega_1 \begin{pmatrix} -u_{qC} \\ u_{dC} \end{pmatrix} \tag{10}$$

are transformed into the state-space representation

$$\frac{d}{dt}x = Ax + Bu \quad \text{and} \quad y = Cx\ . \tag{11}$$

u represents the voltage, i the current, and ψ the flux linkage in the machine. The indices 1, 2 and C label the stator, the rotor and the capacitor, respectively. The angular frequency ω_1 represents the stator frequency and the mechanical velocity is given by ω. The state vector is defined as

$$x = (i_{id}, i_{iq}, \psi_{2d}, \psi_{2q}, u_{Cd}, u_{Cq})^T\ , \tag{12}$$

The input vector u is equal to the stator voltage and the output vector y is the stator current. This transformation yields the system matrix given by

$$A = \begin{pmatrix} -\left(\frac{1}{\sigma T_1} + \frac{1-\sigma}{\sigma T_2}\right) & \omega_1 & \frac{1-\sigma}{\sigma T_2 L_h} & \omega\frac{1-\sigma}{\sigma L_h} & -\frac{1}{\sigma L_h} & 0 \\ -\omega_1 & -\left(\frac{1}{\sigma T_1} + \frac{1-\sigma}{\sigma T_2}\right) & -\omega\frac{1-\sigma}{\sigma L_h} & \frac{1-\sigma}{\sigma T_2 L_h} & 0 & -\frac{1}{\sigma L_h} \\ \frac{L_h}{T_2} & 0 & -\frac{1}{T_2} & -(\omega-\omega_1) & 0 & 0 \\ 0 & \frac{L_h}{T_2} & (\omega-\omega_1) & -\frac{1}{T_2} & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 & \omega_1 \\ 0 & \frac{1}{C} & 0 & 0 & -\omega_1 & 0 \end{pmatrix}, \tag{13}$$

where L_h is the main inductance and T_1 the stator time constant of the machine. Comparing A to the system matrix given in [2], it can be seed, that the upper left 4-by-4 sub matrix is due to the IM itself, and that the bottom two rows and two right most columns are due to the capacitor.

The system stability depends on the eigenvalues of A, determined by

$$\det(A - \lambda I) = 0\ . \tag{14}$$

If all eigenvalues are located in the left half plane, the system is considered to be stable, if one eigenvalue has a positive real component, the excitation of this pole will not decay over time, hence the system is unstable. All four eigenvalues due to the IM are located in the left half plane for all different values of frequency and speed. Thus, the IM itself is stable as expected. However, the poles due to the capacitors may have a positive real component, hence causing the system to be unstable.

The instability of the SC IM due to the self-excitation effect was observed previously [3,4] and is called subsynchronous resonance [5]. A similar phenomenon can occur if a synchronous generator is connected to a power grid, which contains series capacitors for compensation purposes [6].

Due to the drawback of the subsynchronous resonance, the SC IM cannot be operated without an additional measure to stabilize the system. In [5], it was proposed to connect a resistor in parallel with the series capacitor. This however, would cause additional losses, and hence would deteriorate the power efficiency of the drive. Since the SC IM is used together with a voltage source inverter, which is able to impress voltages of variable amplitude and frequency, the idea is to develop a stabilizing control concept, which is subject of the next section.

State-Space and Field-Oriented Control

One popular method to stabilize and unstable system is to use state-space control [7]. This approach is also taken to stabilize the SC IM. The state-space control of the IM by itself has been studied [2, 8]. In these cases, however, the state-space control was proposed for different reasons than stability. For example in [8] the state-space approach was used to construct a control law, which is robust towards parameter uncertainties. In [2] state-space control was studied as an alternative to the standard field-oriented control (FOC) based on PI-controllers. In most industrial and traction drive applications the use of standard FOC has prevailed, due to less effort and satisfactory results of this method.

The basic idea of state-space control is to shift the poles of the closed-loop system to desired positions in the complex plane. For an unstable system, shifting the poles from the right half plane to the left one, means to stabilize the system. If the full state vector of equation (12) is multiplied by a matrix K, and fed back onto the input, the poles are determined by

$$\det(A - BK - \lambda I) = 0 \ . \qquad (15)$$

The choice of K can be made in several different ways [7], e.g. K can be chosen by means of direct pole placement. Another method to determine K, which is called optimal control, equalizes between the control effort and the dynamic response. This method is used to construct the control law for the SC IM.

The state-space representation of the series-compensated induction machine, derived above, is based on a continuous time system. To design a control law, which is implemented in digital hardware, it is necessary to transform the system representation into its equivalent discrete-time form. Therefore, the inverter is modeled as a discrete-time adjustable voltage source with time delay of approximately one sampling period. The delay is due to the computational time lag between obtaining the current measurement at instance k and the voltages being applied by the inverter at instance $k + 1$. The current measurement is considered a zero-order hold-element.

Applying the continuous to discrete transformation to the system of equations (11), the discrete time state-space representation of the SC IM is obtained. The output matrix C is chosen to be

$$C = \begin{pmatrix} 0 & 0 & 1/L_h & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix} . \qquad (16)$$

This is advantageous, because the magnetizing current can be controlled immediately and no separate flux controller is necessary. Considering the inverter a zero-order delay-element, the system is augmented by two additional states, one for each voltage u_d and u_q. The system representation becomes

$$A' = \begin{bmatrix} A_d & B_d \\ 0 & 0 \end{bmatrix}, \qquad B' = \begin{bmatrix} 0 \\ I \end{bmatrix}, \qquad \text{and} \qquad C' = \begin{bmatrix} C & 0 \end{bmatrix}, \qquad (17)$$

where A_d and B_d are the discretized system and input matrix, respectively. In addition to this state augmentation, two additional states are added to perform integral control to achieve steady state precision independent of parameter uncertainties.

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The augmented system becomes

$$A''=\begin{bmatrix} I & C' \\ 0 & A' \end{bmatrix},\; B''=\begin{bmatrix} 0 \\ B' \end{bmatrix}, \quad \text{and} \quad C'=\begin{bmatrix} k_i I & C' \end{bmatrix}, \tag{18}$$

where k_i is the integral gain. The complete state vector is given by

$$x=(e_{i_\mu}, i_{id}, i_{iq}, \psi_{2d}, \psi_{2q}, u_{Cd}, u_{Cq}, u_{0dD}, u_{0qD})^T, \tag{19}$$

where e_{i_μ}, and e_{i_q} represent the integral over the error of i_μ and i_q, respectively. And the delayed stator voltages are stored in u_{0dD}, u_{0qD}.

The basic principles of field-orientation apply to the state-space control, as well. Thus, the three-phase stator currents are transformed onto a two-phase coordinate system. After that these quantities are transformed from the stationary reference frame onto a reference frame rotating with the angular velocity of the rotor flux linkage. The orientation of the coordinate system is chosen, such that the d–axis is aligned with the rotor flux linkage. The control command d- and q-voltages are transformed back to the stationary reference frame, and then back to the three-phase system. To take the inverters time-delay into account, the inverse transformation is performed by adding ω_μ times the sample period. The orientation and the magnitude of the rotor flux linkage are obtained using the same flux model as used in standard field oriented control.

In the derivation of the state-space representation of the SC IM, the non-linearities of the system equations have been linearized by assuming speed and the angular velocity of the rotor flux linkage to be constant. Since the system matrix, and hence the derived feedback gain *K* depends on both these quantities, it is necessary to repeat the computation of *K*, if the speed or the load changes. In this proposed implementation, this is done by means of pre-calculating the values of K and storing them in a look-up table. Therefore, the reference value of the angular velocity of the rotor flux linkage is calculated according to [2] by:

$$\omega_{\mu,ref} = \omega + \frac{i_{1q,ref}}{T_2 \cdot i_{\mu,ref}} \,. \tag{20}$$

Fig. 5 shows the control diagram of the SC IM.

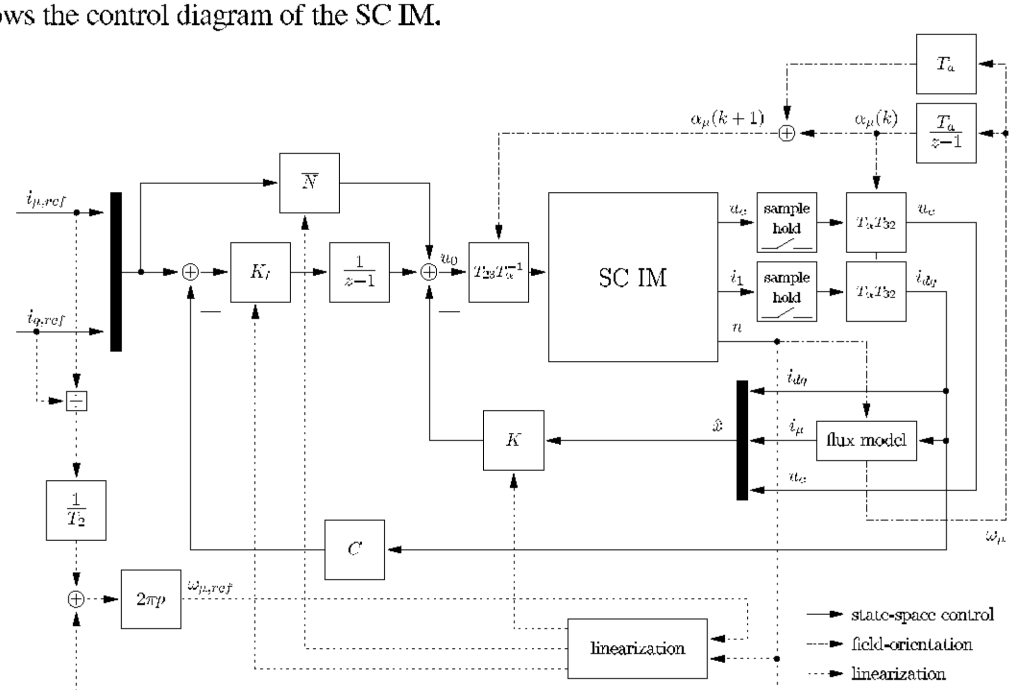

Fig. 5: State Space Control of the SC IM.

Switching of the Capacitors

The operational range, in which the capacitor is used, is determined by the stator frequency. Therefore, the turn-on and turn-off process of the capacitor is initiated by a change of speed. To avoid unnecessary switching, when speed crosses the speed threshold, a hysteresis is applied. The capacitor is switched

$$\text{on, if } n > n_a + \Delta n \text{, and off, if } n < n_a - \Delta n \text{ is true.} \quad (21)$$

The waveforms of signals and quantities during the switching operation are shown in Fig. 6. At $t = t_1$, speed exceeds the threshold value $n_a + \Delta n$. The reference value i_{ref} , which represents both, $i_{\mu,ref}$ and $i_{q,ref}$, is set to zero. Using standard field oriented control, the stator current is controlled to go to zero. The response to this reference steps is sketched in terms of I_1. Note, that in this case, the capacitor voltage U_C is still equal to zero, because the capacitor has been short-circuited so far. At $t = t_2$, current has been reduced sufficiently. Thus, the switching command is given to the isolation breaker and all valves of the inverter are disabled, which means the enable signal is set to zero. The isolation breaker, a mechanical switch, takes the time T_{SW} to be opened completely. Therefore, the operation with capacitor begins at $t = t_3 + T_{SW}$. At this instance, the reference values are reset appropriately and the inverter is enabled again. Now, state-space control is used to increase current and capacitor voltage. At $t = t_4$ steady state is attained, and the induction machine is operated in SC mode. The reference values and the speed may vary according to the desired operation point of the machine. The capacitor is used until, at $t = t_5$, the speed reduces below $n_a - \Delta n$. At this instance, the turn-off process is initiated. It follows the same procedure as the turn-on process. In this case, both, the capacitor voltage and the current are decreased to zero. This is done by setting the reference input of the state-space controller equal to zero.

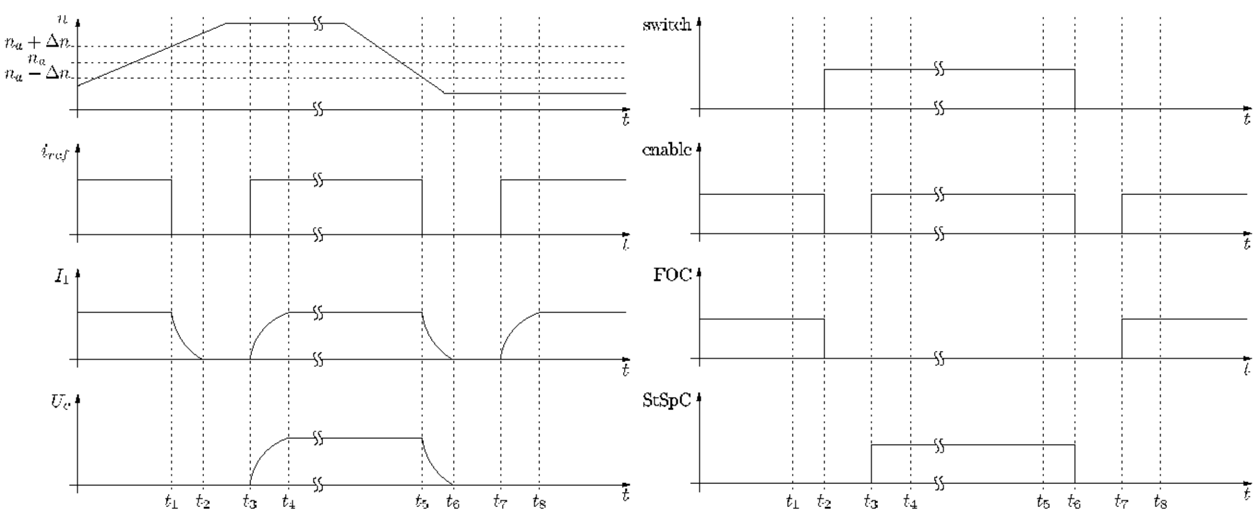

Fig. 6: Waveforms during the switching operation.

Simulation Results

For an immediate comparison between the IM drive with and without SC, a computer simulation is performed. Fig. 7 shows the results from this simulation: torque and voltages vs. speed for both cases. It can be seen that the delivered torque of the SC IM is larger than that of the IM without SC. In addition, Fig. 7 shows the magnitude of the applied voltages. The inverter (and terminal) voltage u without SC is larger than the inverter voltage, if SC is applied (u0 with SC). The terminal voltage u1 with SC is increased due to the series capacitors. Again, this voltage increase yields the additional torque, which can be seen from the simulation. Since the capacitor voltage uC is not in phase with the inverter and terminal voltage, the voltage increase is less than uC.

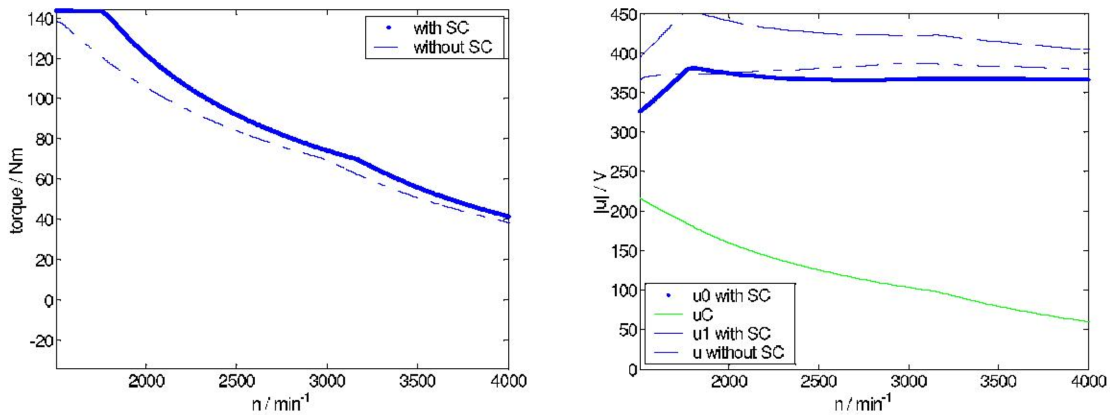

Fig. 7: Torque and voltages vs. speed.

Measurements

To verify the proposed approach, experimental results from a medium power test bench are presented. A 22kW/400V machine together with a standard industry IGBT VSI was used. The control algorithm was implemented on a DS1103 controller board, which was connected to the inverter via an interface board.

Fig. 8 shows the torque during an acceleration and deceleration experiment, which was performed on the test bench. In the lower speed range, the capacitors are short-circuited and standard FOC is applied. At approx. t=9s, the threshold speed is obtained and the reference currents are set to zero, which yields a torque dip. After switching on the SC, the proposed state-space method is used to accelerate the machine to its maximum speed. Starting from this point the deceleration process, during which the SC is switched off, is initiated. For practical application, the switching interval may be reduced to obtain a minimum torque dip.

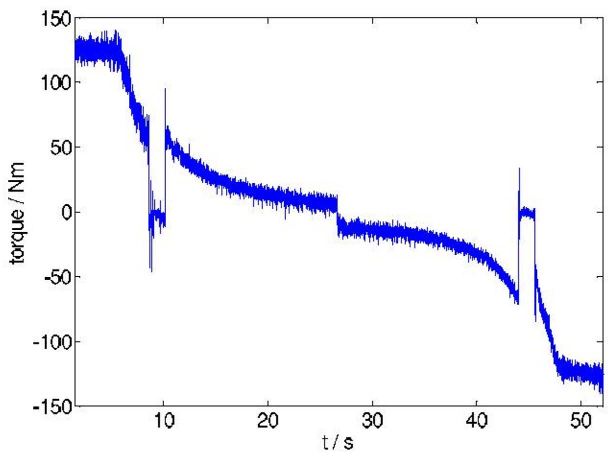

Fig. 8: Torque during acceleration and deceleration of the SC IM.

As it can be seen from Fig. 9, the SC adds almost a pure sinusoidal component to the applied terminal voltage. Since this voltage is not in phase with the inverter voltage, particular attention has to be taken to not exceed the maximum admissible terminal voltage of the machine.

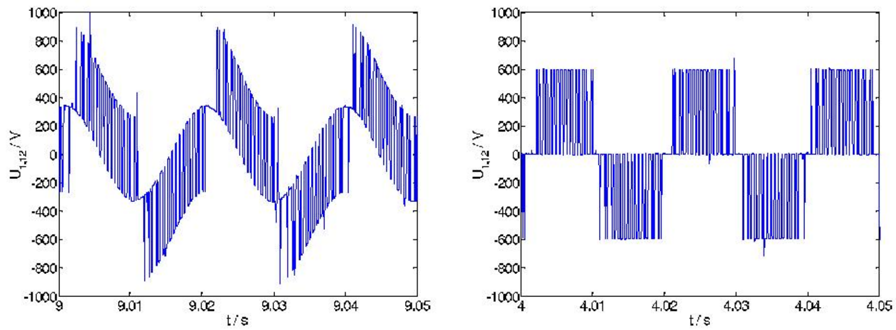

Fig. 9: Terminal voltage waveforms with and without SC.

Application Example

A practical application example is e.g. a Multi-System railway vehicle, which is used at 15/25 kV AC and at 1.5kV DC voltage supply. The DC-link for these drives will be designed for a nominal voltage of e.g. 3kV and so the motors and converter are designed to be used with this DC link voltage. Without additional implementations, such as a step-up-converter or changing the motor circuit at 1,5kV DC much less power is available. Using the SC for the operation at 1.5 kV DC, the power or traction effort can be significantly increased. Thus, the SC is considered an alternative solution for Multi-System railway vehicles.

Summary and Conclusions

The SC of IM has been proposed to overcome the torque reduction at high speeds for traction applications. This can be used either to increase the inductance of the machine, or to use the same machine at a lower DC-link voltage.

The steady state analysis of the SC IM has led to an optimal choice of series capacitor with respect to the maximum torque. Considering the eigenvalues of the system, the unstable nature of the self-excitation effect has been pointed out. To stabilize the system, a state-space control concept has been developed. Measurements demonstrate the effectiveness of the proposed control concept. They show that the proposed concept works throughout the entire operational range.

The proposed control concept uses the measured values of the capacitor voltages. For practical implementations, costs may be reduced by means of implementing a reduced order observer, which estimates the capacitor voltages from the current measurement and the applied inverter voltages.

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