Improved Voltage Sag Ride-Through for Line-Connected Synchronous Machines

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Abstract—**In this paper, the voltage sag ride-through capabilities of the line-connected electrically excited synchronous machine with damper windings (EESM) is investigated. We will design an algorithm for voltage sag ride through by controlling the flux. Two aspects are investigated, first the capability to keep the nominal speed and second the damping of speed oscillations. We will show through simulations that the proposed algorithm has good speed oscillation damping capability and that the ride-through capability is improved.**

Index Terms—**Power quality, Protection and control, Voltage sag ride-through, synchronous machine.**

I. Introduction

VOLTAGE SAGS account for the major part of power quality problems in industry [1]–[5]. Voltage sags may cause machines to trip and generate large costs in stand stills of the plant (industrial site). The voltage sag ride-through capability is therefore of great importance and a better performance should be welcome from the industry's point of view.

Voltage sags are mainly caused by lightning strikes but also animals that have come in contact with the power lines can cause short circuits. The voltage sag duration is the time it takes for the protection circuit to disconnect the faulted line. The remaining voltage is dependent on the proximity to the fault as the power line will act as a voltage divider from the generator to the industrial site and the fault, the farther from the fault the higher the remaining voltage at the industrial site [6]. Line-connected EESMs are used in high-power applications with constant speed, such as blowers in steel mills and refiners in paper plants. For the steel mill it would be disaster if a blast furnace blower should trip due to a voltage sag. The furnace would cool and the steel stiffen and destroy the furnace, with enormous cost as a result [9]. Further, the voltage sag may cause poor quality of the generated product.

In the literature the power quality problems usually concerns adjustable speed drives [2][7][8], which are sensitive to voltage sags.

Line-connected synchronous machines (SMs) are, however, not much investigated. In [9][10], the EESM is investigated and found to be sensitive to voltage sags. Simulations show that there are large current oscillations and torque oscillations for a voltage sag. The complications can be that the settings of the protections may trip the machine when the transient currents are very large, and if the sag is long and severe enough, the EESM will pulled out of synchronism and will not synchronize with the return of voltage. The temperature rise in the rotor due to large currents at start will limit the number of starts per day as the machine must cool down between the attempts, for large machines the number can only be a few per day. Further, the research shows that there are speed oscillations are also generated from the voltage which are dependent of the mechanical dynamics. These conditions will be further displayed in the next section.

Improvement of the voltage sag ride through and minimizing the oscillations would give the machine a longer life and give cost reduction for the industry. In [10] voltage sag ride through is improved by altering the setting of the protective circuits, we will further improve the ride-through capability by design an algorithm for voltage sag ride-through for the line-connected EESM by control of the flux and analyze the performance through simulations.

A. Voltage Sag Induced Complications for the EESM

As mentioned earlier the EESM is sensitive to voltage sags. Seen in Figure 1 is a 3-phase voltage sag with duration of 20 ms to 70% remaining voltage. A variety of complications can occur for the EESM. For a better understanding of the complications given by a voltage sag we will give a short introduction here. Further, we will give different scenarios for the machine system. Starting with the voltage sag induced phenomena, we have

- **Flux oscillations:** The transient voltage drop will generate a DC-flux component in stator coordinates, named stationary reference frame in [11], that will decrease exponentially. With the transformation to synchronous coordinates this DC-flux will be transformed to an oscillating flux part, $\Delta\psi$, circling around the tip of the stationary flux, ψ_s, with the transformation frequency, ω_r, as displayed in Figure 2 and 4. This oscillating flux will in turn generate the following.

1. **Current oscillations:** These oscillations are generated from the flux and are fairly large, see Figure 12, the middle graph. These currents may trigger current limitations and cause a shut down of the machine.
2. **Torque oscillations:** The torque oscillations will also be fairly large, with peak torque a couple of times the nominal. The peak torque during the torque oscillations may give an shaft brake of the machine. For a machine connected to a gear box, the box can be damaged and rendered useless [10]. These things are obviously very costly.

- **Cycle slips:** The voltage sag will increase the load angle, as the available voltage is smaller, and in severe cases the load angle will exceed $\pi/2$ *rad*. The machine will then rotate out of synchronism. This will in turn generate very large transient torques.
- **Return of the voltage:** The transient return of the voltage will generate flux oscillations similar to the voltage drop of the voltage sag. Comparing Figure 3 and Figure 5 we see that, if the voltage return is a multiple of the transformation frequency period time, the oscillating flux part $\Delta\psi$ is minimized, as the flux is aligned with the returning flux, also mentioned by Fredric in [9].
- **Speed oscillations:** The return of the voltage will increase the torque and generate a smaller load angle which will stabilize at nominal speed with oscillations, exponentially decreasing with the systems dynamics.

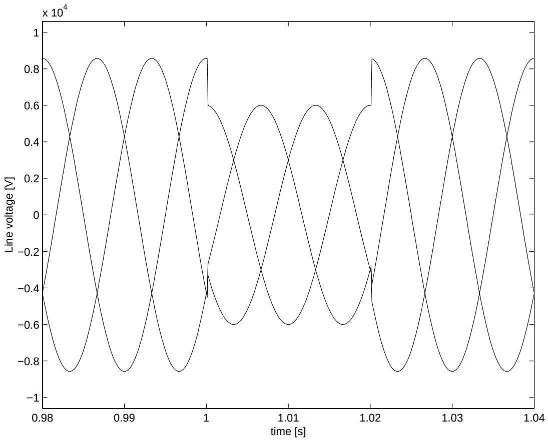

Fig. 1. A 20 ms, 3-phase voltage sag to 70% remaining voltage at 1 s.

Voltage sag ride-through is useful for sensitive systems with large costs for standstills. We will consider cases where the machine will not be damaged (shaft break) from the large transient torque oscillations. For a line-connected machine the following scenarios can be considered [9].

- **Tripping:** The under-voltage protection circuit or the over current protection circuit breaks the supply.
- **Ride-through with plant disturbance:** The machine survives the voltage sag, but the production-line produces a poorer quality of the product.
- **Ride-through with no disturbance:** The voltage sag is small enough and does not disturb the process.

If we can improve the voltage sag ride through capability and minimize the impact from the voltage sag for the line-connected EESM with damper windings, the benefit would be better product and there would be fewer trippings.

II. Voltage Sag Ride–Through with Flux Control

For a synchronous machine connected to the grid, voltage sags and load disturbances will cause oscillations in the speed of the machine. The EESM is usually equipped with a control circuit on the field winding to enable control of either the flux, power factor or reactive power. By extending the control algorithm with a ride-through and speed oscillation damping algorithm we can reduce the wear and tear of the machine.

A. EESM Model

We will work in synchronous coordinates aligned with the rotor flux. The use of synchronous coordinates yields DC-quantities in the steady state. The voltage and flux equations become

$$\boldsymbol{v} = R\boldsymbol{i} + \frac{d\boldsymbol{\psi}}{dt} \quad (1)$$

$$\frac{d\boldsymbol{\psi}}{dt} = L\frac{d\boldsymbol{i}}{dt} + j\omega_r L\boldsymbol{i}. \quad (2)$$

Or in matrix notation

$$\begin{bmatrix} v_f \\ v_D \\ v_d \\ v_q \\ v_Q \end{bmatrix} = \begin{bmatrix} R_f & 0 & 0 & 0 & 0 \\ 0 & R_r & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 \\ 0 & 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_f \\ i_D \\ i_d \\ i_q \\ i_Q \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \psi_f \\ \psi_D \\ \psi_d \\ \psi_q \\ \psi_Q \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \dot\psi_f \\ \dot\psi_D \\ \dot\psi_d \\ \dot\psi_q \\ \dot\psi_Q \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} L_f & L_{md} & L_{md} & 0 & 0 \\ L_{md} & L_D & L_{md} & 0 & 0 \\ L_{md} & L_{md} & L_d & 0 & 0 \\ 0 & 0 & 0 & L_q & L_{mq} \\ 0 & 0 & 0 & L_{mq} & L_Q \end{bmatrix} \begin{bmatrix} i_f \\ i_D \\ i_d \\ i_q \\ i_Q \end{bmatrix}$$

$$+ \omega_r \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -L_q & -L_{mq} \\ L_{md} & L_{md} & L_d & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_f \\ i_D \\ i_d \\ i_q \\ i_Q \end{bmatrix} \quad (4)$$

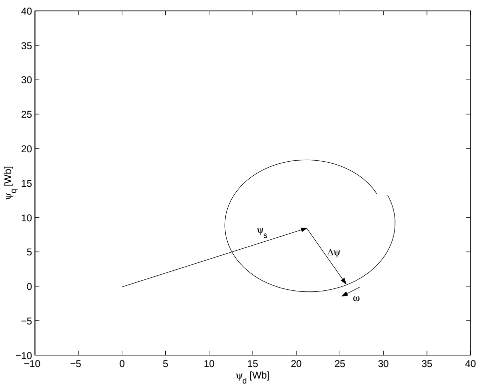

Fig. 2. Stator flux for a 20 ms voltage sag to 70%, showing the first 20 ms.

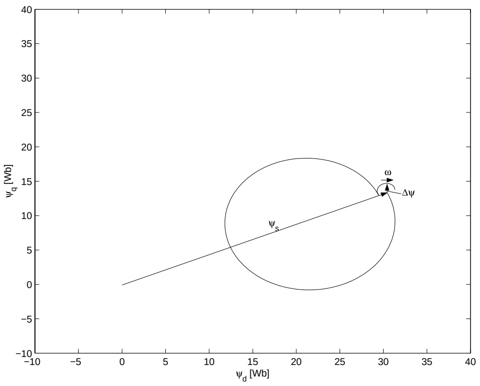

Fig. 3. Stator flux for a 20 ms voltage sag to 70%, showing the first 30 ms.

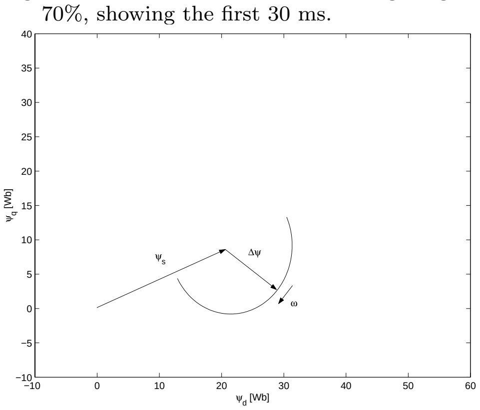

Fig. 4. Stator flux for a 10 ms voltage sag to 70%, showing the first 10 ms.

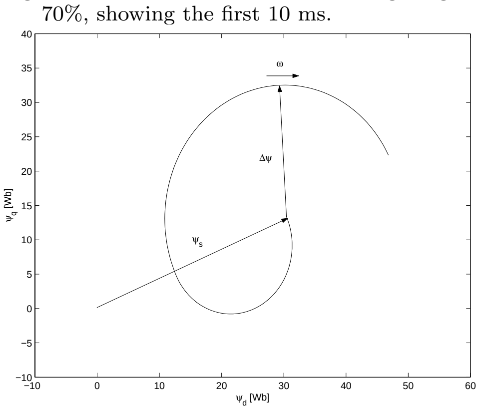

Fig. 5. Stator flux for a 10 ms voltage sag to 70%, showing the first 20 ms.

where

$$\begin{aligned} L_d &= L_{md} + L_{sl},\ L_q = L_{mq} + L_{sl},\ L_Q = L_{mq} + L_{rl} \\ L_D &= L_{md} + L_{rl},\ L_f = L_{md} + L_{fl}. \end{aligned} \quad (5)$$

The electrical torque is given by

$$T_e = \frac{3n_p}{2k^2}\,\mathrm{Im}\{\boldsymbol{\psi}\boldsymbol{i}^*\} = \frac{3n_p}{2k^2}[\psi_d i_q - \psi_q i_d]. \quad (6)$$

We can express the torque by currents only, using the relation, $\psi = Li$, giving

$$T_e = \frac{3n_p}{2k^2}[L_{md}i_f i_q + (L_{md} - L_{mq})i_d i_q + L_{md}i_D i_q - L_{mq}i_d i_Q]. \quad (7)$$

Now we can identify the different parts of the torques: $L_{md}i_f i_q$ is the contribution from the rotor magnetization, $(L_{md} - L_{mq})i_d i_q$ is the reluctance torque, due to the difference in parameters in d and q direction, and the two last parts are the contributions from the damper windings. The mechanical dynamics are described by

$$\frac{J}{n_p}\frac{d\omega_r}{dt} = T_e - T_l - b\omega_r \quad (8)$$

where b is the viscous damping constant, and the load torque $T_l = k\omega_r^2$, is modelled for a fan.

B. Voltage Sag Ride-Through Algorithm

The flux control consists of a PI-current controller, with an option for reactive or power-factor control. For the design we have used IMC-design [12]. The speed oscillations of the EESM for voltage sags can be reduced if we can control the torque fast enough through the flux control, in order to cancel the oscillations. The field circuit is fairly slow; therefore the fast torque oscillations are not possible to cancel with reasonable field voltages. Slower speed oscillations are, however, possible to cancel with the field control circuit. The proposed algorithm requires a speed sensor for the oscillation detection. The extra cost for this sensor is, however, small in comparison to the machine.

B.1 Setpoint Adjustment

For nominal speeds without speed oscillations, the flux should be nominal, and the torque should be decreased if the speed is higher than nominal, and increased if the speed is lower. This means that we should increase the flux if the speed is lower than nominal and decrease the flux if the speed is higher than nominal. This gives us the following setpoint adjustment:

$$\psi = \psi_0 + k_{1\psi}(\omega_1 - \omega_r) \quad (9)$$

where ω_1 is the line frequency and $k_{1\psi}$ is the gain for the damping algorithm. As we see, the flux will reset itself to nominal as the speed is returned to nominal. Now for the setpoint $i_f L_f = \psi_0$ we get

$$i_f^{\mathrm{ref}} = \underbrace{\frac{\psi_0}{L_f}}_{i_0} + k_\psi(\omega_1 - \omega_r). \tag{10}$$

The flux control bandwidth $\alpha_f \approx 11\ rad/s$ and setpoint adjustment gain $k_\psi \approx 3000$. The system is depicted in Figure 6, where $F(p)$ is the PI-controller, $G(p)$ is the EESM

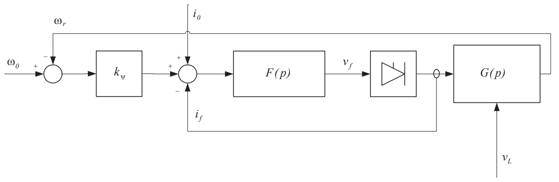

Fig. 6. Block diagram of the voltage sag ride-through algorithm.

and V_L is the line voltage.

III. Implementation Issues

For power factor and reactive power control, i_f^{ref} should not be directly controlled, rather $i_0 = \psi_0/L_f$, as these are equal when $\omega_r = \omega_1$. Although the proposed algorithm gives a better ride through capability, the load angle should be monitored to detect a pull out of synchronism for the machine. If the machine is pulled out of synchronism, either of these two things should be done:

- Turn off the flux, wait for the voltage return and wait further a couple of seconds. Then activate the field control system for re-synchronization.
- Shut down the process and restart after voltage return.

Considerations for deep and long duration voltage sags have to be taken in order *not* to burn the field winding as the field current may become very large.

IV. Simulations

Simulations have been made on a 3.6-MW 4-pole EESM with damper windings fed by 10.5 kV and 225 A current. The field winding is originally fed by 38 V and 417 A, so $i_0 = 417$ A. The controller bandwidth $\alpha = 11$ rad/sec and $k_\psi = 3000$. The load has been modelled as a fan load. The behavior is similar for a constant load torque, not shown here.

A. Directly Fed Field Circuit

The EESMs field winding can either be excited directly by slip rings or by a brush-less feeder. The difference is that the directly fed excitation can handle both positive and negative voltage, whereas the brush-less feeder can only handle positive field voltage. The possibility of using both positive and negative voltage increase the control range and give a better speed oscillation damping.

Here we simulate a common load such as a blower in a steel mill, or a compressor.

In Figure 7 a simulation of a three-phase voltage sag to 70% remaining voltage for 200 ms, is shown indicating that the proposed algorithm has good oscillation damping and faster ride-through than the undamped system, for which the speed is oscillating around the nominal speed.

For severe voltage sags, Figure 8 shows a voltage sag to 20% remaining voltage. The proposed algorithm improves the ride-through capability by keeping a higher speed, while the system loses synchronism without the proposed algorithm. The load torque is too large for the machine to re-synchronize if the machine's synchronization is lost.

B. Brush-Less Feeder with Rectifier in the Field Circuit

The brush-less feeder is a small synchronous generator with a DC-stator circuit and a three phase rotor circuit. The rotor voltage is rectified with a 6-pulse diode-bridge feeding the field circuit. The simulation of the feeder is simplified to a rectified positive voltage.

In Figure 9 a simulation of a three-phase voltage sag to 70% remaining voltage for 200 ms, where the field voltage is restricted to be positive, simulating a brush-less feeder with a rectifier circuit in the rotor circuit, as we can see the oscillation damping is good and the flux is increased faster than it is lowered because of the restriction of the negative field voltage.

For severe voltage sags, Figure 10 shows a voltage sag to 20% remaining voltage. The proposed algorithm improves the ride-through capability by keeping a higher speed, while the system loses synchronism without the proposed algorithm. The speed oscillations are rather larger, much larger than for the case with directly fed field circuit. This is expected as the dampening of the overshoot is smaller. The flux is restricted to simulate saturation of the flux. The load torque is too large for the machine to re-synchronize if the machine's synchronization is lost.

C. Impact of Voltage Restriction

The field circuit is a fairly weak circuit with a power of a couple of percents of the total power, therefore it is necessary to restrict the voltage from the control system. The impact of voltage restriction is that the voltage sag induced speed drop is larger and the speed oscillations become larger. Figure 11 showing voltage restrictions of 400 V. 200 V and 100 V, for a 200 ms voltage sag to 50 % remaining voltage and the speed drop and speed oscillations are approximately equal for 200- and 400 V voltage restriction, and for the hardest restriction the speed drop and speed oscillations are significantly larger. The performance is however better than the system without the proposed algorithm.

D. Voltage Sag Ride-Through Failure

Figure 12 shows a voltage sag ride-through failure for the proposed algorithm. As we can see, for a severe voltage sag with long duration the machine will run out of synchronism for the proposed algorithm. Further the currents become very large when the machine is out of synchronism. The machine will not synchronize when the voltage returns. This implies that, monitoring of the load angle is necessary for detection of voltage sag failure.

V. Conclusion

The algorithm has proved successful for voltage sag ride-through with flux control. The research of [9] shows that voltage sag ride–through for a EESM can be obtained down to 55 % remaining voltage up to 150 ms, by altering the settings of the protection circuits. This will, however, even if successful, generate large speed oscillations. The conclusions of the proposed algorithm are:

- The speed oscillations generated by voltage sags are significantly reduced. This will reduce the stress of the machine and give the machine a longer life.
- The speed drop for voltage sags are significantly reduced.
- The ride-through capability for severe sags is enhanced.
- The load angle should be monitored for detection of pull out of synchronism.
- Voltage restriction of the flux controller generate larger speed oscillations, but the performance is enhanced, even for a strict boundary.

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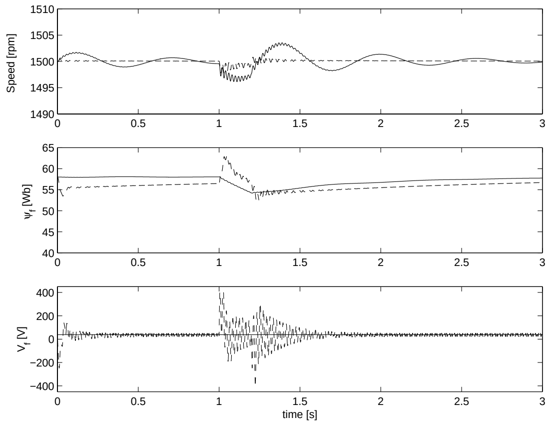

Fig. 7. Simulation of a voltage sag to 70% remaining voltage for a synchronous machine with damper windings, showing the speed (upper graph), flux (middle) and field voltage (bottom) with constant field voltage (solid) and the proposed algorithm (dashed).

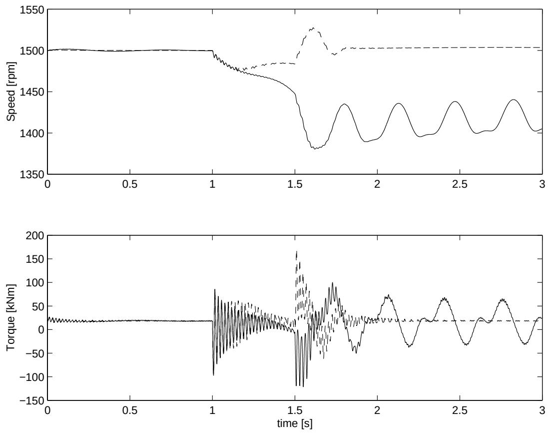

Fig. 8. Simulation of a voltage sag to 20 % remaining voltage for 500 ms for the proposed algorithm (dashed) and with a constant field voltage (solid). The top figure shows the speed and the bottom figure shows the electrical torque.

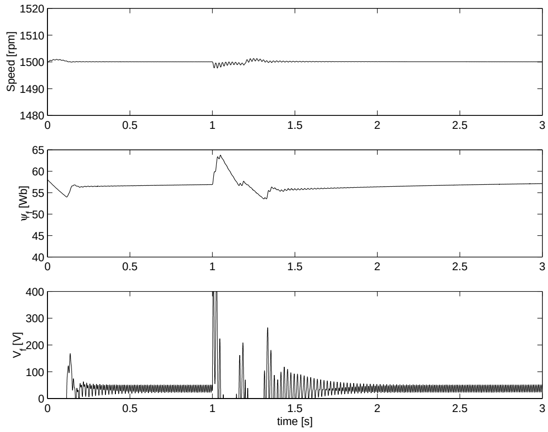

Fig. 9. Simulation of a voltage sag to 70% remaining voltage for a synchronous machine with damper windings with a brush less feeder,, showing the speed (upper graph), flux (middle) and field voltage (bottom) with constant field voltage (solid) and the proposed algorithm (dashed).

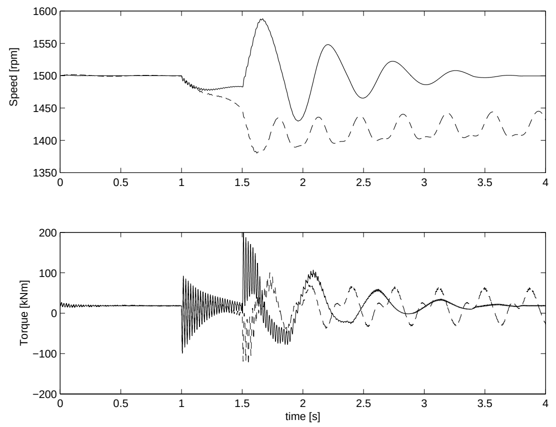

Fig. 10. Simulation of a voltage sag to 20 % remaining voltage for 500 ms for the proposed algorithm (dashed) and with a constant field voltage (solid), concerning an EESM with a brush less feeder. The top figure shows the speed and the bottom figure shows the electrical torque.

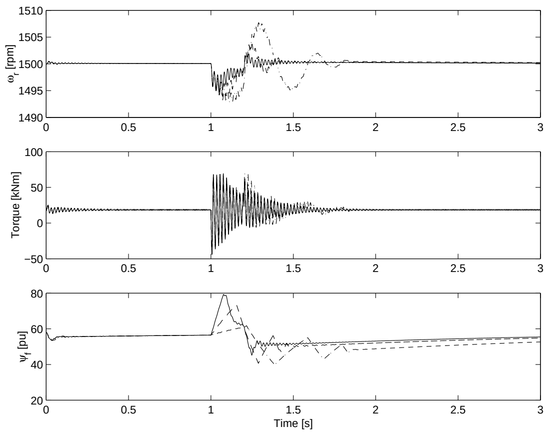

Fig. 11. Simulation of a voltage sag to 50 % remaining voltage for 200 ms for the proposed algorithm, showing machine speed (upper), electrical torque (middle) and ψ_f (lower), for voltage restriction of 400 V (full), 200 V (dashed) and 100 V (dash-dotted).

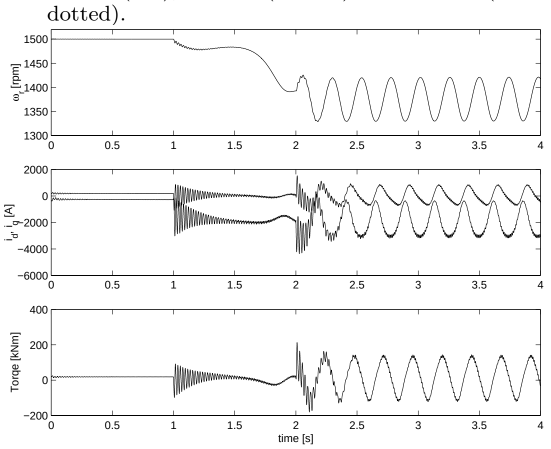

Fig. 12. Simulation of a voltage sag to 20 % remaining voltage for 1s for the proposed algorithm, showing machine speed (upper), stator currents (middle) and electrical torque (lower).

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