Controled AC Drives
with Ride-Through Capability at Power Interruption

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Abstract — **General purpose PWM inverter drives are equipped with an undervoltage protection mechanism, causing the system to shut down within a few milliseconds after a power interruption in the mains. This may entail loss or damage of material in such critical applications as the production of textile fibers, paper, or with extruder drives. The proposed solution to this problem is to recover some of the mechanical energy stored in the rotating masses. When a power interruption occurs, a sequence of fast feedforward commands is applied to force an immediate transition into the regeneration mode. During the interrupt interval, the drive system continues to operate at almost zero torque, just regenerating a minor amount of power to cover the electrical losses in the inverter. The method is implemented in an additional software package to be used with general purpose inverter drives of limited dynamic performance. Experimental results are presented.**

1. Introduction

Variable speed ac drives using a PWM controlled induction motor fed from a constant voltage dc link circuit have matured as a standard drive technology for a wide range of industrial applications. In this system, the amount of energy stored in the dc link capacitor is relatively small. When the supply of power is interrupted, the dc link energy is absorbed by the motor load within a few milliseconds. Since the electronic control system loses power as well, the inverter must be shut down by an undervoltage protection scheme in order to avoid ill-defined operating conditions and possible damage to the power semiconductors. The machine gets deenergized, but continues rotating for some more time owing to the inertia of the mechanical system.

Many electrically driven production plants will tolerate a temporary reduction of operating speed and resume normal operation if acceleration to the commanded speed value could take place as soon as the supply of power returns. This, however, is not possible as the inverter control, once deactivated, has lost synchronization with the rotating machine. An air-gap flux wave may be still in existence in the machine, but its magnitude and phase angle, as well as its rotational speed keep changing. The required inverter settings for stator voltage and frequency are therefore un-

known. Restarting the inverter with inadequate settings would necessarily produce current transients, however no substantial average torque. The inverter will operate in the current limiting mode for a longer period of time without really accelerating, and will eventually trip again.

It is therefore required to wait until the machine has come to a complete standstill. *Baader et al.* [1] describe how the time for deceleration can be reduced by operating the induction motor in the dc breaking mode and how standstill can be subsequently detected to enable restarting.

Deceleration to zero speed and restarting following a power interruption of only a fraction of the fundamental period is obviously not an adequate solution. Many continuous production processes in the paper and textile industry are sensitive to larger variations in operating speed. Especially multi-motor drives will lose synchronization with each other which makes it extremely difficult to counteract power interruptions. The resulting shut-down of a production line may entail loss or damage of material. Also the time and additional workload required to get a plant ready for restart may be considerable. Such economic losses can be avoided by using inverter drives with a ride-through capability for critical production processes.

This paper discusses the design concept for a tripless general purpose inverter drive which maintains operation even when there are power interruptions of several seconds and more.
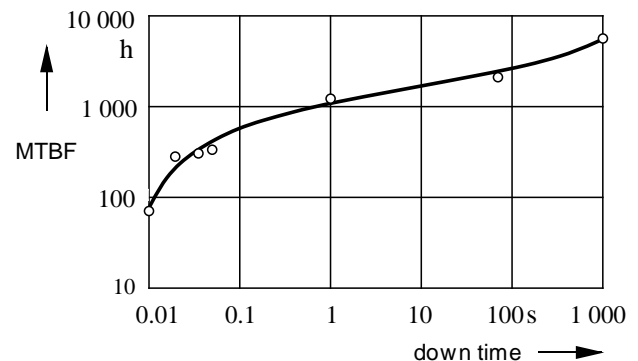

Fig. 1: Mean time between failures (MTBF) versus down time of the public power supply (according to [2])
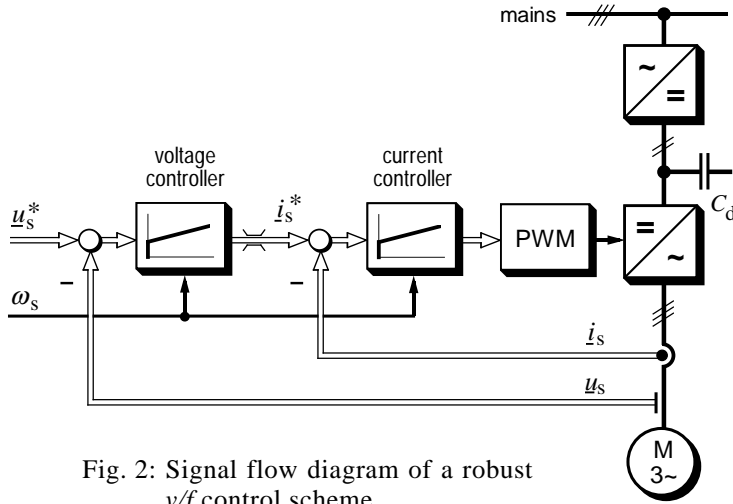

Fig. 2: Signal flow diagram of a robust
v/f control scheme

2. Reenergizing a Running Machine

The availability of electrical power from the public supply as a function of the down time at interruptions is given in [2]. The data are displayed in Fig. 1. They indicate that a power interruption of more than 10 ms duration is likely to occur every 200 h, on average. Against this, MTBF values for power converters are of the order of several 10 000 hours. Short time interruptions of the power supply are therefore the most frequent cause for inverter tripping.
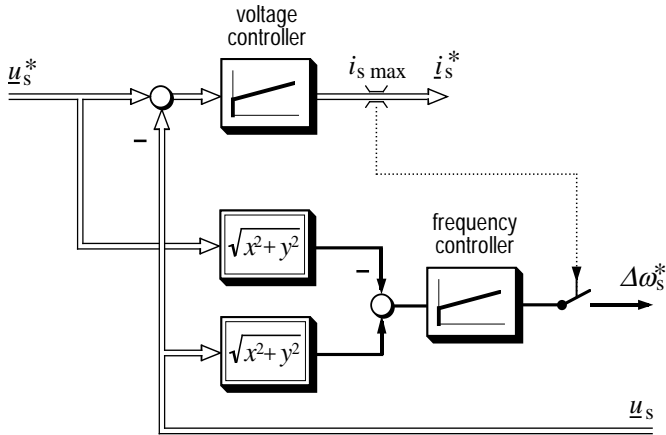

Fig. 3: Generation of a modifying stator frequency signal
for the resynchronization of a running machine

A first proposal to avoid the standstill interval following a power interruption was made by *Seibel et al.* [3]. It is applicable to general purpose inverters with moderate dynamic requirements. The structure is shown in Fig. 2, in which in inner control loop for the stator currents receives its reference signals from a superimposed voltage control loop. The voltage reference is derived from the speed reference via an acceleration/deceleration limiter, the output of which also controls the stator frequency. The voltage as

well as the current regulator, both processing complex signals, comprise of an inner oscillator which is controlled to run at frequency ω_s. The oscillators are formed by cross-coupling the integrator channels for the real and imaginary component of the respective space vector signal.

This kind of control structure was primarily designed for limiting the inverter currents at overload [4]. The scheme was then extended with a view to handle impact loads without inverter tripping [3].

The operation is as follows. A sudden rise of the load torque increases the slip and the stator currents of the machine. The reference signal of the current control loop is eventually pushed against its limit. This causes the machine voltage to reduce below its setpoint, owing to the low impedance of the motor. The signal flow diagram Fig. 3 shows that such difference in amplitudes between the voltage reference and the actual voltage acts upon another PI controller, which in turn reduces the stator frequency command whenever current limiting occurs. The speed drops until the load torque returns to a normal value.

Its sensitivity to the machine impedance makes this scheme suitable to handle also power interruptions. The inverter will immediately trip in such event, and the machine will deenergize and then gradually reduce its speed. On return of the supply power, the inverter resumes operation at the same voltage and frequency settings that had prevailed before the interruption. Current transients will occur at the moment of reconnection, as the space vector of the back emf is quite different from that of the applied stator voltage. Overcurrent limiting will initiate and subsist even after the transients have died out. This is because the mismatch between stator frequency and speed reduces the machine impedance to values below normal. The low impedance enables the stator frequency reduction mechanism in Fig. 3 until slip returns to its nominal value, and flux and torque build up again.

Experiments by *Seibel* [3] demonstrate a case where the motor speed drops to 50% of its original value following a 150 ms power interruption. Resynchronization and acceleration to the commanded speed value takes about 4 seconds.

Although this scheme can restart a running machine following a short interruption of power, the time required for resynchronization may appear too long for many critical loads. The problem becomes even more severe with multi-motor drives. The individual motors are likely to assume different speeds during the power fail interval and the ensuing resynchronization period.

The following paragraph describes a concept enabling ride-through at short power interruptions with insignificant drop in speed.

3. Fast Ride-Through at Power Interruption

3.1 Principle of operation

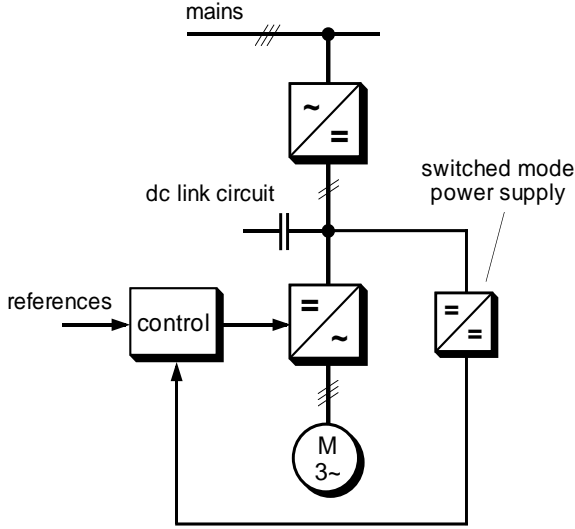While the amount of stored energy in the dc link capaci-

Fig. 4: Block diagram of an inverter drive with ride-through capability

tor is normally not sufficient to maintain the inverter active during a short power fail interval, the kinetic energy of the rotating masses of the motor and the driven plant is substantially higher. This reservoir can be tapped for the purpose of bridging the time interval of power interruption [5]. The approach requires that the inverter does not trip in the event of a power failure, but is maintained operating. A fast reversal of the machine operation from motoring to generating mode is then commanded. Energy is fed back from the rotating masses to the dc link circuit so as to maintain the dc link voltage at a preset level. This is possible also in the presence of additional loads connected to the dc link. In particular, the supply of power to the electronic control circuits of the inverter must continue without interruption so as to maintain the system in operation. The required power can be taken from the dc link circuit. Modern inverters usually employ switched mode power supplies having a separate dc link circuit supplied through a rectifier from one phase of the mains. The rectifier is abolished and the electronic power supply is alimented from the dc link circuit of the inverter, as shown in Fig. 4. In this way, continuous operation of the electronic control is ensured, provided the dc link voltage does not sag too much.

3.2 Reversal of power flow by closed loop control

The principle of forcing a fast reversal of power flow following a breakdown of the supply voltage is explained with reference to Fig. 5. The dc link voltage u_d is normally permitted to change within certain limits as indicated by the hatched band in this figure. The width of the band allows for residual harmonic ripple, fluctuations of the supply voltage, and load dependant voltage sags.

It is assumed that the supply power is interrupted at $t = t_0$. The drive continues operating, maintaining its torque and speed values as commanded since the inverter control provides the adequate adjustments to compensate for the

reduction of the dc link voltage. The power interruption is detected at t_1 when the dc link voltage reaches a predetermined level $a \cdot u_{dN}$, where u_{dN} is the nominal value of the dc link voltage and $a < 1$. The lower trace of Fig. 5 shows a logic signal indicating the detected event of power interruption. If the inverter control did not react to this signal, the link voltage would continue reducing as indicated by the dotted line, and the inverter would be shut down by the undervoltage protection at the voltage level $u_d < b \cdot u_{dN}$, where $b < a$.

During the interval $t_1 \ldots t_2$, the drive power is exclusively drawn from the dc link capacitor C_d, and hence the maximum duration of this interval can be determined by solving

$$\frac{1}{2} C_d \left[(a \cdot u_{dN})^2 - (b \cdot u_{dN})^2 \right] = \int_{t_1}^{t_2} p_d(t), \qquad (1)$$

where $p_d(t)$ is the power consumed by the load, which is approximately equal to the mechanical power at the motor shaft.

In the worst case, $p_d(t)$ equals the nominal inverter load p_{dN}. The minimum time for the inverter to trip after a power interruption is then

$$t_{min} = \frac{1}{2} C_d \cdot \frac{(a \cdot u_{dN})^2 - (b \cdot u_{dN})^2}{p_{dN}}. \qquad (2)$$

Typical values of t_{min} are of the order of several 10 ms.

Naturally, the ride-through mechanism must become effective before t_{min} has elapsed. It overrides the regular drive control in order to reduce and reverse the power flow from the dc link circuit to the machine. Fig. 5 shows that the dc link voltage starts rising again at $t > t_3$. Thereafter, the voltage is maintained by closed loop control at a level slightly lower than its lower limit for normal operation from the power supply.

The time interval with the dc voltage control engaged is $t_3 \ldots t_4$. It ends when the supply power returns, at which instant the dc link circuit is automatically reconnected to the mains through the front-end converter. The return of
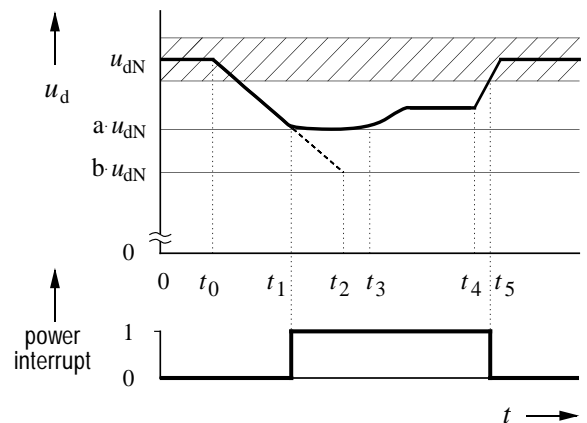

Fig. 5: Voltage of the dc link during a power interruption

Fig. 6: Ride-through scheme with field oriented control

power is detected a little later at t_5, and the logic signal indicating power interruption is reset. This reactivates the regular drive control which compensates the loss of speed incurred during the interrupt period by accelerating the motor to the commanded speed value.

The ride-through procedure is critical in that it requires a fast torque control scheme for power reversal. The well-known principle of field orientation [6] could be employed here. The torque reference is temporarily switched from the regular speed controller to a superimposed regulator for the dc link voltage, whenever the logic signal indicating power interruption is true. This concept is illustrated in the signal flow diagram Fig. 6. Note that a positive torque decreases the dc link voltage, and hence the sign of the error signal in this loop apppears reversed.

The practical application of a ride-through scheme with closed loop torque control based on field orientation is impeded by the higher cost of such system as compared with a general purpose drive. Especially in the low and medium power range, the percentage of cost for the electronic control as referred to the total cost of the inverter is relatively high. General purpose drives have a simpler and cheaper control hardware. They are preferred whenever their reduced dynamic performance satisfies the requirements.

These considerations make another approach attractive which incorporates ride-through performance into the simpler control structure of general purpose inverters.

3.3 Control structure of a general purpose inverter

The structure of the general purpose inverter to be considered here [7, 8] is shown in the signal flow diagram Fig. 7.

The magnitude u_s* of the stator voltage reference is formed as the sum of two signals: The first signal is derived from a function generator to be proportional to the stator frequency ω_s in the base speed range and constant at field weakening, while a minimum voltage level is maintained at low speed for high starting torque. The second signal compensates for the voltage drop across the stator resistor. The compensation produces the effect that the stator flux vector is forced on a determined trajectory, assuming desired values of magnitude and angular velocity which are independent of the load. This leads to a partial dynamic decoupling of the machine structure and ensures better dynamic performance than the regular v/f control method [9].

To minimize computation time, only the active component i_{sp} of the stator current is used for the compensation. The approximation has almost no effect on the magnitude of the stator flux vector, while the influence on the phase angle is negligible. The active stator current component is computed as

$$i_{sp} = i_{s\alpha} \cos \alpha_u + i_{s\beta} \sin \alpha_u, \qquad (3)$$

where α is the phase angle of the stator voltage vector, and $i_{s\alpha}$ and $i_{s\beta}$ are the respective components of the stator current in stator coordinates.

Since the stator flux vector is forced on a circular trajectory of given diameter, the active current i_{sp}, and hence the machine torque follow the rotor frequency fairly fast, being only delayed by the transient rotor time constant $T_{r\sigma}'$ of the machine. Accordingly, a PI controller for the active current is provided in the structure Fig. 7, which changes the stator frequency, and the rotor frequency accordingly. A speed control loop is superimposed. The actual speed is estimated from the stator frequency and the rotor frequency signals, the latter being computed from the active current i_{sp}.

3.4 Reversal of power flow by open loop control

This ride-through method is based on applying a sequence of fast feedforward commands following the detection of a power interruption. The feedforward signals are

Fig. 7: Signal flow diagram of a general purpose inverter

parameter dependent and may not always exactly bring the machine to the desired state of operation, owing to inaccurate settings, or to changes of the system parameters. Therefore, additional closed loop control must take over following the first fast control signals. The required accuracy is achieved at low dynamic performance, in accordance with the limited performance of general purpose inverters.

The method is described considering three different time intervals. The indicated timings are referred to the graph in Fig. 5.

Interval I

The power interruption is detected at t_1 from the sag of the dc link voltage. In this moment, the gate control signals of the inverter are inhibited. The phase currents of the machine continue flowing. Depending on their respective direction, they pass through one of the inverter flyback diodes of the associated halfbridge. This automatically forces a stator voltage on the machine windings which is described by the space vector

$$\underline{u}_s = \frac{2}{3}\Big[sign(i_a(t_1)) + a \cdot sign(i_b(t_1)) + a^2 \cdot sign(i_c(t_1))\Big] \quad (4)$$

where $a = exp\,(j\,2\pi/3)$. The stator current vector will subsequently change according to

$$\frac{d\underline{i}_s}{dt} = \frac{\underline{u}_s - \underline{u}_i}{l_\sigma}. \quad (5)$$

The stator resistance is neglected in this equation. $\underline{u}_i$ is the back emf vector.

According to (4) and (5), the rate of decay of the stator current vector depends largely on the operating condition of the machine prior to the interruption of power. Fig. 8 illustrates a situation where the power fails while the machine is operated at 60% nominal speed and about nominal torque. The interpretation of this diagram shows that the stator voltage vector resulting from inhibiting the inverter control will alway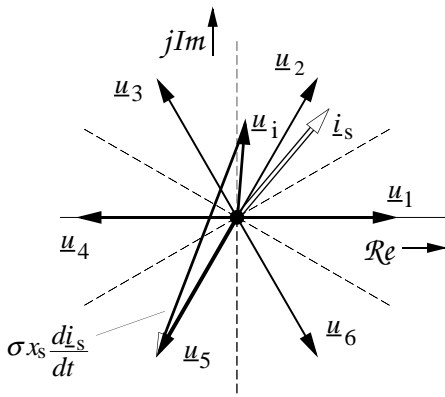s ensure a rapid decay of the stator currents. During this process, a major portion of the magnetic energy stored in the leakage fields of the machine is returned to the dc link circuit, while the rest is converted to mechanical power. In effect, the stator cur-

Fig. 8: Space vector diagram at the beginning of interval I

Fig 9: Idealized trajectories of the stator current space vector during interval II
a) fast, and
b) gradual increase of the stator voltage

rents will be forced to zero in minimum time.

Interval II

This interval starts with a fixed delay of 1 ... 2 ms after the power interruption. Since the sampling period of the microprocessor in a general purpose inverter drive is typically around 500 Hz, the time duration of interval I is about 2 ms. The ensuing interval II is very short, too, and hence speed and rotor flux magnitude can be considered constant during this interval. The stator currents being zero, the induced voltage which appears at the machine terminals is

$$\underline{u}_i(t) = \underline{u}_i(t_1) \cdot exp\big(j\omega(t_1) \cdot (t - t_1)\big), \quad (6)$$

where ω is the mechanical speed of the representative two-pole machine under consideration. The initial value $\underline{u}_i(t_1)$ in (6) can be computed from those values of the voltage reference $\underline{u}_s{}^*(t_1)$, the stator current vector $\underline{i}_s(t_1)$, and the stator frequency $\omega_s(t_1)$ that existed at the time of power interruption:

$$\underline{u}_i(t_1) = \underline{u}_s{}^*(t_1) - \big(r_s + j\omega_s(t_1)l_\sigma\big) \cdot \underline{i}_s(t_1). \quad (7)$$

Since accuracy is not a predominant requirement for the following commands, (7) can be as well approximated by

$$\underline{u}_i(t_1) \approx \underline{u}_s{}^*(t_1) - j\omega_s(t_1)l_\sigma \cdot i_{sp}(t_1). \quad (8)$$

The firing signals of the inverter are enabled next, in order to establish a magnetizing current in the machine. To avoid current transients, the pulsewidth modulator starts operating with the reference voltage setting

$$\underline{u}_s{}^*(t) = \underline{u}_i(t), \quad (9)$$

where $\underline{u}_i(t)$ is given by (6) and $\underline{u}_i(t_1)$ is approximated by (8). The magnitude of the reference voltage is then gradually increased to the value $u_s(\omega_s)$, as determined by the volts per hertz characteristic of the drive. The gradient of the changing reference voltage is fixed and predetermined such that no major transients occur. Fig. 9 shows the idealized trajectories of the stator current space vector for fast and for gradual increase of the stator voltage.

At the end of interval II, the machine has built up nominal air-gap flux, but its torque is still zero.
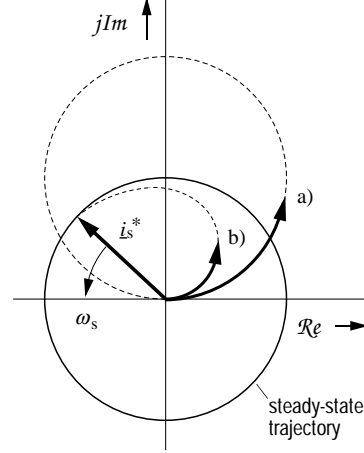
Fig. 10: Signal flow structure during interval III: control of the dc link voltage

Interval III

The machine has come close to steady-state no-load operation by the aforementioned feedforward manipulations. A minor change of this operating condition is now required to feed a small amount of power through the inverter into the dc link, just sufficient to maintain the dc link voltage at a predetermined level. The required power accounts for the inverter losses and the power consumed by the electronic inverter control.

To achieve this, the control structure of Fig. 10 is established, in which a PI controller for the dc link voltage is now superimposed to the control loop of the active stator current. The output of the dc link voltage controller represents the charging current of the dc link capacitor C_d. This signal is divided by the modulation index to obtain the active current reference i_{sp}^* on the machine side of the inverter. The signal is limited to prevent overload.

The output signals of both PI controllers are initially held at zero. At the beginning of interval III, u_d^* is higher than u_d. Hence, the reference signals i_{sp}^* and ω_r^* will start decreasing from zero to negative values as soon as the PI controllers are enabled. This adds a negative rotor frequency signal ω_r^* of increasing magnitude to the no-load value $\omega_s(t_1)$ of the stator frequency. Torque in the generating mode is smoothly built up, and the dc link capacitor is charged to the commanded voltage.

3.4 Return of the supply power

The supply power returns at $t = t_4$, Fig. 5. The event is detected at t_5, when the dc link voltage crosses the lower limit of the regular voltage range. The signal flow structure of Fig. 7 is then reestablished. The drive accelerates to the commanded speed.

4. Performance

The ride-through scheme was primarily developed for applications in the textile industry. It was later implemented in a family of general purpose inverters for the power range of 11 - 90 kW which is now in series production.

The inverter control is based on the 16-bit microcomputer INTEL 80 186. The software performs pulsewidth modulation, generation of the stator flux trajectory based on a voltage/frequency characteristic, control of the active component of the stator current, speed estimation and speed control, torque and overcurrent limiting, protection and user interface. The sampling rate is 500 Hz, at which frequency the control algorithms for active stator current, speed and dc link voltage are executed.

4.1 Control method I

The oscillogram Fig. 11 shows the active current component i_{sp} and the dc link voltage u_d

Fig. 11: a) Active stator current i_{sp} and dc link voltage u_d during a power interruption
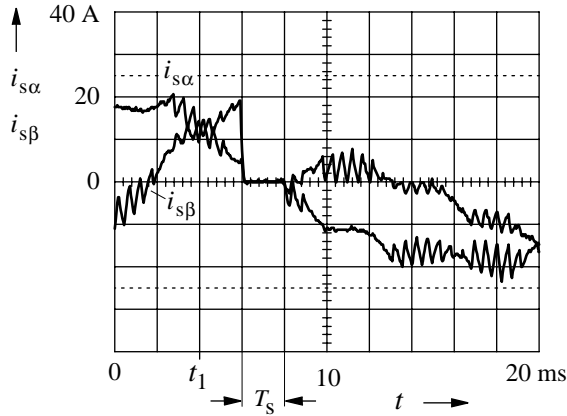b) as Fig. 11(a), expanded time scale

Fig. 12: Stator current components during a power interruption

during a power interruption of 1.2 s duration. The event is detected at t_1, and the stator currents are forced to zero almost instantaneously which can be observed from the expanded traces in Fig. 11(b). The magnetizing current is built up during a time interval marked T_1. Following that, a smooth transition into the generating mode takes place as commanded by the dc link voltage controller and the underlying active current control loop. The oscillogram Fig. 11(a) shows that the negative active stator current which represents the power supplied by the machine is very small. Regeneration starts 14 ms after the power interruption, as marked by T_1 in Fig. 11(b).

The α- and β-components of the stator currents are displayed in Fig. 12. This oscillogram shows that the currents decay indeed very fast, and build up again after one sampling interval of duration T_s.

Fig. 11(b) shows that the synchronization between the inverter and the machine is lost during the short time interval T_0, which lasts only 2 ms. Hence the ride-through method can be also applied to multi-motor drives, since the

speed values of the individual motors will not significantly change during such short interval.

The power returns at $t = t_4$ in Fig. 11(a). The speed controller gets engaged after a delay time of 200 ms. The delay allows the machine flux to build up before acceleration. This accounts for cases where the machine operates in the field weakening mode during an interruption and the reduced dc link voltage does not suffice for full magnetic excitation. After the delay, the rising active current i_{sp} indicates that the motoring mode is reestablished.

The speed of the test equipment was not recorded as the inertia of the mechanical system may vary in a wide range, depending on the application. This is true also for the tolerated dip in speed.

4.2 Control method II

A different control philosophy consists in forcing the dc link voltage during the power interruption interval to a higher level than during regular operation, for example to 650 V. In this case, the power interruption must be detected
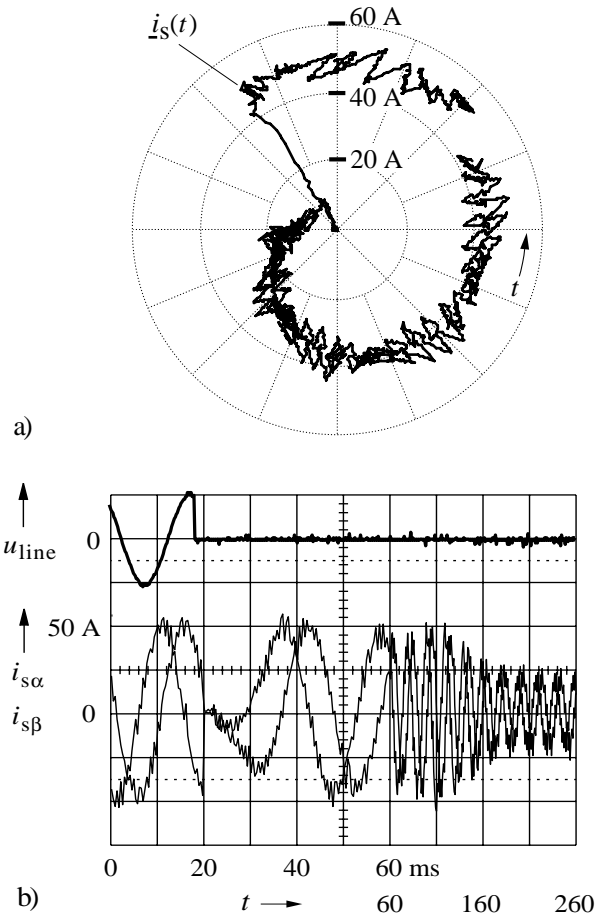

a)

b)

Fig. 14: Interruption of power, control method II
a) stator current space vector trajectory
b) line voltage and motor currents (time scale partially expanded)

Fig. 13: Active stator current i_{sp} and dc link voltage u_d during a power interruption, control method II
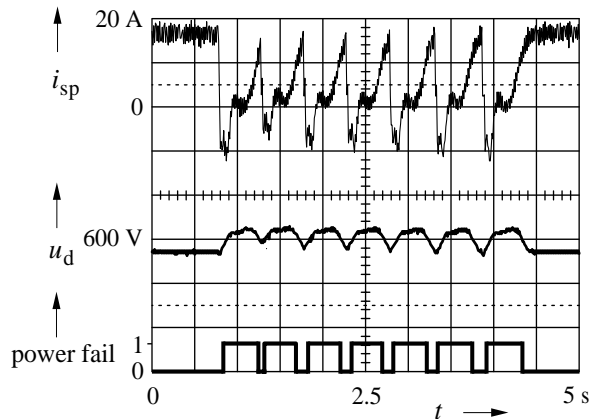
Fig. 15: Multiple reversal of power flow caused by a large motor load on the same ac bus

by monitoring the line voltages. Fig. 13 shows that regeneration is immediately enforced after the interruption, and the dc link voltage is boost up to its higher setting. Fig. 14 shows a recorded trajectory of the stator current space vector. It demonstrates the fast reaction of the feedforward control and the ensuing smooth, but fairly fast transition to the new operating point. A sag of the dc link voltage does not occur here. The control structure during the interruption interval is the same as before, Fig. 10. Control of speed is resumed immediately after the return of power has been detected.

The second scheme reacts faster than the first one. Owing to the higher dc link voltage, the full flux level can be maintained even at field weakening. There is no impulse current drawn from the power supply to recharge the dc link capacitor when the mains returns. Even so, the first method may be preferred in cases where a major portion of load on the common three-phase bus consists of motors, and the inverter rating relatively is high. When disconnected from the power supply, the motors will temporarily maintain their magnetic energy, inducing a voltage on the common bus which makes the inverter drive reconnect. With the inverter load reapplied, the voltage may break down again, and a sequence of reconnections and trips may occur. Although undesired, the inverter control can handle such situation very well, which is demonstrated in Fig. 15.

5. Summary

PWM inverter drives will shut down even at short interruptions of the power supply, initiated by their undervoltage protection scheme. So far, restarting was possible only from standstill, or after a longer resynchronization interval during which the speed drops considerably. Critical productions plants in the textile and paper industry need to be cleared and prepared for restarting, which may entail loss of material and additional down time.

The proposed solution for this problem is to recover some of the mechanical energy stored in the rotating masses by operating the drive system as a generator during the interval of power interruption. This maintains the dc link voltage at an appropriate level and also keeps the electronic control circuits active, since they are supplied from the dc link through a switched mode converter.

In the event of a power failure, the direction of power flow must be rapidly reversed. Field oriented control can provide the required dynamic performance using little extra software. Against that, general purpose inverter drives use cheaper control hardware, and perform nevertheless satisfactorily. They are used with preference in those applications where ride-through at power interruptions is most desirable. The limited dynamic performance of these drives is overcome by a combination of feedforward control for fast reaction, and closed loop control for steady-state accuracy. The approach satisfies all cost and performance requirements. The drive continues operating and the temporary dip in speed is generally tolerable, since the most frequent power interruptions last only for a few milliseconds. Since synchronism between the inverter and the load is never really lost, the ride-through mechanism can be applied to multi-motor drives as well.

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