Assessment of duration of the drive operation in the mode of kinetic energy recovery under power supply voltage sags in electrical grids of mechanical engineering enterprises

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Abstract. Voltage sags in electric grids of mechanical engineering enterprises may lead to disconnection of important power consumers with variable frequency drives from the power grid and further interruption of the production process. The paper considers a sensorless V/f control system of an induction motor drive under normal conditions and under voltage sags on the basis of a computer model of the drive and derivation of a formula for assessment of possible duration of the drive operation in the mode of controlled recovery of kinetic energy accumulated in rotating mass of the drive. Results of simulations have been used to validate results of calculations of the rotor velocity deceleration made in a closed form obtained from the equation reflecting the balance of torques. It is shown that results of calculations practically coincide with results of simulations in the range up to 5% of the velocity initial value. The proposed formula may be useful for estimation of the duration of the drive operation in the mode of recovery of kinetic energy depending on parameters of the motor and driven mechanisms.

1. Introduction.
Variable frequency electric drive (VFD) is widely used in mechanical engineering industry because of its high level of reliability, controllability and flexibility – characteristics which are in great demand for numerous processing units [1, 2]. In spite of advantages, VFD is found to be susceptible to voltage sags, advent of which causes tripping of under-voltage relay in order to prevent the components of electric drive from damage due to inrush currents flowing at the recovery of normal power supply conditions [3-7].

Momentary power interruptions and voltage sags are normally caused by short circuiting in transmission lines and distribution lines. Parameters of voltage sags are known to depend on characteristics of protection relays tripping the faulted lines and topology of the network, that determines the area of propagation of voltage sags. Duration of voltage sags usually constitutes 0.1-3s and voltage magnitude is equal or less than 90% of nominal voltage value. Such events occurring 20-30 per year lead to restarting delays and disruption in technological processes and significant economic detriment because of lost productivity and distorted quality products [7-9]. Ensuring the reliability of VFD operation under voltage sags in order to keep the continuity of processes in industrial facilities is of great importance.
In order to run a facility through power interruptions and sags, either standby power is supplied or internal resources of the drive are utilized in the form of maintaining the velocity of driven mechanism at the expense of controlled operation in the field weakening zone and/or recovering the kinetic energy accumulated in the driven mechanism in order to keep the voltage of DC link at predetermined level.

Feasibility and the cost of implementing each solution depend on practicality, economics and the losses incurred due to downtime[10, 11]. Running a facility through power interruptions and sags by means of internal resources of the drive is preferable in most cases because of its simplicity and low cost of realization via modification of control system through software.

Algorithm-based strategies for improvements to voltage sag ride-through performance of VFD are normally implemented for the FOC electric drive. However, for widely spread v/f control systems realization of these kinds of strategies is also in great demand. For both types of VFD, it is essential to know possible duration of operation in the mode of recovery of kinetic energy available in rotating mass during a sag. Keeping the controls energized only solves a part of the problem and the actual motors and drives must also be analyzed.

The paper is devoted to building up a sensorless scalar control system of VFD with ability to be configured for realizing the ride-through strategy on the basis of maintaining the voltage of DC link by regulating an active component of the motor current. The second goal of the paper is to obtain a theoretical tool for assessment of possible duration of the drive operation in a regenerative mode.

2. Sensorless v/f control system for IM drive under normal and voltage sags conditions.

The structure of a sensorless IM VFD with the two-loops v/f control system (figure 1) is built up on the basis of the rotor velocity observer [12] according to the principle of subordinate regulation.

![Figure 1. The sensorless v/f control system of IM VFD](image_url)

The inner loop of regulating an active component of the stator current is under control of outer loop producing reference value $I_{sa}^*$. The control system comprises two outer loops depending on conditions of the drive performance – normal conditions when the rotor velocity is controlled to follow set-up reference value $\omega^*$ and under emergency conditions during AC voltage sags when the voltage of the DC link is kept at set value $U_{dc}^*$ via charging the condensor from IM operating in...
regenerative mode which is controlled by varying angular velocity of rotating magnetic field in the air-gap of IM vs observed angular velocity of the rotor. Configuration of control system is changed via a virtual switch which state 1 - normal mode or 2- emergency mode is controlled by signals from the block responsible for identification of AC voltage sags through processing the signals of input voltages.

In the normal mode of operation, the system under consideration is functioning as follows. Measured stator currents \( i_a, i_b, i_c \) are converted into \( \alpha\beta \) -components of the current vector which then are projected onto the \( x \) – axis of the rotating frame (figure 2). These transformations allow determining the active component of the current as a sum of two projections:

\[
I_{sa} = i_a \cos \theta + i_b \sin \theta.
\]  

(1)

Angle \( \theta \) of fundamental harmonic of stator voltage \( \vec{E}_s \) is set by VSI modulating vector \( \vec{e}_s \), which is aligned along the \( x \) – axis. Slip frequency \( \omega_s \) estimated according to linear relationship \( \omega_s = k_{sa} I_{sa} \), where \( k_{sa} = \omega_{r,nom}/I_{sa,nom} \) is used to calculate the rotor angular velocity as follows:

\[
\omega_{ext} = (\omega_s - \omega_r)/z_p, \quad \text{where} \quad z_p \quad \text{– pole-pairs number.}
\]

\[ y \]  
\[ x \]  
\[ \beta \]  
\[ I_\beta \]  
\[ I_m \]  
\[ \angle \theta \]  
\[ I_a \]  
\[ I_{sa} \]  
\[ E_s \]  
\[ \vec{e}_s \]  
\[ \vec{e}_a \]  
\[ \vec{e}_b \]  
\[ \vec{e}_c \]  

\[ \text{Figure 2. The stator current in stationary and rotating reference frames.} \]

Comparison of estimated and set values of the rotor velocities produces a signal \( \Delta = \omega^* - \omega_{ext} \) that is fed to PI-regulator, which outputs reference \( I_{sa}^* \) of active stator current for the inner control loop. The output of current PI-regulator \( \Delta \omega_s \) is used to produce required frequency of PWM modulating signals \( \omega_s = \omega_{r,nom} - \Delta \omega_s \), where \( \omega_{r,nom} \) is a nominal value of the frequency. Obtained value \( \omega_s \) is used to determine angle \( \theta \) of generalized rotating vector \( \vec{e}_s \), via the integrator and modulation index \( m \), which for control law \( E/\omega_s = \text{const} \) is calculated as follows:

\[
m = \omega_s/\omega_{r,nom}.
\]

This allows producing reference values for modulation signals \( \hat{e}_a(t), \hat{e}_b(t), \hat{e}_c(t) \), which then are corrected with IR-compensation block. Comparison of calculated voltages \( \hat{u}_a(t), \hat{u}_b(t), \hat{u}_c(t) \) with PWM carrier signals results in generating the switching functions \( S_a, S_b, S_c \) for IGBT modules of VSI.

If AC voltage dips are identified, the control system is reconfigured to implement the controlled recovery of kinetic energy stored in the drive. In this mode of operation, the reference value of active current \( I_{sa}^* \) is formed by a PID regulator as a reaction to input signal \( \Delta U_{dc} = U_{dc}^* - U_{dc} \), where \( U_{dc}^* \) and \( U_{dc} \) – required and measured values, respectively.
3. Assessments of ride-through capability of proposed control system

3.1 Results of simulation

Investigation of IM VFD with the proposed control system in two modes of operation has been carried out via a computer model built up in MatLab/Simulink environment. The model includes squirrel-cage IM, inverter, fan load model, current sensors and sinusoidal PWM block. The motor parameters are as follows: \( P_{\text{nom}}=37\text{kW} \), \( U_{\text{ph}}=220\text{V} \), \( f=50\text{Hz} \), \( z_p=7 \), \( s=0.02 \), \( R_s=0.084\text{Ohm} \), \( L_{so}=0.0009\text{H} \), \( R'_s=0.0564\text{Ohm} \), \( L'_{so}=0.0011\text{H} \), \( L_m=0.0109\text{H} \), \( U_{dc}=540\text{V} \), \( J=18\text{kg} \cdot \text{m}^2 \).

In the normal mode, the rotor velocity constitutes 36.7 rad/s. Power supply interruption at time \( t_1=5\text{s} \) is reproduced by a controlled three-phase voltage source. Period of interruption was set up long enough to estimate maximum duration of the drive operation in the mode of controlled recovery of stored kinetic energy. Results of simulation (figure 3) represent time dependences of the rotor speed, DC-link voltage, electromagnetic torque and currents.

![Figure 3. Characteristics of VFD under controlled recovery of kinetic energy.](image)

Observation of submitted curves allows revealing following peculiarities of the processes under study. In the background of smooth deceleration of the rotor, transition from one mode to another is featured by a decrease in electromagnetic torque up to practically zero value, change of its sign and consequent increase in order to compensate for energy loss in the motor: \( \Delta P=3R_sI_s^2 \). Behavior of current component \( I_{sa} \) is similar to that of electromagnetic torque while reactive component \( I_{sr} \) stays practically unchanged which corresponds to the fact that energy loss during regenerative mode may be considered constant. This allows determining electromagnetic torque as a function of the rotor velocity as follows: \( T_{em}=\Delta P / \omega^2 \). In the normal mode, the input current of VSI \( i_{inv}(t) \) is pulsated in respect to its mean value \( I_{inv} \), which along with DC-voltage defines the power of DC-link. In the regenerative mode, offset value \( I_{inv} \) gets close to zero. As we can see from Figure 3b, DC-voltage is kept approximately equal to set value \( U'_{dc} \) during interval of time \( T_{max}=t_2-t_1 \). Moment \( t_2 \) is defined as a moment when the rotor velocity slows down up the value of \( \omega_2=0.1\omega_1 \). In the range of variables variations \( t \geq t_2 \) and \( \omega \leq \omega_2 \), the drive goes to the braking mode at the expanse of growing electromagnetic torque.
3.2. Theoretical approach

Calculation of maximum duration of controlled recovery of kinetic energy \( T_{\text{max}} \) is possible to execute having a solution of equation, reflecting the balance of torques. For a driven mechanism with mechanical characteristic of the fan is possible to write down:

\[
- \Delta P \cdot \omega^{-1} - K_f \omega^2 = J \frac{d\omega}{dt}, \quad K_f = \frac{P_{\text{nom}}}{\omega_{\text{nom}}^3}, \quad \omega(0) = \omega_1
\]  

(2)

Solution of differential equation (2) may be presented as follows:

\[
t(\omega) = \frac{1}{\Delta P \cdot K_f^2} \left( \ln \left( \frac{\alpha^2 \omega^2 - \alpha \omega + 1}{(\alpha \omega + 1)^2} \right) + 2\sqrt{3} \arctg \left( \frac{2\alpha \omega - 1}{\sqrt{3}} \right) \right) \omega_1, \quad \alpha = \frac{1}{\sqrt{\Delta P}}
\]

(3)

\[\hat{\omega}(t), \ (p.u.)\]

![Figure 4](image)

**Figure 4.** Characteristics of the drive under controlled recovery of kinetic energy.

Results of calculations obtained in accordance with formula (3) are presented in figure 4, where curve 1 relates to results of simulation, curves 2, 3, 4 – to results of calculations. Curve 2 depicts an uncontrolled deceleration of the motor in case of power supply interruption; curve 3 describes deceleration of the motor under condition that braking electromagnetic torque is constant, curve 4 takes into account dependency of electromagnetic torque on the rotor velocity.

As we can see from figure 4, results of simulation (curve 1) and calculations (curve 4) practically coincide that allows recommending formula (3) for assessment of maximum duration of VFD operation in the mode of controlled recovery of kinetic energy.

4. Conclusion.

Results of the paper may be summarized as follows.

The V/f control system of VFD with an observer of the rotor velocity has been elaborated to regulate the drive in two modes of operation: the main mode to secure required coordinates of the driven mechanism and the auxiliary mode to sustain the controllability of the drive during interruption of power supply and/or voltage sags. Stabilization of DC link voltage is achieved by extracting the kinetic energy in a regenerative mode of the motor operation. Control of the drive in both modes is executed in accordance with the principle of a subordinate regulation.

Simulation of the drive in Simulink/MatLab environment allows revealing basic peculiarities of the processes in the drive under voltage sags which were used to estimate possible duration of efficient
extraction of kinetic energy $T_{\text{max}}$ under condition $\omega(T_{\text{max}}) = 0.1\omega(0)$ and to substantiate the necessity of taking into account the contribution of braking electromagnetic torque in theoretical assessment of the process parameters. The use of proposed formula for calculation of time span $T_{\text{max}}$ gives results coinciding with results of simulation in the range of the motor deceleration: $\omega(0) \leq \omega \leq 0.05\omega(0)$.

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