Computer Simulation of Voltage Sag Effects on Adjustable Speed Drives

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Abstract – **In this paper was presented a possibility of computer usage for voltage sag effects on electrical drives with frequency converters. First of all it was given guidelines for making appropriate system simulation model, where especially were stressed how to estimate the most important parameters for modeling. Complete model was made in MATLAB, and than we turn attention to speed and torque deviation in modern speed controlled drives. It is also presented the influence of the adequate control algorithm in drive behavior.**

Keywords – **Voltage Sag, Adjustable Speed Drives, Speed Deviation, Power Quality.**

I. Introduction

The aim of the paper is to introduce the possibility of valid voltage sag (dip) influence simulation on modern adjustable speed drive (ASD) in which case, main parameters to obtain realistic results are pronounced. Computer simulation of ASD, because of the complexity and analog/discrete nature, needs long computing term. On the other side, experimental researches ([1]) of ASD voltage sags sensitivity request very expensive and sophisticated equipments: voltage sag generators, programmable load and high performance data acquisition system with current, voltage, speed and torque sensors. Meanwhile it should be emphasized the fact that it is necessary to accomplish great number of tests, some of which can lead to equipment under test destruction. The installed power rising in equipment results significantly influence in facility price and testing time extending.

The advantage of computer simulation is a chance for virtual equipment testing in wide range of power with no extra cost. Simultaneously it is posed a question of accurate modeling and results validity having in mind disadvantage of particular converter data. Based on authors' practical experience it will be presented recommendation for a good simulation model of the system: voltage sag generator – frequency converter – induction motor.

The following lines will explain this paper organization. The Second section shows, based on previous paper, concrete voltage sag effects on adjustable speed drives. The Third section especially points out mechanical irregularity in drive operation as drop in speed and torque/speed pulsation during voltage sags. It was made analysis in FOC and DTC drives, where in Fourth section was presented some simulation results for mentioned phenomena. In last section parameters where listed which must be known for right converter behavior modeling in voltage sag conditions.

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II. Voltage Sag Effects

Voltage sag problems referring to induction motor drives with frequency converters can be classified in to four categories according to the point of appearance:

(i) input side lapse;
(ii) DC link under-voltage;
(iii) inverter side over-current, and
(iv) induction motor operation disarrangement.

In some sensitive devices, for example adjustable speed drives, it is important to consider the possibility of phase angle jump influences. In [2] voltage sags ranged in 7 types based on sagged phase number and phase angle difference which is shown in Fig.1. Phase angle jump can appear as a result of fault transferring over transformer (for example for transformer winding connection Yd, Dy and Yz) and/or changing X/R ratio of power supply. It should be also known that phase angle jump limited by concrete power supply line parameters and the fact that the phase angle difference between phase and line-line voltages are 30 degrees. Theoretical maximum phase angle jump value is 90 degrees, but the most probable value in real power system is 30^o ([3]).

Input unit at industry standardized frequency converter is usually full bridge diode rectifier. Transient voltage sags or steady-state voltage unbalance conditions in the three-phase input line voltages can cause the rectifier stage to transition into single-phase rectifier operation. Unbalanced voltage sag can cause high current asymmetry with values far over nominal ones. In [2] was discussed the influence of input and DC link inductance on input current RMS values where taken out the circumstances of converter trip.

If the DC link capacitor discharges its energy and the DC link voltage reaches the minimum allowed value (V_{DCmin}) under-voltage protection will be activated. This minimum level can be adjusted in the range from 65-70% up to 85-90% of rated DC link voltage. DC voltage drop under minimum level can lead to the appearance of the high inrush input current when the power-up again. Minimum DC bus voltage depends on maximum diode bridge current, i.e. DC bus charging circuit limitation. In [5] was identified that voltage sag type and depth, value of DC link capacitor and output load

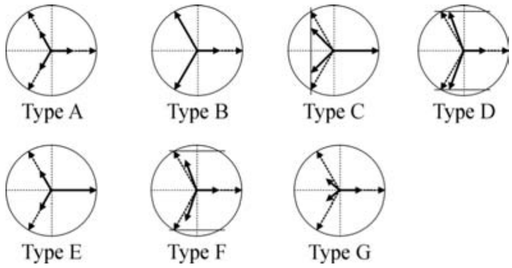

Fig. 1. Voltage sag types

significantly affect on voltage sag tolerance curve.

At output converter terminals Pulse Width Modulation (PWM) voltage was delivered according to the given control rules. Nowadays, three basic control principles are used in frequency converters: V/f, Field Oriented Control (FOC), and Direct Torque Control (DTC) with their own sub-variants. Control principle effect is diverse and noticed in distinction in various voltage sag sensitivity curves ([6]), drop in speed differences ([7]), and speed deviation features during unbalanced voltage sags.

Some processes with multi-motor ASD (for example dried section of the paper machine with speed synchronized drives and load sharing) cannot tolerate the loss of accurate speed or torque control, even for a few seconds due to damage the final product or halt of the process. Beside this, torque pulsation leads to aside effects for example: noise increasing, vibration or mechanical resonance exciting. In this work analytic relation and simulation results for speed deviation were emphasized.

III. Voltage Sag Speed Deviation

Limits as consequences of PWM converter maximum output current (I_{max}) and maximum output voltage (U_{max}) can be represented in relation to the appropriate stator quantity through the following equations:

$$i_{qs}^2 + i_{ds}^2 \le I_{\max}^2 \text{, and} \tag{1}$$

$$u_{qs}^2 + u_{ds}^2 \le U_{\max}^2 \tag{2}$$

where particular variables and their numerical values are given in Table I. Maximum output current is determined by maximum continuous current of inverter semiconductor switches or induction motor rated current, i.e. maximum allowable thermal capacity of the converter or induction motor.

The maximum stator voltage depends on the available DC-link voltage V_{DC} and pulse-width modulation (PWM) strategy. In this paper, PWM strategy based on voltage space vector (SVPWM) is used, and then the output phase voltage on converter terminals, neglecting voltage drop on switches, is:

$$u(t) = (V_{DC}/2)\cdot m \cdot \sin(\omega t + \varphi)\,. \tag{3}$$

Maximum possible modulation index in linear modulation range is 2/√3. In practice, industrial frequency converters have different over-modulation methods, so in simulation model it

TABLE I
List of Symbols and Nominal Values

R_s	Stator resistance, 7.845 Ω
R_r	Rotor resistance, 7.187 Ω
L_{ls}, L_{lr}	Stator and Rotor Leakage Inductance, 31mH
L_m	Magnetising Inductance, 0.815 H
u_{sd}, u_{sq}	Direct and Quadrature axis Stator Voltages
i_{sd}, i_{sq}	Direct and Quadrature Stator Currents
i_{rd}, i_{rq}	Direct and Quadrature Rotor Currents
P	No. Pole Pairs, 1
P_n	Nominal Motor Power, 2200W
U_n	Supply network rated line-line voltage rms value, 380V
ω_n	Nominal rotor angular speed, 297 rad/s
σ	Total leakage coefficient, 0.049
T_r	Rotor time constant, 0.174s
m	Modulation index

has to be taken into consideration. If over-modulation is used it can be supposed that output voltage reconstruct input one in complete.

Induction motor electromagnetic torque, based on two-phase mathematical model ([8]), can be calculated using the following formula:

$$T_e = \frac{3}{2} P \frac{L_m}{L_r} (i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr})\,. \tag{3}$$

Aligning the reference frame *d*-axis with rotor flux linkage phasor, will gain:

$$\lambda_{qr} = 0, \lambda_{dr} = \lambda_r\,. \tag{4}$$

In steady state, all quantity differences will be zero, and can be counted that $i_{dr} = 0$, and:

$$T_e = c_1 i_{ds} i_{qs} \tag{5}$$

where $c_1 = \frac{3}{2} P \frac{L_m^2}{L_r}$.

Equation (2) in steady state and voltage limit condition, having in mind the relationship (4); can be written as ([7]):

$$A i_{ds}^2 + C i_{qs}^2 + B i_{ds} i_{qs} \le U_{\max}^2 \tag{6}$$

where:

$$A = R_s^2 + \omega_s^2 L_s^2;\; B = 2R_s\omega_s \frac{L_m^2}{L_r};\text{ and } C = R_s^2 + \omega_s^2\sigma^2 L_s^2\,.$$

In the above equations ω_s represents synchronous reference frame speed.

To achieve RFO control for set speed value, angular frequency of the stator variables should be:

$$\omega_s = \omega + \frac{R_r}{L_r}\frac{L_m}{\lambda_{dr}} i_{qs}\,, \tag{7}$$

where ω represents rotor angular speed. **It should be mentioned that in case the condition (4) introduction is not**

predicted the drive control method, so simplified Eqs. (5) and (7) are with generalized meaning.

Considering that RFO control is ideal one (actual values follow the commanded ones completely) and for induction motor parameters done in Table I, value of rotor flux reference value λ_r is setting at the value which corresponding to the motor breakdown torque and slip values which result in maximum torque per ampere value. Appropriate value *d*-axis reference current (further named as "breakdown value") is given as:

$$i_{ds}^{*} = \lambda_r / L_m \tag{8}$$

The maximum torque under current limit based on Eq. (5) will be:

$$T_{e\_Imax}^{(RFO)} = c_1\, i_{ds}^{*} \sqrt{I_{\max}^2 - i_{ds}^{*2}}\ . \tag{9}$$

Replacing Eqs. (7) and (8) in Eq. (6), finding out $i_{qs}(\omega, U_{\max}, i_{ds}^{*})$ and final changing in Eq. (5) we achieve torque-speed characteristics for RFO controlled drives under voltage limit (i.e. RFO controlled drive maximum torque under voltage limit):

$$T_{e\_Umax}^{(RFO)} = c_1\, i_{ds}^{*} i_{qs}(\omega, U_{\max}, i_{ds}^{*})\ . \tag{10}$$

Solving Eq. (10) numerically, curves corresponding to maximum torque achieved respecting voltage limit existing. In Fig. 2 were shown curves of motor maximum torque calculated according to Eqs. (9) and (10), where it should be especially have in mind the fact that *d*-axis reference current changing (curves B and C) significantly influence on maximum available torque under RFO control. This fact can be used for voltage sag consequence overcoming as shown in details in [7].

Accepting that the DTC is ideal and that stator flux magnitude λ_s^* remains constant and equal to the proposed one, in synchronous reference frame can be added the following one:

$$\sqrt{(\lambda_{ds})^2 + (\lambda_{qs})^2} = \lambda_s^{*}\ . \tag{11}$$

Solving the last equation for motoring regime operation and having in mind motor flux equation leads to:

$$i_{ds} = \sqrt{(\lambda_s^{*})^2 - \sigma^2 \cdot L_s^2 \cdot i_{qs}^2}\ / L_s\ . \tag{12}$$

Substitution (12) into (5) gives the torque in DTC drive:

$$T_e = \frac{c_1}{L_s} i_{qs} \sqrt{(\lambda_s^{*})^2 - \sigma^2 \cdot L_s^2 \cdot i_{qs}^2}\ . \tag{13}$$

The maximum value of (13) is:

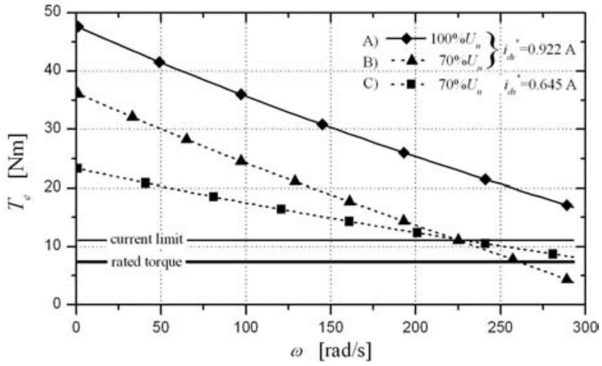

Fig. 2. Maximum torque under voltage and current limit

$$T_{e\max}^{(DTC)} = \frac{c_1}{2} \frac{(\lambda_s^{*})^2}{\sigma L_s^2}\ . \tag{14}$$

Maximum torque value, if the stator current magnitude is constrained by the maximum power converter output current I_{max}, can be found by combining (12), (1) and (5), which leads us to:

$$T_{e\_Imax}^{(DTC)} = \frac{c_1[(L_s^2 I_{\max}^2 - \lambda_s^2)(\lambda_s^2 - \sigma^2 L_s^2 I_{\max}^2)]^{1/2}}{(1-\sigma^2)L_s^2}\ . \tag{15}$$

Considering Eq. (13) under circumstances from Eqs. (6) and (7), the maximum torque values under voltage limit can be found which are presented in Fig. 3 (curve A). In the same figure was shown reference stator flux λ_s^* selection influence on maximum torque as well (curves B and C).

On the basis of the previous discussion can be concluded that for ASDs voltage sag behavior analysis is necessary to know kind of motor control (RFO or DTC), control parameters (i_{ds}* or λ_s^*) and concrete converter limits as well as maximum output current I_{max} and voltage U_{max}.

In [9] was presented input voltage unbalance influence on undesired torque and speed ripple. Especially it is valuable the detail that undesirable low frequency torque component exist in single line to ground faults (SLGFs) on input converter side, which is also the most common fault in power supply network. In the case of V/Hz control induction motor torque can be found as:

$$T_e = T_{e0} + T_{e2}\cos(2\omega_i t + \phi_2) + T_{e4}\cos(4\omega_i t + \phi_4) \tag{16}$$

where subscripts "2" and "4" mean 2nd and 4th magnitude torque components and their appropriate phase angle. Electromagnetic torque mean value is designated as T_{e0} and in steady state regime it is equal to load torque. In next Section we present simulation results which turn attention to torque pulsation difference according to the control method applied.

IV. SIMULATION RESULTS

Great number of simulation results connecting to drop in speed and control algorithm influence can be discovered in [7], when drop in speed minimization is specially stressed. Because of the limited space, we will only present the results

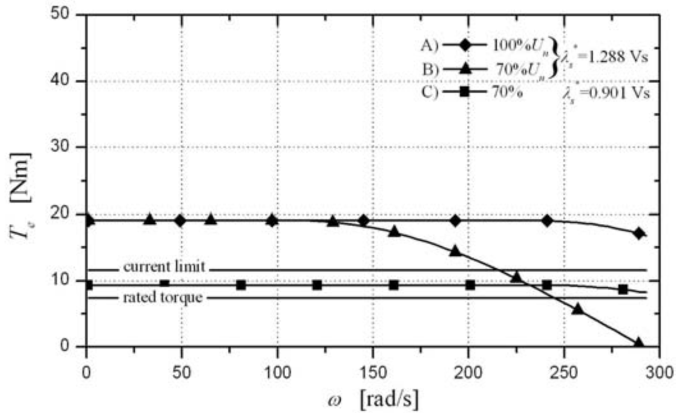

Fig. 3. Maximum torque under voltage and current limit in rated voltage and voltage sag cases

in speed deviation through control method influence. For motor data in Table I and for RFO and DTC control algorithm in Fig. 4 were shown instantaneous torque values and their harmonic spectra in SLGF on converter input terminal (voltage sag type B). It is clearly noticeable that in case of DTC control has no undesirable torque harmonics as in case RFO control

From the point of view of power converter designer, DC link capacitor value is determined by maximum voltage ripple allowed for given output load. DC link capacitor value in practice can be in wide range ([3]) and its influence on torque harmonics components magnitude is shown in Fig. 5. It warns us that for accurate torque deviation modeling under voltage sag condition is necessary to know actual DC bus capacitor value.

V. Conclusion

Based on results in previous papers and this work as well we will recommend the following guidelines for modeling of voltage sag effects on ASDs:

- firstly, voltage sag generator model has to enable all seven voltage sag type simulations including phase asymmetry existence, point of sag initiation and phase angle jump.
- diode model effect in input rectifier bridge is minor.
- the knowing of DC bus inductance value and eventually input side inductance as well is important for input current asymmetry calculation.
- DC link capacitance value has significant influence on its discharge time and torque and speed ripple as well as presented in this work.
- semiconductor switch model influence is minor.
- PWM switching strategy model (modulation scheme) is very important for induction motor behavior modeling.
- induction motor model must be included dynamic effects (*dq*-model) and type and value of mechanical load.

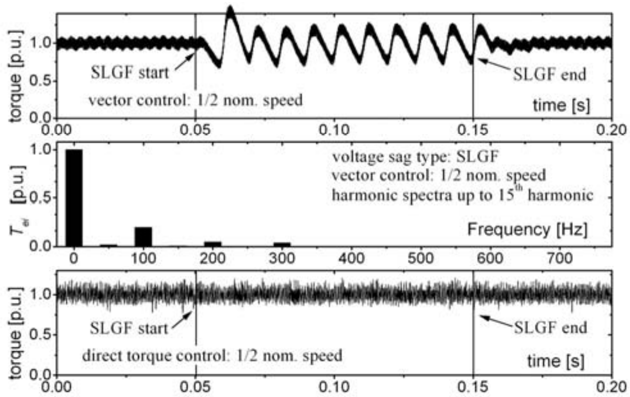

Fig. 4. Motor torque deviation under RFO and DTC control and their harmonic spectra (industrial drive with C=85μF/kW)

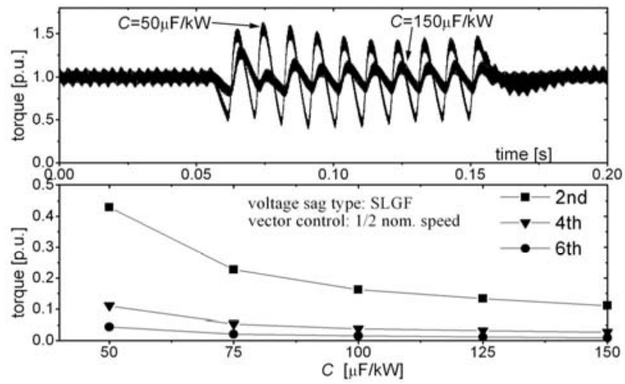

Fig. 5. DC bus capacitor value influence on torque harmonics

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