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VOLTAGE-TOLERANCE CURVES OF PWM DRIVES: COMPARISON OF SIMULATIONS AND MEASUREMENTS

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Abstract: *This paper considers some aspects of using the computer simulations in the process of assessment of equipment sensitivity to voltage sags and short interruptions. Results obtained in simulations with different models of PWM drives are compared and validated against the experimental data identified during the laboratory testing. Influence of various parameters on simulation accuracy is discussed, and some general conclusions are provided.*

Key Words: ***Power Quality/ Voltage sag/ Simulation/ Testing/ Equipment sensitivity/ PWM drive***

1. INTRODUCTION

Voltage sags and short interruptions are probably the two most common types of power quality disturbances and among the most frequent causes of disrupted operations for many industrial processes, particularly those using modern power electronic equipment [1]. The pulse-width modulation controlled voltage source inverter drive (in further text: PWM drive) is a typical example of such recently emerged, rather complex and sophisticated non-linear power electronic equipment. Usually, a PWM drive is used in industrial continuous processes, together with other electrical equipment. If a power quality disturbance is severe enough to cause disconnection of at least one of the critical process equipment, the whole process will be disrupted. Often, that critical component is the PWM drive. Reference [2] states that the average costs of interruptions in industrial processes with PWM drives are eight times higher than the costs in the same industries without the PWM drives.

Basically, the PWM drive is a converter, comprising of a rectifier (or input converter), a dc link (or dc bus), an inverter (or output converter), and additional control, protection and measurement circuits. All these circuits respond to various power quality disturbances both individually and as a complete assembly, leading to a high and complex pattern of the PWM drive sensitivity.

The PWM drives are not affected simply by the temporary reduction in the rms value of the supply voltage. The sag type (single-phase, two-phase or three-phase) and duration of the sag influence drive sensitivity. Loading and operating conditions of both the drive and controlled motor also have significant influence on drive behaviour during the sag. Thus, different load types, variations in loading torque and operation with reduced motor speeds should be also regarded as the factors of influence in the assessment of the PWM drive sensitivity.

Testing is probably the simplest and the most efficient way for assessment of equipment sensitivity. However, when there is a lot of factors of influence (as in the case of the PWM drives), testing with all factors included is cumbersome, time-consuming and related to using of expensive and complex laboratory test beds. As an alternative or an addition to testing, simulations with appropriate component models may provide substantial benefits and can help in understanding the interaction of drive and motor during voltage sags. Specifically, computer simulations are fast and convenient means for characterisation and analysis of effects of various parameters and factors of influence. When used for studying of PWM drive operation, computer simulations allow that all drive components and circuits can be easily analysed, altered, or optimised with regards to various aspects of drive applications. All the causes of drive malfunction/tripping during the voltage sags and short interruptions can be identified, and various solutions for improvement of drive ride-through capabilities can be obtained and compared. However, simulations are only as precise and reliable as are the used models of equipment and system components.

This paper discusses using of computer simulations in the process of assessment of equipment sensitivity to voltage sags and short interruptions. Results obtained in simulations with different software packages and various models of drive components are validated against measured experimental data. The paper shows that simulations may help in analysis of the fundamental characteristics of drive responses to voltage sags and short interruptions. Various types of symmetrical and asymmetrical voltage sags are used in simulations with different loading and operating drive conditions. The most important factors of influence on simulation accuracy are identified and closely discussed in paper.

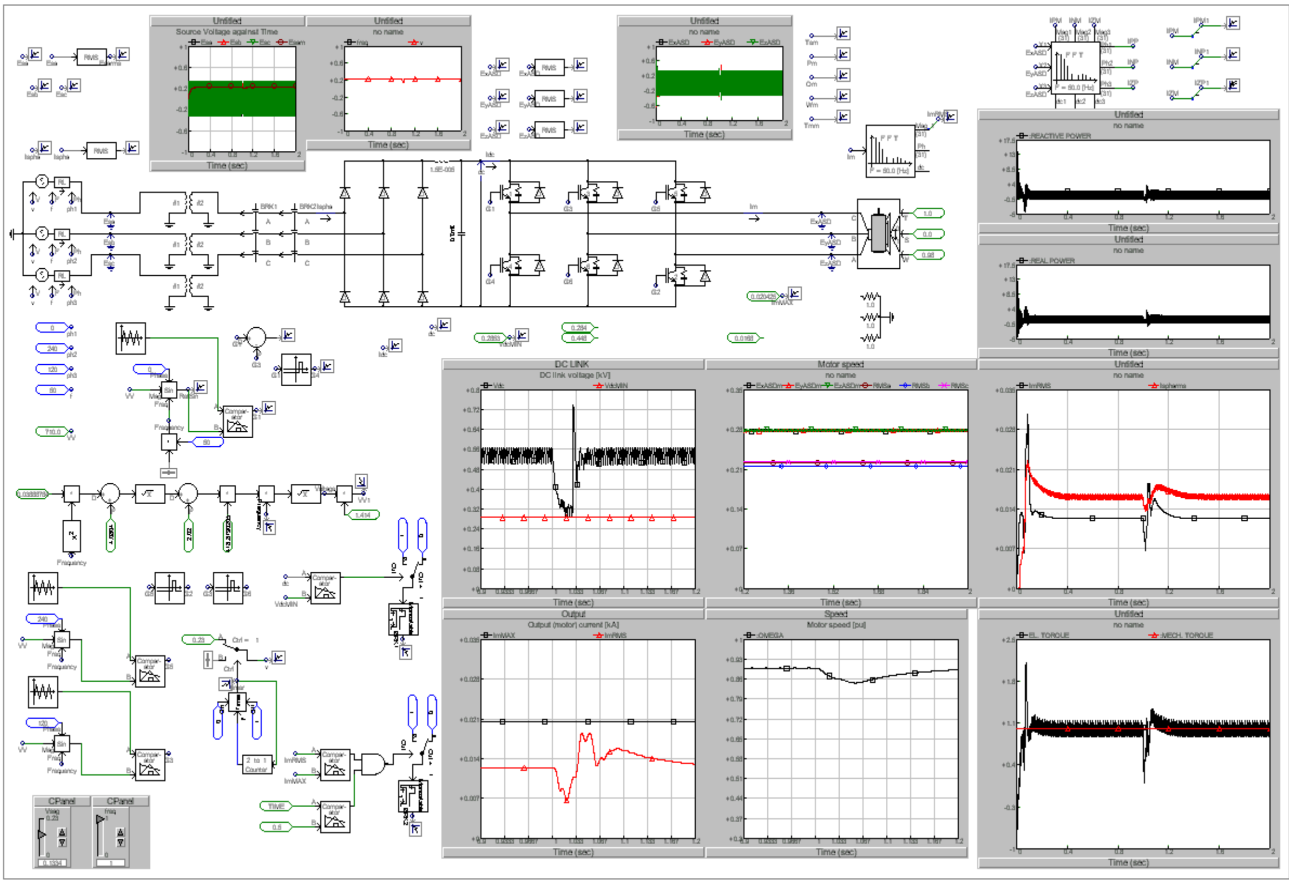

Fig. 1. *Screen snapshot of the PWM drive simulation model with V/Hz control of induction motor realised in the EMTDC/PSCAD [3].*

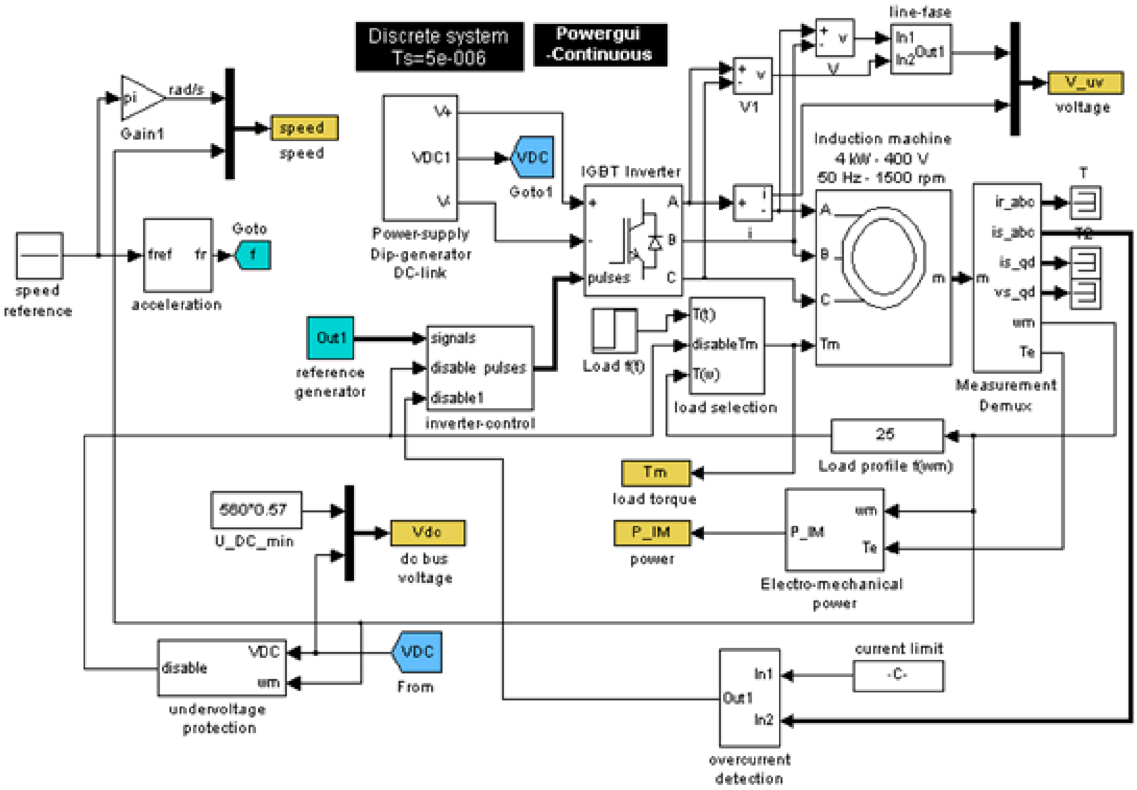

Fig. 2: *Simulation model of the PWM drive with V/Hz-control of induction motor realised with Matlab/Simulink and PowerSystem Toolbox [4], [5].*

2. SOFTWARES USED IN SIMULATIONS

The schematical representations related to two different software packages used in simulations are shown in Figures 1 and 2.

The first software package used in simulations is the EMTDC/PSCAD [3]. Figure 1 shows the screen snapshot of the PWM drive simulation model with all drive circuits, controlled induction motor and graphical output variables. In order to identify characteristics of drive behaviour during the sags and interruptions, following parameters and quantities are monitored:

a) rms and instantaneous phase and line voltages and currents at the drive input and output,
b) dc link voltage and current, and
c) speed, electrical/mechanical torque and real/reactive power of the motor.

Control of the motor operation (i.e., motor speed and torque) was realised as the simple V/Hz modulation, maintaining the maximum motor torque. All drive circuit components used in simulation were modelled as the "typical", as they are given in the EMTDC/PSCAD components library. Induction motor was modelled both with equivalent circuit parameters and as a typical motor (regarding the rated power, voltage and current). No significant differences were identified between these two motor models. Motor was loaded with the constant torque load type. Results obtained with this simulation software are denoted as "Sim1".

The second simulation package used is Matlab/Simulink. The power electronic elements and the machine model are taken from the PowerSystem Toolbox. This allowed fast, low level configuration of the drive hardware, with short execution times for the whole drive system.

The control principle again is based on the simple open-loop V/Hz modulation. The subharmonic pulse width modulation (PWM) is used to provide the gate signals for the inverter IGBT's. Both dc bus voltage and motor current are monitored and used to activate the drive protection circuit. The overcurrent protection is based on the instantaneous motor current and is set at 215 % of I_{outmax}. Results obtained with this simulation software are denoted as "Sim2".

3. COMPARISON OF SIMULATIONS AND MEASUREMENTS

Among the several PWM drives tested in laboratory, one of them is exposed to particularly detailed tests and used for validation of simulation models. Basic data for this PWM drive and controlled induction motor are given in Table 1.

Two different protection systems are responsible for disconnection of the drive during the sags and interruptions. Undervoltage protection is activated after the dc link capacitor discharges its energy and dc link voltage drops below the minimum allowed value (U_{dcmin}=57% of nominal/rated dc link voltage). Figure 4 shows that the undervoltage protection setting determines the duration threshold, i.e., the interruptions and deeper sags activate this protection.

The overcurrent protection system is activated by the increase of the drive output current drawn during the sag

Table 1. *Parameters of the PWM drive and controlled induction motor*

PWM drive	Input	3~, 48-62Hz, 380/480V, 9.5A, 4kW input displacement power factor 0.93
	Output	3~, 0÷1000Hz, 0÷480V, 9.5A (selected switching frequency: 3kHz)
	DC link	C=85μF/kW (2x640μF in parallel, (dis)charging time 17ms), L=1.5mH
	Undervoltage protection	U_{dcmin}=320V dc (57% of U_{dcnom}=560V)
	Instantaneous/fast overcurrent protection	I_{outmax}=20.4A rms (215% of I_{outnom}=9.5A)
Motor	Input	3~, 230/400V, 13.9/8A Δ/Y, 50Hz, p=2, cosφ=0.86
	Output	1440rpm, 26.7Nm, 0.015kgm^2, η=0.84, 4kW/5.36hp
	Equivalent circuit	L_{1h}=0.169H, $L_{\sigma s}$, $L_{\sigma r}$=0.013H, R_1=1.13Ω, R_2 =0.90Ω

(i.e., by the high inrush current occurring immediately after the sag ending, due to charging of the discharged dc link capacitor). This protection determines the magnitude threshold of drive voltage-tolerance curves. Both protections can be implemented as the user-settable or hard-wired options.

The PWM drives are three-phase equipment having a rather complex sensitivity pattern. Each voltage-tolerance curve obtained in tests corresponds to one particular voltage sag type, one particular value of loading torque and one particular value of motor speed. Figures 4-5 show families of voltage-tolerance curves identified in testing with different values of loading torque and motor speed for the three-phase symmetrical voltage sags and short interruptions. Figures 6-7 show changes in drive sensitivity with changes in motor speed for single-phase and two-phase sags and interruptions with rated voltage in unsagged phase(s).

Voltage-tolerance curves obtained in tests with different loading torque values (for constant torque load type and rated motor speed) are compared with simulation results in Fig. 4. It can be seen that the actual loading conditions of the motor have significant influence on drive sensitivity. Decreasing the loading torque results in lower drive sensitivity (i.e., better ride-through capabilities of the drive). A good agreement of tested and simulated results is obtained.

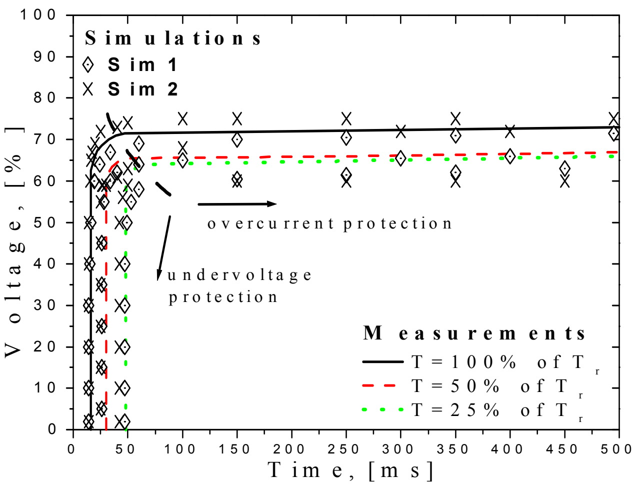

Fig. 4. *Influence of different torque values on sensitivity of PWM drive to symmetrical three-phase voltage sags.*

Figure 5 presents voltage-tolerance curves when motor speed was used as a parameter (for constant torque load type and rated loading torque value). Decreasing the adjusted motor speed also results in lower drive sensitivity. Again, good agreement between the measured and simulated results is obtained.

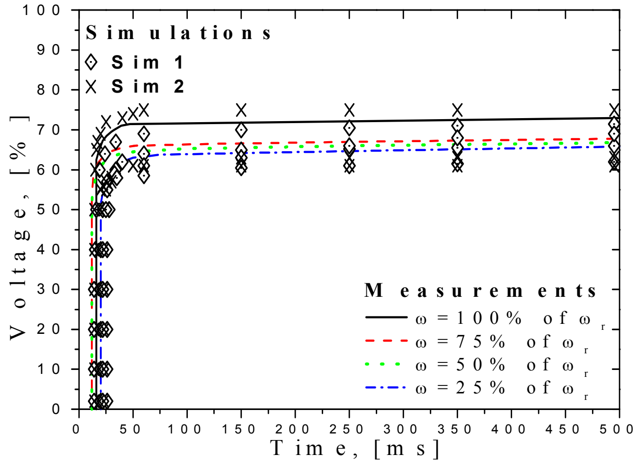

Fig. 5. *Influence of different motor speeds on sensitivity of PWM drive to symmetrical three-phase voltage sags.*

Figure 6 compares voltage-tolerance curves obtained in tests and simulations for two-phase sags and interruptions with the rated voltage in the third phase and different motor speeds (constant torque load type and rated loading torque value). The similar behaviour is identified in this case - decreasing of the adjusted motor speed results in lower drive sensitivity. The results obtained in simulations are again in accordance with the measured results.

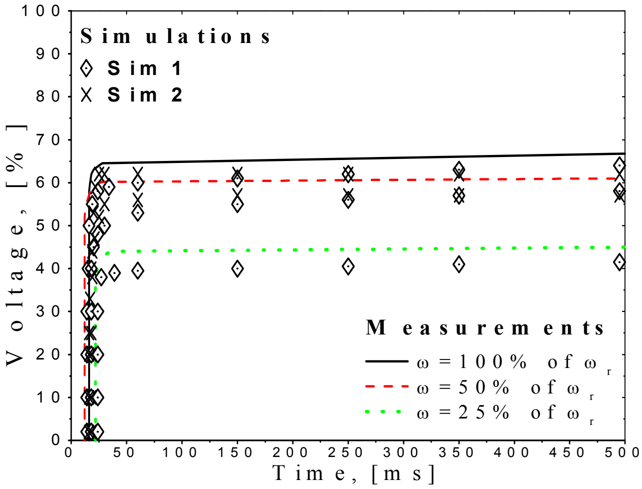

Fig. 6. *Influence of different motor speeds on sensitivity of PWM drive to symmetrical two-phase voltage sags with rated voltage in unsagged phase.*

Only one voltage-tolerance curve for speed different from the rated is shown in Fig. 7. If two unsagged phase voltages are equal to the rated voltage and the speed of the induction motor is lower than 90% of the rated motor speed, the drive will not disconnect the motor even when permanently supplied by only two phases. A similar

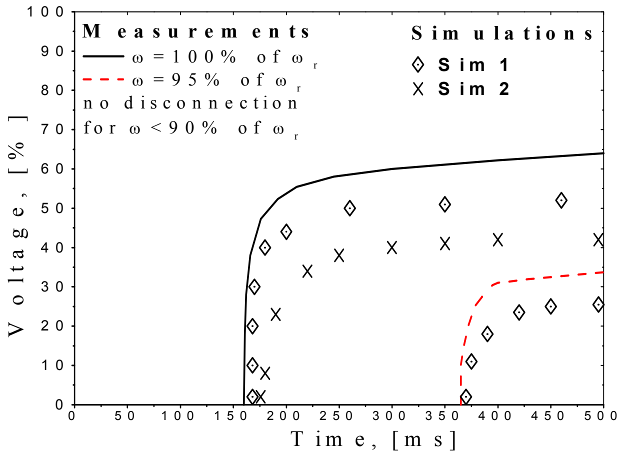

Fig. 7. *Influence of different motor speeds on sensitivity of PWM drive to single -phase voltage sags with rated voltage in two unsagged phases.*

results are confirmed in simulations (no disconnection for 95% percent of rated motor speed for the Sim2).

4. INFLUENCE OF VARIOUS FACTORS ON SIMULATION ACCURACY

The drop in the ac voltage of the power supply during the sag or interruption is essentially seen by the drive as the drop in the dc voltage at the output of the drive rectifier. Thus, acurate modelling of the drive dc link circuit components (i.e., dc link capacitance and inductance) and knowing of the exact setting of the dc link undervoltage protection system are two of the most important aspects of setting up a simulation scheme. They determine vertical parts of the voltage-tolerance curves and duration thresholds for different sag/interruption types and different loading/operating conditions of the drive.

The horizontal parts of the drive voltage-tolerance curves and magnitude thresholds for different sag types and different loading/operating conditions are determined with the instantaneous/fast overcurrent protection setting. Thus, knowing of the exact setting of this overcurrent protection system is also crucial in simulations.

Generally, the behaviour of the PWM drive (i.e., its ride through capability) is determined by the three following main factors: a) the dc link capacitance (i.e., stored energy that is used during the sag or interruption), b) the power/current/energy consumption of the load (i.e., the actual mode of the drive operation and actual loading conditions of the motor) and c) the undervoltage/overcurrent protection settings (i.e., allowed deviations in voltage/currents values during the energy conversion and transfer from the drive to the induction motor). These factors/parameters are the most important for obtaining realistic simulation results regarding the drive sensitivity to voltage sags and short interruptions.

The power electronic components (diodes, IGBTs, snubber circuits, pulse-width modulation circuits, etc.) can be modelled as typical. Regarding the general behaviour of the PWM drive in presence of voltage sags and short interruptions, there is no need for detailed models of power electronic components (including e.g., their thermal dependent characteristics). The induction motor also can be modelled as typical, without the need for complex higher order models of the motor. However, loading conditions of the motor and motor speed should be exactly simulated.

In this paper only a simple V/Hz controller without speed feedback has been modelled. Controller dynamics are slow. For drives with the speed feedback and for field oriented drives, more complicated simulation models have to be considered. Also the influence of the different contollers within such drives on voltage sag behaviour need further research.

5. CONCLUSIONS

The aim of this paper is to investigate the possibility of using the computer simulations for the assessment of the PWM drive sensitivity against voltage sags and short interruptions. It is clearly shown that simulations with appropriate model components can be used instead of cumbersome and time-consuming testing. To obtain good results, characteristics/settings of two different protection systems of the drive must be known. As for the modelling of the power electronics, only the dc bus capacitor value must be known exactly.

Various types of symmetrical and asymmetrical voltage sags and interruptions are used in simulations and validated against corresponding measured results. Also, different motor loading conditions and different motor speeds are investigated in simulations. In all simulated cases, a good agreement between the simulated and measured results is obtained.

Presented resuts of tests and simulations (with two different software packages) demonstrate that the sensitivity of PWM drives to various types of voltage sags and short interruptions has a rather complex pattern. The influence of selected parameters/factors on drive sensitivity is identified and illustrated graphically, using the voltage-tolerance curves as the most efficient and appropriate representation of drive ride-through capabilities. In this way, the paper identifies which models and with what characteristics of idividual components should be used in order to obtain "realistic" results in simulations of drive behaviour when exposed to voltage sags.

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