A Novel Method for Equipment Sensitivity Study During Power Quality Events

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Abstract: This paper presents a new simulation method for performing equipment sensitivity study during power quality events. Power quality waveform events such as voltage sags, swells, transients, etc. may cause sensitive loads to trip or mis-operate. For better coordination between the system and the equipment, it is necessary that the effects of specific events on the equipment behavior be thoroughly evaluated. This paper serves such a purpose. A library has been designed for generating various types of event waveforms. By imposing these waveforms on the equipment and tuning various waveform features, the equipment behavior can be correlated to specific event parameters. Methods and case studies as well as software implementation issues in MATLAB environment are illustrated. It is concluded that the proposed approach is flexible and feasible for practical applications.

Keywords: Power Quality, Testing, Signal Generators, Simulation, Signal Processing.

I. INTRODUCTION

Power quality events such as voltage sags, swells, switching transients, notches, flickers, harmonics, etc. have become far more troublesome than ever because of the increased use of sensitive electronic loads like variable speed drives and computers [1-2]. To improve the immunity or ride-through ability of the equipment to the events and thus enhance the coordination between the system and the equipment, a good appreciation of how various waveform event features affect the equipment operating characteristics will be very helpful [3-6].

To thoroughly evaluate the equipment behavior during various types of events, the event features need to be defined first. IEEE P1159.2 has proposed a list of parameters for characterizing sag events based on digitally sampled data [7]. However, a complete characterization of other types of events has not been available in the literature in the past. This paper contributes to this aspect.

The earlier efforts on equipment behavior evaluation have been mainly focused on the sag events. Effects of sag magnitude, duration and phase angle shift on induction and synchronous motors have been examined in [4-5]. For efficiently tuning waveform parameters, a sag generator is described in [6] and used for evaluating equipment operating characteristics. However, this generator only allows the sag magnitude, duration and phase angle shift to be adjusted while other parameters such as points-on wave, unbalance ratio, etc. that may also have a significant impact on the equipment behavior are not considered.

Considering the limitations of the previous methodology for equipment behavior evaluation, this paper proposes an efficient solution in which other types of events in addition to the sag events are considered, and all the parameters for each event can be flexibly tuned. Specifically, a waveform library has been designed using digital signal processing techniques such as Fourier transform and wavelet analysis to produce various types of events. Then, the equipment of interest is subjected to the generated voltage disturbances. By adjusting the parameters of the event waveforms, the operating characteristics of the equipment can be thoroughly studied and correlated to specific event parameters. One distinctive characteristic of the method is that the event waveforms can be generated either through algebraic equations or through replaying previously recorded waveforms. In either case, the event parameters can be finely tuned by the user to the desired values. Study of the effects of voltage sag events on the equipment behavior is emphasized for illustrating the proposed approaches and some software implementation issues.

In the rest of the paper, the detailed design and implementation approaches for the waveform generator library are presented first. Then the proposed method for equipment sensitivity study is described. Finally, case studies illustrating the application of the proposed approach are presented.

II. A WAVEFORM GENERATOR LIBRARY

This section describes the library for generating various types of waveform events including voltage sags, swells, interruptions, switching transients (oscillatory transients), harmonics, impulses (uni-directional transients), notches, and flickers. Fig. 1 shows the library implemented in MATLAB. Note that the voltage interruptions can be treated as voltage sags with deeper drop, while voltage swells can be treated the same way as sags but with increased rather than decreased magnitude. Hence the voltage sag generator type alone can generate voltage sag, interruption or swell waveforms. The following parts illustrate each of these generators. The signal generation, the process of constructing the signal based on the event features, the parameter extraction, and the process of deriving the event features based on the sampled signal are illustrated. In the following discussion, the voltage magnitude is in per unit, time in second, angle in radian, and frequency in Hertz.

A. Voltage Sag Generator

The voltage sag generator is a masked system whose parameter input interface is shown in Fig. 2.

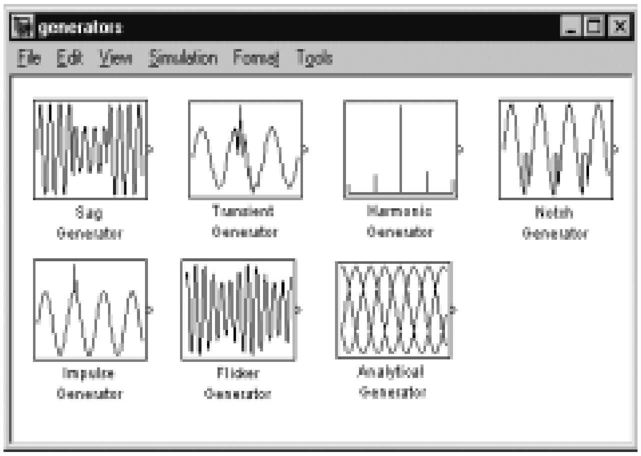
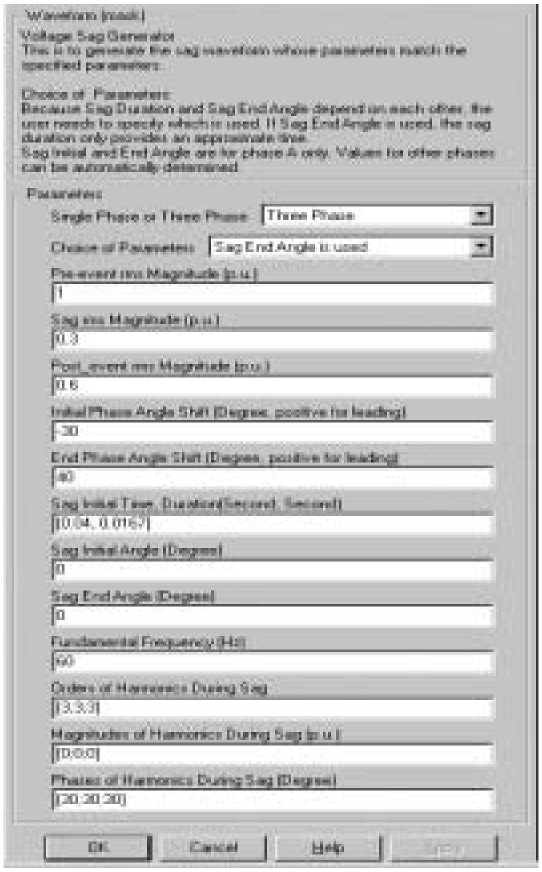


Fig. 1. Library of waveform generators



Waveform (mask)

Voltage Sag Generator
This is to generate the sag waveform whose parameters match the specified parameters.

Choice of Parameters:
Because Sag Duration and Sag End Angle depend on each other, the user needs to specify which is used. If Sag End Angle is used, the sag duration only provides an approximate time.
Sag Initial and End Angle are for phase A only. Values for other phases can be automatically determined.

Parameters

Single Phase or Three Phase: Three Phase

Choice of Parameters: Sag End Angle is used

Pre-event rms Magnitude (p.u.): 1

Sag rms Magnitude (p.u.): 0.3

Post_event rms Magnitude (p.u.): 0.6

Initial Phase Angle Shift (Degree, positive for leading): -30

End Phase Angle Shift (Degree, positive for leading): 40

Sag Initial Time, Duration(Second, Second): [0.04, 0.0167]

Sag Initial Angle (Degree): 0

Sag End Angle (Degree): 0

Fundamental Frequency (Hz): 60

Orders of Harmonics During Sag: [3;3;3]

Magnitudes of Harmonics During Sag (p.u.): [0;0;0]

Phases of Harmonics During Sag (Degree): [30;30;30]

Fig. 2. Parameter input interface for the sag generator

Detailed discussion of the sag parameters and computation approach can be found in [3].

B. Transient Generator

Due to the space limitation, the interface diagram is not shown here. Instead, the defined parameters for characterizing transients are listed in Table 1.

Table 1. Parameters characterizing switching transients

Pre-event magnitude V_{pre} and phase α_0
Post-event magnitude V_{post} and phase β_0
Switching starting time t_s
Magnitudes of the oscillatory components V_{osk}
Frequencies of the oscillatory components f_{osk}
Phases of the oscillatory components β_{osk}
Decay time constants of the oscillatory components T_{osk}

1) Signal construction: Based on the parameters shown in Table 1, the signal v[i] is computed as follows.

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) \quad \text{if } i \le i_{sc} \tag{1}$$

$$v[i] = \sqrt{2} V_{post} \cos(2\pi f_0 i / f_s + \beta_0) + \sum_{k=1}^{M_{os}} \sqrt{2} V_{osk} e^{-(i/f_s - t_s)/T_{osk}} \cos(2\pi f_{osk} i / f_s + \beta_{osk}) \quad \text{if } i > i_{sc} \tag{2}$$

$$i_{sc} = \mathrm{round}(t_s f_s) \tag{3}$$

where,
f_0 is the fundamental frequency of the system
f_s is the sampling frequency of the signal
v[i] represents the generated signal, i=0, 1, …, L-1, with L the defined length of the signal
M_{os} is the number of oscillatory components.

2) Parameter extraction: The formulae for computing the parameters shown in Table 1 based on the sampled signal v[i] are given as follows.

$$V_{pre} = \sqrt{2} \mathrm{abs}(V^1[1]) / N \tag{4}$$

$$\alpha_0 = \mathrm{angle}(V^1[1]) \tag{5}$$

$$i_s = \mathrm{index\_s}\{\mathrm{abs}(WC_1[k]) - \varepsilon\} / L_{wc_1} L \tag{6}$$

$$t_s = i_s / f_s \tag{7}$$

$$V_{post} = \sqrt{2} \mathrm{abs}(V^s[1]) / N \tag{8}$$

$$\beta_0 = \mathrm{angle}(V^s[1]) \tag{9}$$

$$V_{osk} = \sqrt{2} \mathrm{abs}(V^s[k]) / N \tag{10}$$

$$f_{osk} = k f_0 \tag{11}$$

$$\beta_{osk} = \mathrm{angle}(V^s[k]) \tag{12}$$

$$T_{osk} = T_0 / 2 / \ln\{\mathrm{abs}(V^s[k]) / \mathrm{abs}(V^{s1}[k])\} \tag{13}$$

In the above equations,

$V^n[k]$ is the Discrete Fourier Transform (DFT) for the samples contained in the n-th data window defined as

$$V^n[k] = \sum_{i=0}^{N-1} v[i + (n-1) * N] e^{-j\frac{2\pi ki}{N}} \tag{14}$$

N is the number of samples in one data window (one cycle)
j is the imaginary unit, and n=1, 2, …round(L/N)

$$V^s[k] = \sum_{i=i_s}^{i_s+N-1} v[i] e^{-j\frac{2\pi ki}{N}} \tag{15}$$

$$V^{s1}[k] = \sum_{i=i_s+\mathrm{round}(N/2)}^{i_s+\mathrm{round}(N/2)+N-1} v[i] e^{-j\frac{2\pi ki}{N}} \tag{16}$$

$WC_1[k]$ is the first scale wavelet detail coefficients, k=1, 2, …, L_{WC_1}, with L_{WC_1} the length of the detail coefficients. Daubechies-4 wavelet family is used in our work.
ε is a pre-defined constant, normally selected as 0.05
abs(.) gives the absolute value of the argument
angle(.) gives the angle of the argument
round(.) truncates the argument
index_s(.) yields the index of the first element that is greater than zero of the input array

C. Harmonic Generator

The parameters for harmonics are shown in Table 2.

Table 2. Parameters characterizing harmonics

Pre-event magnitude V_{pre} and phase α_0
Harmonic starting time t_s
During-event harmonic frequencies f_{hk}
During-event harmonic magnitudes V_{hk}
During-event harmonic phases β_{hk}

1) Signal construction:

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) \quad \text{if } i \le i_s \tag{17}$$

$$v[i] = \sum_{k=1}^{M_h} \sqrt{2} V_{hk} \cos(2\pi f_{hk} i / f_s + \beta_{hk}) \text{ if } i > i_s \tag{18}$$

M_h is the number of harmonic components including the fundamental component.

2) Parameter extraction: V_{pre}, α_0, and t_s can be calculated from (4-7).

$$V_{hk} = \sqrt{2}\,\mathrm{abs}(V^s[k]) / N \tag{19}$$

$$f_{hk} = k f_0 \tag{20}$$

$$\beta_{hk} = \mathrm{angle}(V^s[k]) \tag{21}$$

D. Notch Generator

The parameters for notches are shown in Table 3. For simplicity, only a single notch in the signal is considered here.

Table 3. Parameters characterizing notches

Pre-event magnitude V_{pre} and phase α_0
Event starting time t_s
Notch width t_w
Notch depth V_d

1) Signal construction:

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) \quad \text{if } i \le i_{sc} \\ \text{or } i \ge \mathrm{round}\{(t_s + t_w) f_s\} \tag{22}$$

$$v_s = \sqrt{2} V_{pre} \cos\{2\pi f_0 i_{sc} / f_s + \alpha_0\} \tag{23}$$

$$v[i] = v_s - \mathrm{sign}(v_s) V_d \quad i_{sc} < i < \mathrm{round}\{(t_s + t_w) f_s\} \tag{24}$$

sign(.) equals to 1 if the argument is non-negative, and –1 otherwise.

2) Parameter extraction: V_{pre}, α_0, and t_s can be calculated from (4-7).

$$i_e = \mathrm{index\_e}\{\mathrm{abs}(WC_1[k]) > \varepsilon\} / L_k L \tag{25}$$

$$t_w = (i_e - i_s) / f_s \tag{26}$$

$$V_d = \max\{\mathrm{abs}(v_s - v[i]), i = i_s, i_s + 1, \ldots, i_e\} \tag{27}$$

index_e(.) yields the index of the last element that is greater than zero of the input array
max(.) gives the maximum value of the argument

E. Impulse Generator

The parameters for impulses are shown in Table 4.

Table 4. Parameters characterizing Impulses

Pre-event magnitude V_{pre} and phase α_0
Event Time t_s
Impulse peak value V_p
Impulse rise time T_r
Impulse decay time T_d

1) Signal construction:

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) \quad i \le i_{sc} \tag{28}$$

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) + \\ V_p (i - i_{sc}) / (i_{pc} - i_{sc}) \quad i_{sc} < i < i_{pc} \tag{29}$$

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) + \\ V_p e^{-(i - i_{pc}) / f_s / T_d'} \quad \text{if } i \ge i_{pc} \tag{30}$$

$$i_{pc} = i_{sc} + \text{round}(T_r f_s) \tag{31}$$

$$T_d^{'} = T_d / \ln(2) \tag{32}$$

2) Parameter extraction: V_{pre}, α_0, and t_s can be calculated from (4-7).

$$\begin{aligned} v_{miss}[i] = v[i] - 2/N * \text{abs}(V^1[1]) * \\ \cos\{\text{angle}(V^1[1]) + 2\pi(i-1)/N\} \end{aligned} \tag{33}$$

$$i_p = \text{index\_max}\{\text{abs}(v_{miss}[i]), i = i_s, i_s + 1, \ldots, i_e\} \tag{34}$$

$$V_p = v_{miss}[i_p] \tag{35}$$

$$i_{p/2} = \text{index\_half}\{\text{abs}(v_{miss}[i]), i = i_p, i_p + 1, \ldots, i_e\} \tag{36}$$

$$T_r = (i_p - i_s)/f_s \tag{37}$$

$$T_d = (i_{p/2} - i_p)/f_s \tag{38}$$

index_max(.) gives the index of the maximum value of the argument
index_half(.) represents the index of the element whose value is half the maximum value of the input array
Note that V_p can be either positive or negative.

F. Flicker Generator

The parameters for flickers are shown in Table 5. Only the dominant modulation frequency component is considered.

Table 5. Parameters characterizing flickers

Pre-event magnitude V_{pre} and phase α_0
Post-event magnitude V_{post} and phase β_0
Event starting time t_s
Magnitude and phase of the modulation component V_{mod} and phase β_{mod}
Frequency of the modulation component f_{mod}

1) Signal construction:

$$v[i] = \sqrt{2} V_{pre} \cos(2\pi f_0 i / f_s + \alpha_0) \quad i \le i_s \tag{39}$$

$$\begin{aligned} v[i] = \sqrt{2}\{V_{post} + V_{mod} \cos(2\pi f_{mod} i / f_s + \beta_{mod})\} \\ \cos(2\pi f_0 i / f_s + \beta_0) \quad i > i_s \end{aligned} \tag{40}$$

2) Parameter extraction: V_{pre}, α_0, and t_s can be calculated from (4-7).

$$V_{rms}[n] = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} v^2[i + (n-1)N + i_s]} \tag{41}$$

Let V^s_{rms} be an array composed of $V_{rms}[n] - V_{post}$, n=1, 2,…, L_{rms} with $L_{rms=}\text{round}\{(L - i_s)/N\}$.

$$V_{post} = \text{mean}(V^s_{rms}) \tag{42}$$

$$\beta_0 = \text{angle}(V^s[1]) \tag{43}$$

$$V_{mod} = \{\max(V^s_{rms}) - \min(V^s_{rms})\}/2 \tag{44}$$

$$V_m[k] = \sum_{i=1}^{L_{rms}} v^s_{rms}[i] e^{-j\frac{2\pi k i}{N}} \tag{45}$$

$$i_m = \text{index\_max}\{\text{abs}(V_m)\} \tag{46}$$

$$f_{mod} = f_0 i_m / L_{rms} \tag{47}$$

$$\beta_{mod} = \text{angle}(V_m[i_m]) \tag{48}$$

G. Analytical Generator

This generator produces waveforms not based on the waveform features, but based on the analytical equations specified by the user. Arbitrary shapes of waveforms can be realized by this generator.

III. PROPOSED APPROACH FOR EQUIPMENT SENSITIVITY STUDY

This section presents the proposed approach for equipment sensitivity study, i.e., how various event parameters affect the equipment operating characteristics. Examination of how sag parameters affect the equipment behavior is emphasized next. As well known, some customer loads may trip or mis-operate due to the voltage sags. With the advent of electronic devices, the trip or mis-operation may no longer be just attributed to the sag magnitude and duration. Instead, other factors like points-on-wave, unbalance ratio, and phase angle shift may also play an essential role in the behavior of the modern loads during voltage sag events. Through equipment sensitivity study, the software can explain why a specific load failed during a sag event, or predict how well a load will perform during a particular sag event.

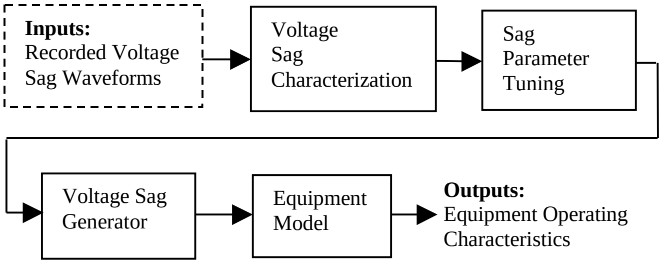


Fig. 3. The overall structure for equipment behavior evaluation

The overall structure for evaluating the equipment behavior under voltage sag events is depicted in Fig. 3. The inputs are the voltage sag waveforms that can either be recorded in the field or be generated by specific simulation packages. The outputs are the operating characteristics of the equipment during the specified sag events. The block “Voltage Sag Characterization” computes the various sag parameters. The block “Sag Parameter Tuning” allows the user to tune or edit the sag parameters, obtained from the block “Voltage Sag Characterization”, to certain values. The “Recorded Voltage Sag Waveforms” provide us with a set of initial sag parameters based on which further tuning can be made. However, the recorded waveforms are optional and if they are unavailable, the user can input any desired initial sag parameters and then tune them for testing. In either case, by tuning the sag parameters such as the sag magnitude, sag duration, phase angle shift, etc., the software allows the user to observe and study how specific sag parameters affect the operating characteristics of the equipment under test. This is what we call the equipment sensitivity study. The block “Voltage Sag Generator”, as described in section II, reconstructs the voltage sag waveforms based on the selected sag parameters. The constructed voltage waveforms serve as the voltage source for testing the equipment. The voltage sources can either be one phase or three phase depending on the equipment being evaluated. The “Equipment Model” allows development of mathematical models for the equipment.

Through the sensitivity studies, the operating characteristics of the equipment during various sag events can be evaluated and responses tabulated. For example, by changing only the sag magnitude while fixing all the other sag parameters at specified values, we can obtain a representation of the equipment operating characteristic versus sag magnitude. Table 6 shows the maximum speed drop of a motor under test (MSDM) versus the sag magnitude during the type A sags while the sag duration and phase angle shift are fixed at 50 ms and 20 degrees respectively. Characteristics such as the electromagnetic torque, currents, etc. can be analyzed similarly. The operating characteristics of the equipment versus other sag parameters can also be obtained and archived in the same way. By comparing the parameters of a specific sag event with the saved equipment operating characteristics, automatic equipment behavior diagnosis can be realized. Table 7 shows such an example. It is seen from the table that the sag magnitude is the main factor that has caused the mis-operation of the equipment. Definitions of the sag type and critical values are referred to [3].

Table 6. MSDM in percent versus the sag magnitude during type A sags

Sag magnitude (p.u.)	0.1	0.3	0.5	0.7	0.9	1.0
MSDM (%)	40.1	35.5	23.6	20.1	8.2	0.0

Table 7. Equipment behavior analysis results

Parameters	Critical Values	Actual sag parameters	Difference	Affect
Sag Type	A	A	\	\
Phase Angle Shift (Degree)	10.0	10.0	0	No
Sag Magnitude (p.u.)	0.59	0.32	-0.27	Yes
Sag Duration (ms)	100.0	100.0	0	No

Note that the above procedure also applies to the equipment sensitivity study under other types of events except that the waveforms of the concerned types are used instead of the sag events.

IV. CASE STUDIES

This section presents several cases for the equipment sensitivity study. The equipment under evaluation is an induction motor fed by a current-controlled PWM (pulse width modulation) inverter. The motor is rated as 3 HP, 220V and 60 Hz. The DC voltage is obtained by a 6-pulse diode bride. The capacitor size at the DC side is 4.4e-3 F. The inverter is built using six MOSFET blocks [8]. The speed control loop uses a proportional-integral controller to obtain the slip frequency reference that is used to control the amplitude and frequency of the three-phase controlled oscillator that produces the current references for the controller. Fig. 4 shows a diagram of the test system. In the figure, the “Sag Generator” generates the sag waveforms with specified parameters. The “Rectifier” provides the DC voltage for the “Variable Speed Drive (VSD)”.

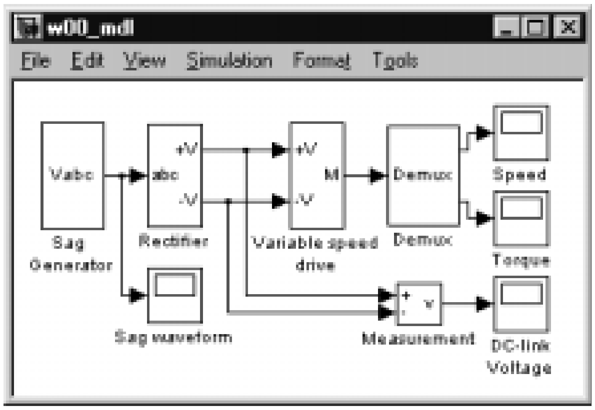


Fig.4. The testing system diagram

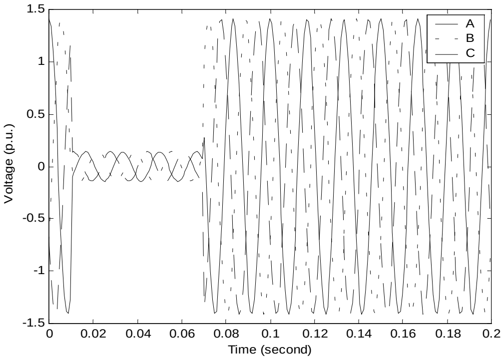


Fig. 5. The sag waveforms for testing

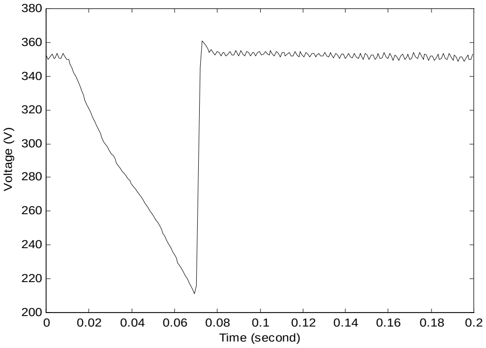


Fig. 6. DC link voltage variation during the event

Fig. 5 plots the sag waveforms used in the test. The sag has a magnitude of 0.1 p.u. and duration of 60 ms. The DC voltage, electromagnetic torque and rotor speed during the event are depicted in Fig. 6-8, respectively. It can be seen that the DC voltage has a 40% drop, and as a result the rotor speed has a 4.5% drop due to the sag event. The torque also has significant changes. In practice, variable speed drives are usually protected by the relaying system that trips the AC supply when the DC voltage drops below a pre-specified level. Through the equipment sensitivity study, critical values for the event parameters that may be useful for the coordination between the protection system and the equipment can be found.

The effects of other types of events on the performance of the VSD can be evaluated similarly. Studies show that the VSD is most sensitive to the sag, swell or interruption events.

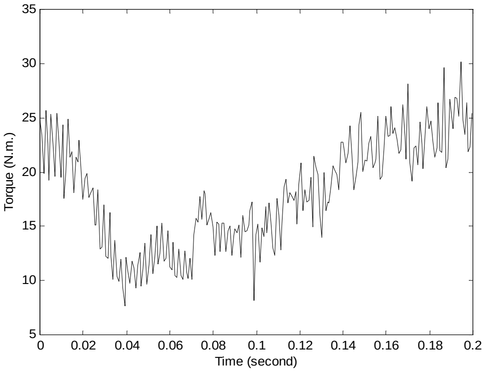


Fig. 7. Electromagnetic torque during the event

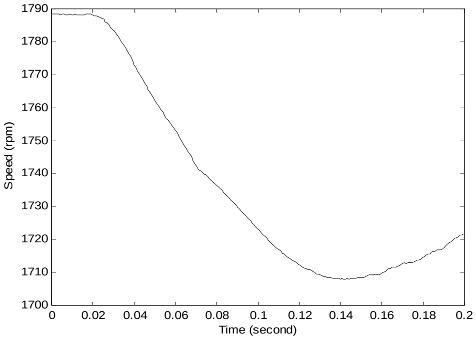


Fig. 8. Rotor speed during the event.

V. CONCLUSIONS

A new simulation approach for equipment sensitivity study during power quality events has been presented. The library for generating various types of events is described in detail. Case studies and simulation results for illustrating the application of the proposed method are presented. This allows one to consider all the power quality events of common types and to tune every event parameter for equipment evaluation purposes. It is shown that the proposed approach has a potential for real word applications.

VI. ACKNOWLEDGEMENT

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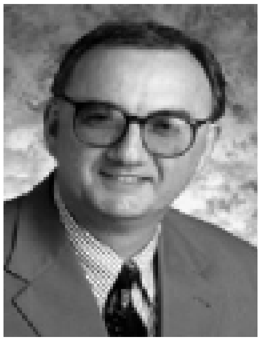
VIII. BIOGRAPHIES



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