RIDE-THROUGH COMPENSATION OF AN INDUSTRIAL MIXER DRIVE SUBJECTED TO VOLTAGE SAGS

*N. Serdar Tunaboylu and +E. Randolph Collins, Jr.

email:*serdar.tunaboylu@dumlupinar.edu.tr* **email:***randy.collins@ces.clemson.edu*

*****Dumlupinar University, Electrical and Electronics Engineering Dept., Kutahya, 43100 TURKEY*
+*Clemson University, Electrical and Computer Engineering Dept. , Clemson, SC 29634 USA*

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ABSTRACT

A new ride-through compensation scheme for an industrial mixer motor/drive system is presented during voltage sags. From d-q dynamic model of the electrical and mechanical processes, simulation equations are derived. A ride-through compensation scheme which exploits the surplus energy stored in the dc-link capacitor is introduced. An open-loop control Volts per Hertz boost strategy has been used in order to compensate the speed loss during the three-phase balanced voltage sags. Both compensated and uncompensated cases have been run and compared with simulation results. Experimental and simulation results shows reasonably good agreement.

I. INTRODUCTION

A voltage sag is a momentary decrease in voltage magnitude for a few cycles. Typically, voltage sags are unbalanced and last for 0.5 cycles to 3600 cycles with a magnitude of 0.1-0.9 pu (per unit) (on an RMS basis), depending on the nature of the disturbance, the type of overcurrent detection, and cause of interruption [1].

Modern industrial equipment incorporates many electronic devices. As more electronic control devices in industry such as adjustable speed motor drives (ASD) have been developed to be more complex and smaller, they have become less tolerant of voltage disturbances. Therefore, it is important to understand voltage sags and to minimize the losses caused by them [2,3].

II. VOLTAGE SAGS AND ADJUSTABLE SPEED DRIVES

Since industrial processes are generally automated, and an interruption can cause long, expensive delays in production due to loss of product, clean-up, and restarting.

Therefore, an improvement in the equipment's ability to "ride-through" a voltage sag will reduce the cost associated with undesired trips. Tripped ASDs may cause not only the production presently but production time and eventually substantial revenue loss [6-10].

A Novel Ride-Through Drive Modification

A typical ac drive only utilizes about 25% of the stored energy in the link capacitor during a voltage sag. Depending on the drive type and control scheme, the additional energy storage in the DC Link can be utilized in order to compensate the speed/torque loss or total shut down during the voltage sag. In this study, the additional dc link energy has been utilized without any extra energy supply. Modification on Volts per Hertz circuit has been implemented so that during the voltage sag speed loss has been minimized.

III. MODELING

If the power supply is balanced three-phase, as is usually the case when fed by a converter, the two axis or *d-q* theory is normally used for dynamic modeling. The details of the mathematical derivations of axes transformations and synchronously rotating reference frame equations for an Induction Motor may be found in [4, 5].

Well-established synchronously rotating reference frame model of the IM has been utilized [5]. In this equivalent circuit model, the input dq-voltages can be obtained from three-phase ac voltages through dq-transformation, and the circuit parameters can be obtained from steady-state model. Using stator and rotor dq-currents, i_{qs}, i_{ds}, i_{qr}, and i_{dr}, as the state variables, the state equations of the IM model can be derived from stator and rotor dq-axes loop equations. The state variable equations (1-6) show the derivation results.

The state variable form of the final equations for computer simulations may be written as:

$$\frac{di_{qs}}{dt} = \frac{1}{L_k}\left[L_r V_{qs} - L_r R_s i_{qs} - (\omega_e L_r L_s - \omega_{sl} L_m^2) i_{ds} + L_m R_r i_{qr} - \omega_r L_r L_m i_{dr}\right]$$

$$\frac{di_{ds}}{dt} = \frac{1}{L_k}\left[L_r V_{ds} - (\omega_e L_r L_s - \omega_{sl} L_m^2) i_{qs} - L_r R_s i_{ds} + \omega_r L_r L_m i_{qr} + L_m R_r i_{dr}\right]$$

$$\frac{di_{qr}}{dt} = \frac{1}{L_k}\left[-L_m V_{qs} + L_m R_s i_{qs} + \omega_r L_m L_s i_{ds} - L_s R_r i_{qr} + (\omega_e L_m^2 - \omega_{sl} L_r L_s) i_{dr}\right]$$

$$\frac{di_{dr}}{dt} = \frac{1}{L_k}\left[-L_m V_{ds} - \omega_r L_m L_s i_{qs} + L_m R_s i_{ds} - (\omega_e L_m^2 - \omega_{sl} L_r L_s) i_{qr} - L_s R_r i_{dr}\right]$$

$$L_k = \frac{1}{L_s L_r - L_m^2} \quad (5) \quad \text{and} \quad \omega_{sl} = \omega_e - \omega_r \quad (6)$$

$\omega_e =$ supply voltage angular frequency, equal to 377 rad/s for 60 Hz systems, $\omega_r =$ rotor angular frequency, and R_s, L_s, R_r, L_r, and L_m are IM parameters where $L_{ls} = L_s - L_m$ and $L_{lr} = L_r - L_m$. IM parameters were obtained via the conventional no load and locked rotor tests. The results are tabulated at the following Table 1 in the Appendix. A typical voltage source inverter drive system uses a constant dc link voltage as the source and three-phase induction motor (IM) as the load.

Boost Strategy

As long as the dc link voltage above 90%, the sag compensator circuit's output would be zero. Whenever dc link becomes less than 90% of the nominal due to a voltage sag, then the comparator and boost output will increase constant K in order to boost V/Hz and hence boost output PWM voltage. Therefore the drive will compensate the dc voltage loss by increasing the Volts/Hz ratio temporarily during the voltage sag. Fig. 1 shows the approximate Volts/Hertz boost region utilized for the analysis in this paper.

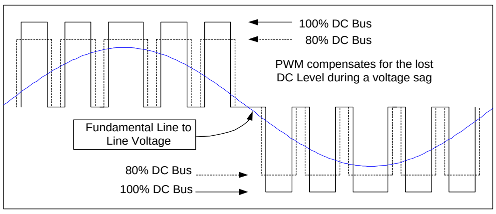

Fig. 1 PWM Voltage Boost Strategy during a voltage sag.

IV. SIMULATION RESULTS:

A. *Uncompensated Case Simulation Results*

The drive and the motor are set to run from standstill to steady-state full speed at no load and then the load torque is applied. The sag is initiated at 2.25 s and terminated at 2.65 s for a total of 400 ms.

Fig. 2 shows a 400ms, balanced 80% three-phase voltage sag, the DC Link voltage and the PWM output voltage. During the event, the DC link voltage drops from 280V to 220V. The PWM pattern and hence modulation index does not change during the voltage sag event. The horizontal line is the time in seconds and each PWM cycle has a period of 20 ms that corresponds to 50 Hz drive output. The DC Link threshold for triggering the Volts/Hertz boost is not activated. Therefore amplitude modulation index m_a stays the same as 1.0. Switching frequency is 750Hz. Frequency modulation index m_f is set to 15 for the simulation.

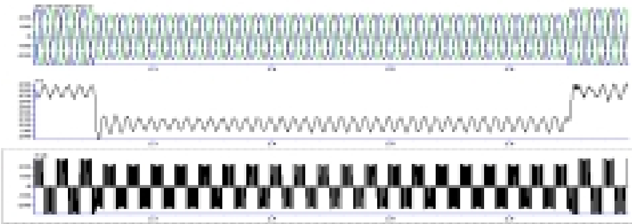

Fig. 2 Uncompensated Case: Balanced 3-phase 80% sag simulation; top: source voltages, middle: DC Link voltage, bottom: inverter PWM line to line output.

Predicted motor shaft torque and motor's power output along with the speed can be seen in Fig. 3. Since experimental setup's speed feedback is from the encoder coupled to the gearbox, speed has been reduced ten-fold in the simulations.

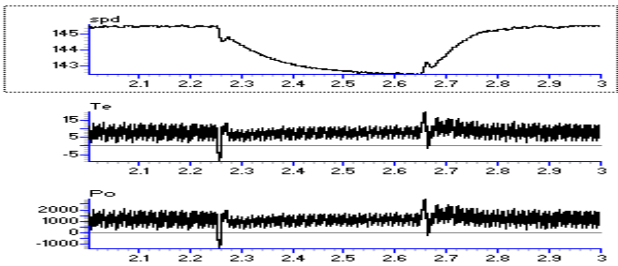

Fig. 3 Uncompensated Case: Predicted curves top: mechanical speed in rpm; middle: output torque in N-m; bottom: output power in watts.

As expected there is about 2.5 r/min speed loss during the voltage sag. Speed recovery after the sag takes about 150 ms. Both of the curves, decrease and recovery, appear to be exponential in nature. The torque pulsations have the two times the fundamental frequency.

B. Compensated Case Simulation Results:

Fig. 4 shows the same source voltages, dc link similar curve as compared to the uncompensated case.

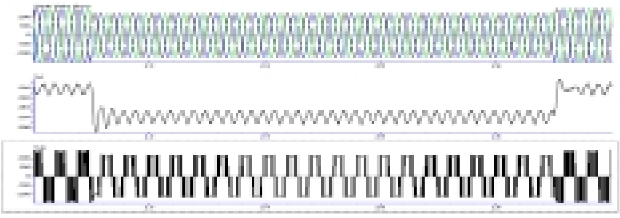

Fig. 4 Compensated Case: Balanced 3-phase 80% sag simulation; top: source voltages, middle: DC Link voltage, bottom: inverter PWM line to line output.

For the same operating conditions, the boost compensation on Volts/Hertz is made active. Now, there is a noticeable change in PWM pulse pattern. Whenever sag reduces the dc link voltage below 90% of the nominal, the PWM pulse pattern changes to more wider and higher voltage fundamental. Speed loss in this case is very limited, less than 0.5 r/min as it is clear from Fig. 5. Speed essentially stays at 146 r/min during the transient event.

V. EXPERIMENTAL RESULTS

A. *Experimental setup*

The laboratory prototype of an industrial mixer setup was built on a mobile platform to assess the effectiveness of the modeling and Simnon simulations as shown in Fig. 6.

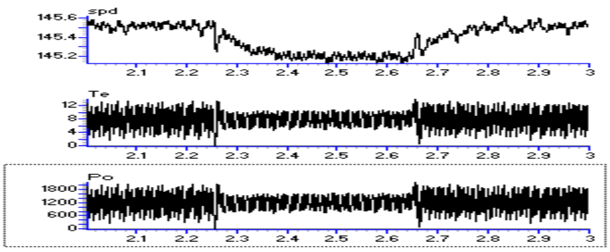

Fig. 5 Compensated Case: Predicted curves top: speed in rpm; middle: output torque in N-m; bottom: output power in watts.

The mixer shaft has a rigid coupling that can be easily dismounted in case of changing mixed materials inside the barrel. A VSI, open-loop control, 0-60Hz, adjustable frequency drive, and manufactured late in the 80's, was connected to an (inverter-duty) squirrel cage induction motor (IM). The speed reducer (worm gear) with 10:1 ratio was coupled directly to the motor's shaft. Then the speed reducers' vertically aligned output shaft is connected to a mixer with four blades. The mixer had a cylindrical container of 27x20" (width x height) where it could mix various materials (grain, rice, seed etc.) at different speeds.

The experimental setup consisted of a Sag Generator, an Adjustable Speed Motor Drive, an Induction Motor, a Speed Reducer, a Mixer, an Encoder, a Tachometer, various Multimeters, a Digital Oscilloscope, and a Power Transducer (Wattmeter).

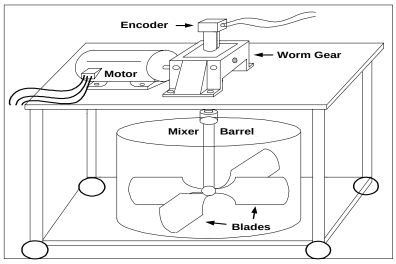

Fig. 6 Motor-Gear-Mixer Laboratory Prototype Setup.

The sag generator in the Power Quality Laboratory at Clemson University has rated 20 Amp output capability, and 208 Volts line voltage [11]. All three phases individually or any combination can be sagged for a desired duration of (0-450ms), and sag amplitude levels for each phase adjustable at certain percentage levels as 0-20-40-60-80%. It also provides triggering pulse for synchronization.

Boost Circuit: Volts per Hertz (V/Hz) compensation is accomplished by modifying the voltage source (VSI), sinusoidal PWM inverter's V/Hz Boost circuit. Since we do not have a direct access to the amplitude modulation index, m_a, the desired effect can be achieved indirectly by boosting drive's internal reference V/Hz circuit. The strategy here was to get fastest response of V/Hz Boost output whenever a voltage sag is detected or sensed on the DC Link.

The circuit has been designed on two OpAmp (Operational Amplifier) stages as seen in Fig. 7. The output of the second stage has been tuned so that at nominal DC Link voltage it's output is around 1.0 volts. The circuit is designed on a breadboard and tested with a 0-230VAC, 0-20Amp Variac.

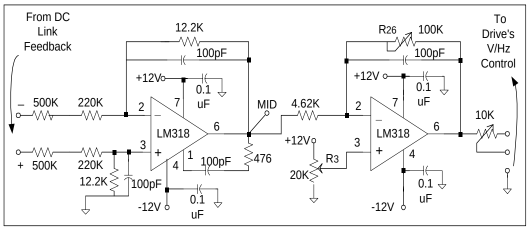

Fig. 7 Drives Volts/Hertz compensation circuit with a boost pulse.

The boost circuit has been connected to the Volts/Hz compensation circuit mounted on the control circuit boards of the drive.

Mixer Design: In order to load the motor with a non-inertial load, there is a need to design an experimental mixer. Having a speed reducer like worm gear is a first step to cancel the inertial effect on the motor's shaft. Then second issue is to have a load that functions properly with the gear. A mixer from fan blades has been made along with its surrounding barrel. After trying sand, rice, water; bird feed has been chosen as the qualifying material for the mixer because it is less prone to friction, noise, and dust. The mixer barrel has 27" diameter (68.6 cm) and 20" height (50.8 cm) and the volume of the barrel is 6.65 ft^3 which is equal to 0.185m^3. The mixer blades have 15" diameter (38.1 cm) and 1" (2.54 cm) bore size.

B. Laboratory Measurements

The mixer was loaded with seed that fully covered the mixer blades (50% of the barrel volume). Motor current was stabilized at 6.5 Amps r/min at a speed of 146 r/min on the mixer shaft. The drive was set to 50Hz with 161V r/min output. The DC bus was at 280-285VDC.

Uncompensated Case: As shown in Fig. 8, pre-event steady-state speed of 146 r/min down to 144.5 r/min on the mixer. The total speed loss is about 1.5 r/min, compared to 2.5 r/min on the simulations. The error is likely coming from the drives double horsepower rating, i.e. the drive is rated for twice the motor rating and the averaging delay of the tachometer.

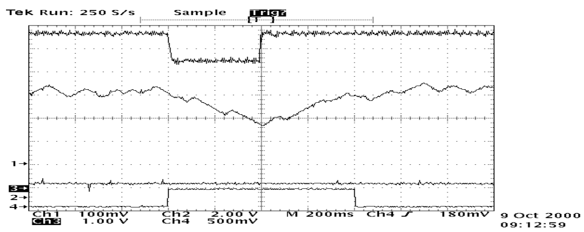

Fig. 8 Uncompensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: speed, third: boost voltage, bottom: trigger.

The speed recovery takes about 400 ms back to original speed. The third flat curve is the boost circuit's output that stays the same at 1.08Volts level during the voltage sag. The last curve at the bottom is the sag generator and scopes triggering pulse that activates the sag generator output and the scopes recording functions.

Fig. 9 shows the other important measurements for the same uncompensated case. The top curve is again the DC Link voltage collapse and the bottom is the trigger. The PWM voltage amplitude has been reduced during the sag and there is no change in modulation index. Motor current is briefly reduced at the beginning of the sag and made an overshoot to two times the nominal at the recovery.

Fig. 10 enlarges the sag initiation part of the sag in order for a closer look at the PWM pulse pattern and current waveforms. These results are very similar to the ones in the simulations

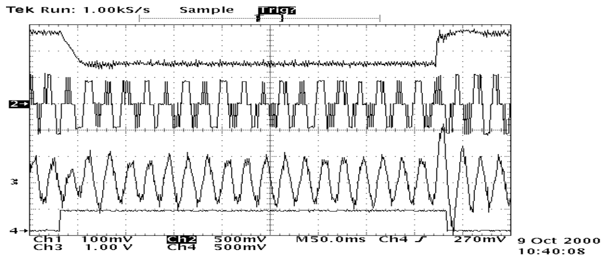

Fig. 9 Uncompensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: PWM voltage, third: motor current, bottom: trigger.

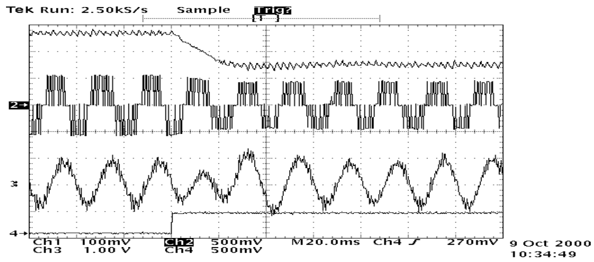

Fig. 10 Sag Initiation of the Fig. 9 uncompensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: PWM voltage, third: motor current, bottom: trigger.

Fig. 11 shows the recovery part of the sag enlarged. Current overshoots and the PWM pulse pattern don't change, but the only change in amplitude. The DC Link voltage and the motor current have a high frequency modulation envelope coming from the process irregularities (wobbling on the shaft, modulation in the speed).

Compensated Case: The compensated case DC Link voltage, speed, boost voltage output and the trigger pulse are shown in Fig. 12. The speed has been compensated during the sag with less than 0.5 speed loss and small recovery overshoot. The third curve is the 6 volts boost voltage pulse. It has a response time of about 10 ms. It maintains its level as long as the DC Link is less than the 90% nominal. Whenever the DC Link recovers, it returns to the normal 1.0 volts boost level.

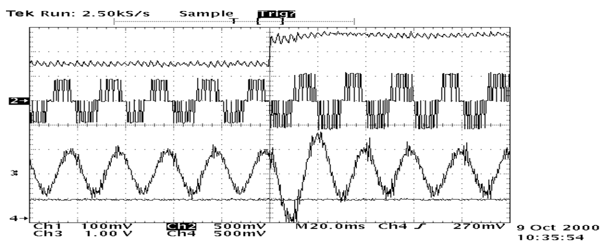

Fig. 11 Sag Recovery of the Fig. 9 uncompensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: PWM voltage, third: motor current, bottom: trigger.

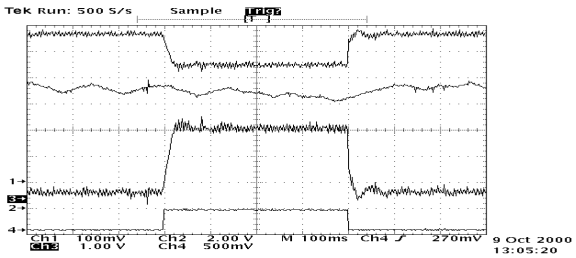

Fig. 12 Compensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: speed, third: boost voltage, bottom: trigger.

Fig. 13 shows the compensated case PWM pulse pattern and the motor current behavior during the balanced 80% three phase voltage sag of 400 ms duration during the sag initiation.

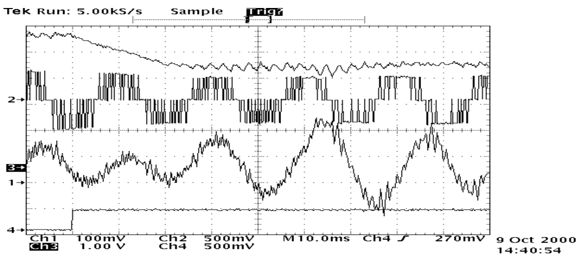

Fig. 13 Sag Initiation of the Fig. 12 compensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: PWM voltage, third: motor current, bottom: trigger.

The current has a bigger overshoot than the uncompensated case because of the pulse pattern transition with an open loop control. It is clear that the pulse pattern changes after 40 ms time delay when the boost circuit requests an increase in modulation index. The motor current swells during the modulation index change transition time.

Fig. 14 shows the sag recovery side of the waveform for compensated, balanced, three phase, 80%, 400 ms voltage sag case. It takes longer than 40 ms for the pulse pattern and hence the amplitude modulation index to change back to the initial conditions.

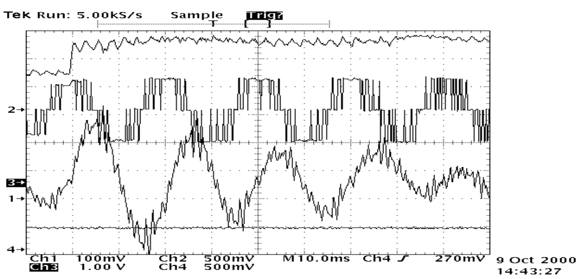

Fig. 14 Sag Recovery of the Fig. 12 compensated case of 80% balanced voltage sag of 400ms duration; top: DC Link voltage, second: PWM voltage, third: motor current, bottom: trigger.

VI. CONCLUSIONS

An adjustable speed drive, motor and an industrial mixer laboratory prototype setup has been designed, built and operated for voltage sag studies. Modification for the drive circuit has successfully implemented. Three phase balanced voltage sags of 80% remaining have been applied to the setup and compensated and uncompensated cases have been explored. Modeling of the complete system has been done in Simnon (Nonlinear Simulator) environment. Open-loop (Volts per Hertz) control model of a squirrel cage induction motor has been modeled along with the sinusoidal PWM drive and the mixer load. Experimental and simulation results shows reasonably good agreement.

VII. APPENDIX

Table 1. IM Data

Nameplate Data	Test Data
3 hp	$R_S = 0.6\ \Omega$ (+)
208 V	$R_R = 0.66\ \Omega$ (*)
8.5 A	$X_S = 1.28\ \Omega$ (*)
60 Hz	$X_R = 1.28\ \Omega$ (*)
1765 r/min	$X_M = 28.4\ \Omega$ (#)

(+):DC measurement (cold) (*):From locked rotor test (#): From no-load test

VIII. BIBLIOGRAPHY

[1] IEEE Recommended- Practice for Monitoring Electric Power Quality, IEEE Std. 1159-1995 (2001).

[2] M. F. McGranaghan, D. R. Mueller, and M. J. Samotyj, "Voltage sags in industrial systems," *IEEE Trans. on Ind. Appl.*, vol. 29, no. 2, pp. 397-402, March/April 1993.

[3] L. Conrad, K. Little, and C. Grigg, "Predicting and preventing problemsassociated with remote fault-clearing voltage dips," *IEEE Trans. on Ind. Appl.*, vol. 27, no. 1, pp. 167-172, January/February 1991.

[4] B. K. Bose, Power Electronics and AC Drives, Prentice-Hall, Inc., 1986.

[5] P.C. Krause, O. Wasynzuk, S. D. Sudhoff, Analysis of Electric Machinery, IEEE Press, New York, 1995.

[6] N. S. Tunaboylu, E. R. Collins, Jr., S. W. Middlekauff, and R. L. Morgan, "Ride-through issues for DC motor drives during voltage sags," *Proceedings of 1995 IEEE Southeastcon*, Raleigh NC, pp. 52-58.

[7] N. S. Tunaboylu, E. R. Collins Jr., P. R. Chaney, "Voltage Disturbance Evaluation Using the Missing Voltage Technique", *8th International Conference on Harmonics and Quality of Power Proceedings*, Oct. 1998., pp. 577-582.

[8] M. H. J. Bollen, P. Wang, N. Jenkins, "Analysis and consequences of the phase jump associated with a voltage sag," *Power Systems Computation Conf.*, August 1996, Dresden, Germany.

[9] M. H. J. Bollen, "The influence of motor re-acceleration on voltage sags ," *IEEE Ind. Appl. Society Annual Meeting Conf. Rec.*, pp. 2235-2242, 1994.

[10] A. E. Turner and E. R. Collins, Jr., "The performance of AC contactors during voltage sags," *Proceedings of 7'th Int. Conf. on Harmonics and Quality of Power*, Oct. 1996, pp. 589-595.

[11] S. Middlekauff, "Using a Sag-Generator to Identify Power Quality Problems in Industry", Master's Thesis, Clemson Univ. , May 1996.