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Content

Power Engineering and Power System

Voltage Sag Compensation Using Two Three-Phase Voltage-Fed PWM Converters

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***Abstract*-Voltage sag compensation using two three-phase voltage-fed PWM converters is presented. This is new approach to mitigate the voltage sags without using special energy storage devices or power transformers. In the normal incident, the load is fed the power from utility supply via main static transfer switch. When voltage sag is occurred, the main static transfer switch is opened and the auxiliary static transfer switch is closed respectively to feed the power from two three-phase voltage-fed PWM converters into the load instead of faulted utility supply. The operation under 4 conditions of voltage sag of 7.5-kW voltage sag compensator using two three-phase voltage-fed PWM converters is verified by simulation using MATLAB/Simulink. It can be seen that the load received continuous power during voltage sags, the transition from utility supply to two three-phase voltage-fed PWM converters is almost seamless, and the synchrony between utility supply and two three-phase voltage-fed PWM converters is correct. Moreover, utility supply current is kept to be sine wave during sag occurrences and line power factor is also maintained nearly unity.**

I. Introduction

Of all known power quality problems, voltage sag is one of the major factors that affect the quality of power supply which occurs in a power system. Several studies report that 92% of all disturbances in electrical power distribution systems are due to voltage sags [1]. It has a significant influence on high-technology equipment related to communication, advanced control, automation, precise manufacturing techniques, and on-line service. These disturbances can cause equipment to fail, or shut down, which could produce huge losses to the customers.

Nowadays, several ideas have been reported on the mitigation of voltage sags. Some approaches using dynamic voltage restorer by means of energy storage devices and power transformers [2]. Some approaches using boost or buck-boost converters incorporate with inverter [3], this approaches introduced the input current distortion during voltage sags. Some approaches using interphase AC-AC topology by means of AC choppers and isolation transformers [4]. A conventional three-phase voltage sag compensator consists of a three-phase full-bridge rectifier, a boost converter, a three-phase PWM inverter. The rectifier and the boost convert the input voltage sag into the dc-link voltage with PWM strategy. On the other hand, the inverter converts the dc-link voltage into the output voltage with PWM strategy. Therefore, the regulated sinusoidal output voltage can be achieved. The set of AC/DC/AC converters is operated when sag of the input voltage occurs. For proper operation of the bypass circuit, the input voltage is in the normal condition, the critical load is connected to the utility supply via the main static transfer switch (STS). When the voltage sags occur, the main STS are opened and the auxiliary STS are closed. The inverter delivers power to the critical load [3]. However, the drawback of this circuit topology caused by the boost converter. In practice, it is difficult to design a boost converter with high step-up gain due to the equivalent series resistance element that cause poor efficiency and degraded voltage gain.

This paper proposes voltage sag compensation using two three-phase voltage-fed PWM converters to mitigate the voltage sag. The proposed voltage sag compensator draws the power from utility supply and feed the power to load during voltage sags occurrences. Its advantages are not needed special energy storage devices or transformers likes several method [2]-[4], ability to compensate deep and long-duration voltage sags, low total harmonic distortion of the input currents, and high input power factor.

II. Principles of Operation

Fig. 1 shows the circuit schematic of the voltage sag compensator with two three-phase voltage-fed PWM converter. It consists of two static transfer switches, two three-phase voltage-fed PWM converters, and output LC filters. Two three-phase voltage-fed PWM converters can be easily considered to be AC/DC/AC converter with wide range input voltage. It also can be noted that two three-phase voltage-fed PWM converters are consisted of supply-side converter and the load-side converter. Supply-side converter is performing a voltage rectification from the AC utility supply voltage to constant dc-link voltage. While the load-side converter is performing a voltage inversion from constant dc-link voltage to the AC load voltage. It can be considered that supply-side converter is a major part of the proposed voltage sag compensator since dc-link voltage must be kept constant regardless of varying utility supply voltages. This is such a simple system because load-side converter is controlled by means of open loop scheme, only supply-side converter is controlled by means of closed loop control scheme i.e. vector control scheme that provide low total harmonic distortion of the input currents and high input power factor.

In the normal incident, the utility supply directly feeds the power to load via main static transfer switch. Whenever the voltage sags occur, the main static transfer switch is opened to

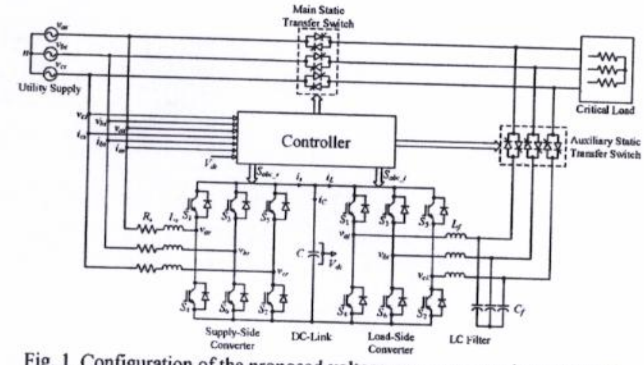

Fig. 1. Configuration of the proposed voltage sag compensation using two three-phase voltage-fed PWM converters.

disconnect load from the utility supply and then auxiliary static transfer switch is closed to connect between the load-side converter and load. It can be noted that in this incident, the load is fed the power from the load-side converter instead of faulted utility supply during voltage sag occurrences. The load is then fed the power with no interruption and continuous operation is available.

III. Control Method

A. Control strategy of supply-side converter.

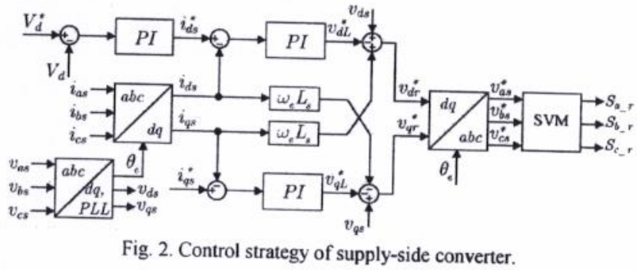

Fig. 2. Control strategy of supply-side converter.

As show in Fig. 2, the control scheme of supply-side converter contains internal current regulation loops and external dc-link voltage control loop. The objective of supply-side converter is to keep the dc-link voltage constant regardless of the variation of the utility supply voltages. To obtain this purpose, a vector control is adopted. The utility supply voltages can be expressed as follows:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = R_s \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} v_{ar} \\ v_{br} \\ v_{cr} \end{bmatrix}. \tag{1}$$

where v_{as}, v_{bs}, v_{bs} are the utility supply phase voltages, v_{ar}, v_{br}, v_{br} are the converter phase voltages, i_{as}, i_{bs}, i_{bs} are the utility supply phase currents, R_s and L_s are the utility supply inductor and resistor, respectively. Having the *abc-dq* transformation [5], the utility supply voltage in the *dq* reference frame equations are obtained.

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_e L_s \\ \omega_e L_s & 0 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix}, \tag{2}$$

where v_{ds}, v_{qs} are the $d-q$ axis utility supply voltages, v_{dr}, v_{qr} are the $d-q$ axis converter voltages, i_{ds}, i_{qs} are the $d-q$ axis utility supply currents. From (2), it can be seen that the $d-q$ axis voltages are cross coupled by terms of $-\omega_e L_s i_{qs}$ and $\omega_e L_s i_{ds}$, respectively.

The utility supply voltage angle has to be determined. By definition, the utility supply voltage angle as follow:

$$\theta_e = \int \omega_e dt = \tan^{-1} \frac{v_{\beta s}}{v_{\alpha s}}, \tag{3}$$

where $v_{\alpha s}, v_{\beta s}$ are the $\alpha - \beta$ axis utility supply voltages, ω_e is the utility supply angular frequency, $\omega_e = 2\pi f_e$, and θ_e is the utility supply voltage vector position. The angular position can be also obtained from Phase Locked Loop (PLL).

The dc power has to be equal to the active power flowing between the utility grid and the dc-link inverter. Thus,

$$V_{dc} i_s = \frac{3}{2} v_{ds} i_{ds}, \tag{4}$$

$$C \frac{dV_{dc}}{dt} = i_s - i_L. \tag{5}$$

where V_{dc} is the dc-link voltage, i_s is the current between the dc-link and the utility supply, i_L is the current between the dc-link and the critical load, and C is the dc-link capacitor.

B. Control strategy of load-side converter.

For the simple structure, the open loop scheme is applied to load-side converter as shown in Fig. 3. When v_{ds} is a load voltage command, while v_{qs} is set to zero and the angular position is obtained from supply-side converter control scheme. It can be seen that if dc-link voltage is constant value then the constant AC load voltage can be also achieved.

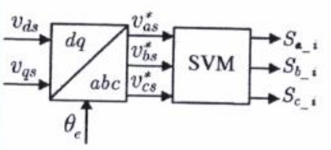

Fig. 3. Control strategy of the load-side converter.

C. Voltage sags detection method.

Voltage sags detection method in this paper is based on the *abc-dq* transformation due to its advantages [3]. This *abc-dq* transformation gives dc quantities proportion to ac quantities of the utility supply which no delays.

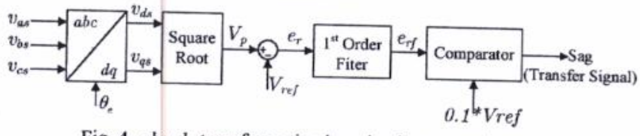

Fig. 4. *abc-dq* transformation based voltage sags detection.

From Fig. 4 $V_p = \sqrt{v_d^2 + v_q^2}$, this voltage varies with the utility supply voltage then the voltage sags can be detected from value of V_p. The amplitude of V_p is compared to the reference voltage V_{ref} and it is then filtered by first order low-pass filter. The low-pass filter output e_{rf} is compared to a voltage-variation tolerance limit (10% of V_{ref}). The comparator output is a transfer signal, which starts a transfer process when the utility supply fails.

IV. Simulation Results

The proposed control system for the voltage sag compensator is investigated in this section via computer simulations using MATLAB/Simulink simulation program, as shown in Fig. 1. The system parameters of the test setup are given in TABLE I. The load in this case is a series R-L branch.

TABLE I Simulation Setup Parameters

R-L Load	7.5kW
Supply-side converter input inductor, L_s	10 mH
Supply-side converter input resistor, R_s	0.1 m Ω
Dc-link capacitor, C	4,700 μF
Supply-side converter switching frequency	2 kHz
Load-side converter output inductor, L_f	4 mH
Load-side converter switching frequency	2 kHz
Utility supply phase voltage	220 Vrms, 50 Hz
Dc-link voltage set point	600 V

Fig. 6-9, show simulation results for the utility supply voltage, load voltage, and dc-link voltage, respectively. All cases of voltage sags have the 200 ms or 10T sag duration.

In Fig. 6, the case of a 75% single-phase voltage sag, only one utility supply voltage will be affected and two utility supply voltages remain undisturbed. In this case, at the inception of the voltage sag entry, the dc-link voltage is less dropped than other cases. While in the case of a 75% two-phase voltage sag, only one utility supply voltage remains undisturbed and two utility supply voltages will be affected and the dc-link voltage at the inception of the voltage sag entry is more dropped than single-phase voltage sag, as shown in Fig. 7.

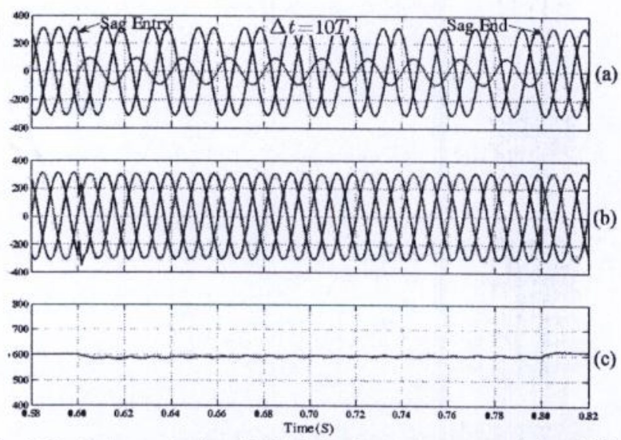

Fig. 6 Simulation results for a 75% single-phase voltage sag, $\Delta t = 10T$. (a) The utility supply phase voltages for a single-phase voltage sag, (b) The load phase voltages, and (c) The dc-link voltage.

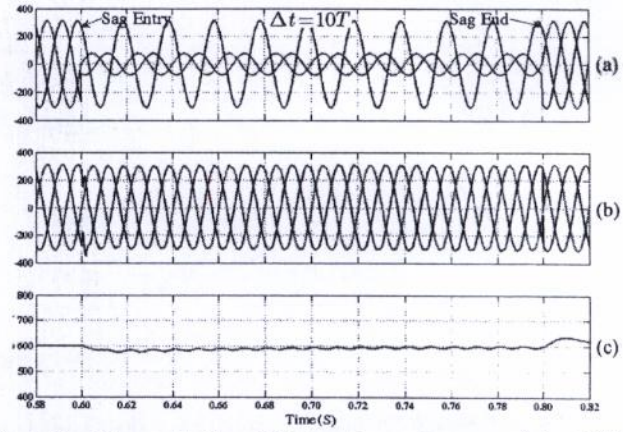

Fig. 7 Simulation results for a 75% two-phase voltage sag, $\Delta t = 10T$. (a) The utility supply phase voltages for a single-phase voltage sag and (b) The load phase voltages and (c) The dc-link voltage.

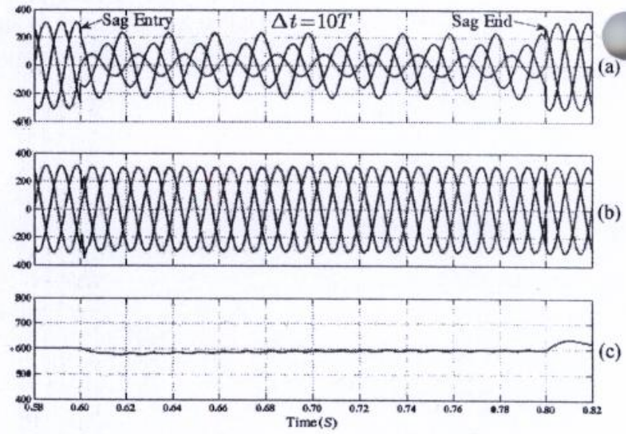

Fig. 8 Simulation results for a 75%-50%-25% unbalance three-phase voltage sag, $\Delta t = 10T$. (a) The utility supply phase voltages for a single-phase voltage sag, (b) The load phase voltages, and (c) The dc-link voltage.

Fig. 9 Simulation results for a 75% balance three-phase voltage sag, $\Delta t = 10T$. (a) The utility supply phase voltages, (b) The load phase voltages, and (c) The dc-link voltage.

Fig. 8 shows the case of a 75%-50%-25% unbalance three-phase voltage sag, all of three utility supply voltages will be affected but different depth of the sag. In this case, the dc-link voltage is slightly more dropped than two-phase voltage sag. In Fig. 9 shows the case of a 75% balance three-phase voltage sag, all of three utility supply voltages will be affected in the same depth of the sag and the dc-link voltage is the most dropped than other cases. It can be noted that all the case of voltage sags, load voltage is regulated during voltage sag by keeping the dc-link voltage regulated using vector control scheme applied to the supply-side converter.

Load voltage waveforms in all cases of voltage sags illustrates that load is seeing an almost seamless transition from the utility supply to load-side converter and then back to the utility supply when the voltage sag is end. In addition, it can be seen that the synchrony between both sources is correct.

Fig.10 shows simulation results for balance three-phase voltage sag operation condition. Fig. 10(a) shows the waveform of the utility supply voltages and utility supply currents, for a balance 75% three-phase voltage sag when sag duration is $\Delta t = 10T$. Fig. 10(b) shows the extended view of utility supply voltages and utility supply currents in the same condition, it can be seen that the compensation method is keeping the line power factor to nearly unity, low harmonic pollution. Additional, the total harmonic distortion of the current (THDi) under proposed is about 1.24% of the fundamental current.

Simulation results for verifying load voltage generation during balance three-phase voltage sag condition are shown in Fig. 11. Fig. 11(a) shows the waveform of load voltages, for a 75% balance three-phase voltage sag when sag duration is $\Delta t = 10T$. Fig. 11(b) shows the extended view of load voltages in the same condition, it can be noted that load voltage under voltage sag duration is almost sine wave, the total harmonic distortion of load voltage (THDv) is about 1.26% of the fundamental voltage.

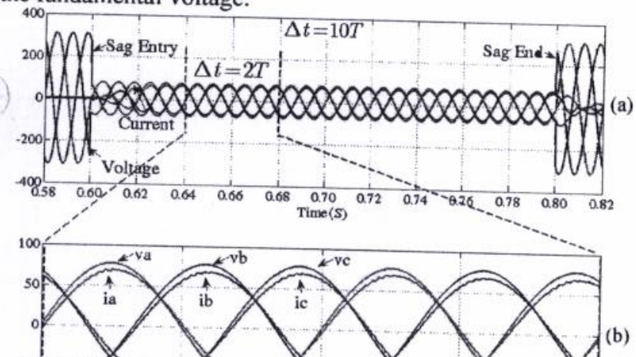

Fig. 10 Simulation results for verifying power factor correction operation. (a) The utility supply phase voltages and utility supply phase currents, a 75% three-phase voltage sag, $\Delta t = 10T$. (b) Extended view of the utility supply phase voltages and utility supply phase currents, 75% three-phase voltage sag, $\Delta t = 2T$.

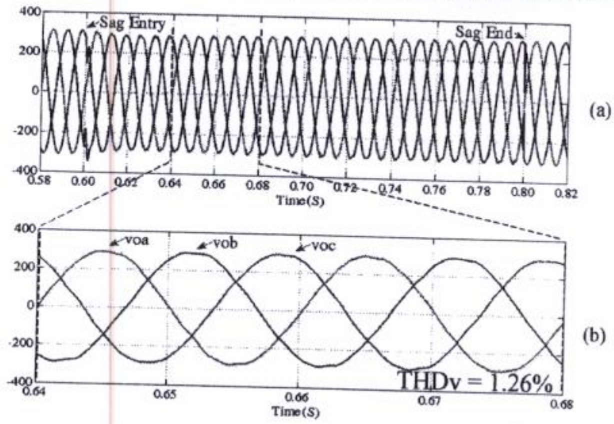

Fig. 11 Simulation results for verifying load voltage generation during voltage sag. (a) The load voltages, 75% balance three-phase voltage sag, $\Delta t = 10T$. (b) Extended view of The load voltages, 75% balance three-phase voltage sag, $\Delta t = 2T$.

V. Conclusion

In this paper, a new type of voltage sag compensation using two three-phase PWM converters have been proposed to mitigate voltage sag. This voltage sag compensator has many advantages such as no bulk storage devices, ability to compensate up to 75% of various voltage sags, low total harmonic distortion of the utility supply current and load voltage, and high input power factor. The simulation results are shown that the proposed voltage sag compensator can provides continuous power to load under 4 conditions of voltage sag. The output of voltage sag compensator is synchronized with the utility supply voltage, and it is regulated by keeping the dc-link voltage regulated via vector control scheme that applied to the supply-side converter. The simulation results are also shown that during sag, the utility supply currents have low total harmonic distortion and the input power factor is maintained to be nearly unity which caused the less power quality problem.

VI. References

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Message from general chairman of ECTI-CON 2011

It is my great pleasure and privilege to welcome you to the 2011 Electrical Engineering, Electronics, Telecommunications and Information Technology Conference (ECTI-CON 2011). This conference aims to gather researchers to share information and bring old friends together. The venue is at the Pullman Raja Orchid, down town in KhonKaen, and the conference date is May 17-19, 2011.

ECTI-CON 2011 is the eighth ECTI-CON, which started in 2004 at Pattaya. It makes a remarkable progress in the fields related to ECTI-CON that achieves the objective of the conference. This time, the conference is technical co-sponsored by IEEE Thailand Section and Faculty of Engineering, KhonKaen University.

I appreciate Dr.AdisornTuantranont of National Electronics and Computer Technology Center, Prof.Jun-ichi Takada of Tokyo Institute of Technology, and Prof.K.R.Rao of University of Texas at Arlington for spending their time to give keynote addresses at the opening ceremony and during the conference.

We organize a special issue on ECTI-CON 2011. The authors are encouraged to extend the materials published in the proceedings for consideration for publishing in ECTI-EEC and ECTI-CIT Transactions.

The social events during the conference will be a reception party and a banquet on May 17 and 18, respectively. The best paper will be awarded in the banquet.

I would like to express my sincere appreciation to all the sponsors and all committee members including reviewers to make this conference success. Last but not least, I appreciate all the authors and speakers whom without them the conference might not be possible.

I look forward to seeing in KhonKaen.

MonaiKrairiksh
General Chair ECTI-CON 2011

Message from Dean of Faculty of Engineering KhonKaen University

On behalf of the ECTI-CON 2011 organizing committee, we are very pleased to welcome you to KhonKaen, Thailand for the eighth Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI) Association (or ECTI-CON 2011).

This is the first time ECTI conference is held in KhonKaen, and it is an honor for the Faculty of Engineering of KhonKaen University to be the host and to have the opportunity to receive a large number of participants from many parts of the world. KhonKaen is the commercial and political center of Northeastern Thailand. The city is well known for high quality silk, noteworthy Buddhist temples, dinosaur fossils, and delicious Isan food. We hope you enjoy your stay in KhonKaen.

We would like to thank the technical program committee members, staff and reviewers for their diligent reviews of the submitted papers, the organizing committee members for their dedication and time preparing ECTI-CON 2011 and the authors, presenters and delegates for their contribution and participation. Also we are grateful to all distinguished keynote speakers: Prof.Dr.Jun-ichi Takada, Prof.Dr.K.R.Rao, and Dr.AdisornTuantranont as well as all session chairs.The success of the conference depends on the help of many people, and our thanks go to all of these people.

Welcome to ECTI-CON 2011 and the City of KhonKaen. We hope that you enjoy both the technical program and the city of KhonKaen.

Associate Professor Dr. SomnukTheerakulpisut
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Voltage sag compensation using two three-phase voltage-fed PWM converters

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ABSTRACT

Voltage sag compensation using two three-phase voltage fed PWM converters is presented. This is new approach to mitigate the voltage sags without using special energy storage devices or power transformers. In the normal incident, the load is fed the power from utility supply via main static transfer switch. When voltage sag is occurred, the main static transfer switch is opened and the auxiliary static transfer switch is closed respectively to feed the power from two three-phase voltage-fed PWM converters into the load instead of faulted utility supply. The operation under 4 conditions of voltage sag of 7.5-kW voltage sag compensator using two three-phase voltage-fed PWM converters is verified by simulation using MATLAB/Simulink. It can be seen that the load received continuous power during voltage sags, the transition from utility supply to two three-phase voltage-fed PWM converters is almost seamless, and the synchrony between utility supply and two three-phase voltage-fed PWM converters is correct. Moreover, utility supply current is kept to be sine wave during sag occurrences and line power factor is also maintained nearly unity.

INDEX TERMS

- **IEEE terms**
  Delay , Feeds , MATLAB , Power quality , Pulse width modulation , Pulse width modulation converters , Switches
- **INSPEC**
  - **Controlled Indexing**
    PWM power convertors , energy storage , power supply quality , power transformers
  - **Non Controlled Indexing**
    MATLAB , Simulink , energy storage devices , power 7.5 kW , power transformers , static transfer switch , three-phase voltage-fed PWM converters , utility supply , voltage sag compensation , voltage sag compensator

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