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New Power Quality Solutions Especially Designed For Industrial Applications

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***Abstract*— While modern industrial facilities are enjoying huge benefits from the evolution of power electronic devices in terms of productivity, quality or cost-reduction, their high sensitivity and little ride-through capability to common power quality disturbances result in significant economic losses.**

Nowadays it is possible to reach almost 100% availability of power supply with both DC and AC for many applications. However there is still a gap when facing to apply some of these power quality solutions in high power industrial processes, for several reasons (investment, space, long-term energy losses cost, high temperatures or dirtiness, regenerative loads), since most of them were developed for IT industries. When immunizing against disturbances, purchasing cost, return on investment versus saving, maintenance cost, efficiency, size, reliability or availability are the key decision criteria to industrial decision makers.

Driven from the real need of industrial customers to solve power quality problems and having in mind these criteria, IBERDROLA in collaboration with CORPORACION ZIGOR has developed two families of power conditioning solutions specifically designed for industrial end-users and created to cover almost any kind of power quality issues.

These solutions have been validated in a variety of industrial facilities including ceramic tiles manufacturing, plastics and polymers processing, paper manufacturing or pumping stations.

Keywords – industrial customers; power quality; UPS; DVR

I. Industrial Power Quality Problems

Although utilities keep on trying to improve the reliability of the grid, sensitivity of industrial equipment to power quality disturbances increases as automation and electronics become more ubiquitous in industry.

Tipically industrial equipment complies with sensitivity curves as the one defined by IEEE 446 standard (Fig. 1) or others similar.

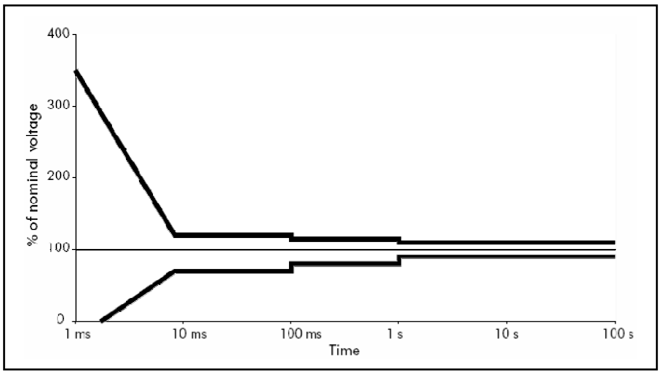

Figure 1. IEEE 466 standard for equipment sensitivity.

Unfortunately, it is known that electrical networks cannot guarantee these thresholds in a continuous way.

Fig. 2 shows the most common pertubances affecting the adequate operation of industrial equipment, namely: transient overvoltages (surges), flicker, voltage deviations, voltage dips, interruptions and waveshape disturbances.

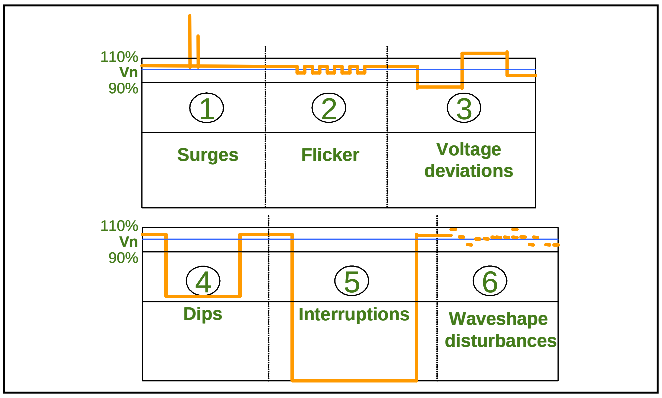

Figure 2. Typical power quality problems.

This paper presents two innovative solutions concieved with preciseness to industrial enviroments and deals with problems 2 to 5.

II. NEW POWER QUALITY CONDITIONERS

As mentioned above, interruptions and voltage dips are probably the perturbances causing higher losses in industry. Nowadays it is possible to find different types of power conditioning equipments (static or rotary double-conversion UPS, DVR) able to reach almost 100% availability of supply. Nonetheless there are several restrictions that frequently made difficult their application for industrial processes, since most of them were developed for the IT industries. Thus, traditional online-UPS are not properly adapted to high power demanding industrial applications (investment, space required, long-term energy losses cost, not ready for high temperatures or dirtiness, not ready for regenerative loads). When immunizing from disturbances, the key criteria for industrial decision makers is to balance purchasing cost and return of investment versus saving, maintenance cost, efficiency, size, reliability or availability.

A first group of mitigation equipment with battery-based energy storage has been designed to cover short interruptions and others important power quality issues (voltage sags/swells or surges) but also to avoid common problems of double-conversion UPS. Operating efficiencies higher than 99%, integrated air-conditioning system for batteries and robustness are some of its features. This solution has been named SEPEC.

But some of the customers are mainly affected by voltage dips and not by interruptions, either due to the network topology or because the customer is capable of working in an islanding mode. Typical values of dip that frequently cause industrial problems range from few to 500 ms in time and from 10 to 40% in voltage drop, although severe dips can reach 60% or longer periods. Automatic reclosing mechanisms in order to restore the supply in the shorter timemight result in series of dips. This series of dips often requires the voltage compensation equipment to be able to operate several seconds.

Due to previous reasons, a second group of conditioning equipment without any kind of energy storage (i.e. batteries, ultracapacitors or flywheels), has been developed to protect industrial facilities particularly affected by voltage sags, offering a cost-effective solution cheaper than conventional UPS. The design targets were to improve both the time frame of dip compensation as well as the percentage of voltage drop compensation. This solution has demonstrated to be highly effective, maintaining stable output voltage with input voltage drops of 30% in a continuous way or 40% during 30 seconds. The designed topology looked also to mitigate other power quality problems (flicker, slow and fast voltage regulation problems, harmonic voltage distortion and some level of spikes). This solution has been named SET-DVR.

III. MITIGATION EQUIPMENT WITH ENERGY STORAGE

The first device (see Fig. 3) is a 200 kVA modular system that allows to cover power ratings from 200 kVA to 1200 kVA and provides an innovative alternative for expensive solutions based on static or rotary double-conversion UPS.

Figure 3. SEPEC 600 KVA

Sumarizing fundamental characteristics:

- High efficiency emergency supply system (>99%).
- Compatibility with existing protection system.
- Reduction of the necessary investment.
- Minimal running costs (energy, maintenance, etc.).
- Maximum system robustness guarantee.
- Good integration with gensets, avoiding oversizing.
- Permanent temporary overvoltages protection.
- Optional surge protection.
- Operating temperature up to 50ºC.
- Register of disturbance events (date-time&duration).

Fig. 4 shows the basic scheme of the designed system.

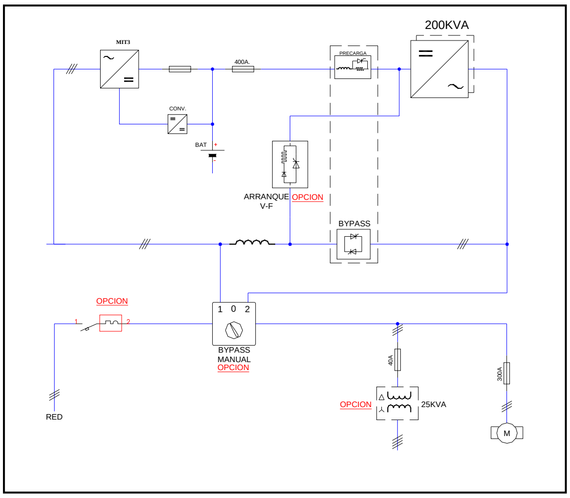

Figure 4. Topology of the SEPEC.

Fig. 5 shows the compensation capabilities of this device. It is also possible to protect loads against temporary overvoltages adjusting the "maximum voltage transfer" parameter.

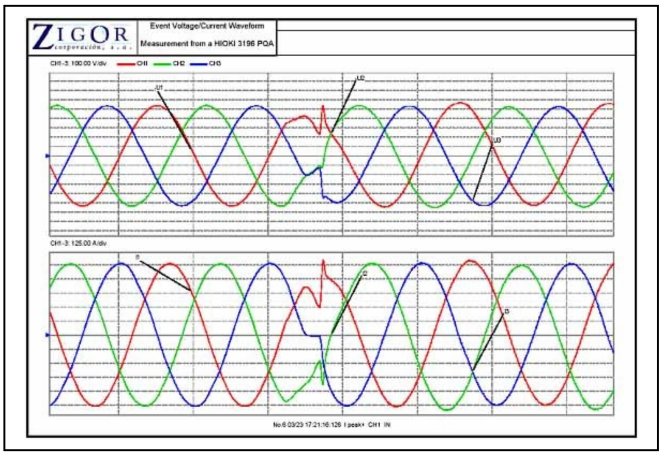

Figure 5. Transfer log between mains and SEPEC.

IV. Compensation Equipment Without Energy Storage

So far, different topologies and products have been developed and tested in the industry to solve fast voltage regulation problems, nevertheless many of the traditional technologies are not adequate for the time frame and time response required for dips as defined previously. Some of the products use ultracapacitors or batteries as energy backup to compensate the dips.

Most topologies use standby strategy, that is, the active compensation components of the electronics operate only during the dip.

The design target for the second family of equipment was to solve some limitations of existing topologies, namely:

- Free of any energy storage components.
- Longer time frame for repetitive dips events.
- Allow continuous operation to offer very high stabilization accuracy.
- Allow bi-directional energy flow.
- Improve time response to allow permanent voltage distortion filtering.

The problem that dips cause to industry can therefore be represented by the area created between the lower line of the IEEE 466 standard and the distributions of the dips duration and percentage voltage drop of the network.

As shown in Fig. 6, based on a booster transformer plus a set of a reversible rectifier, plus an inverter, the device builds up a flexible energy injection/absorber compensator capable to correct input voltage deviations, offering an extremely stable output voltage with a very fast response.

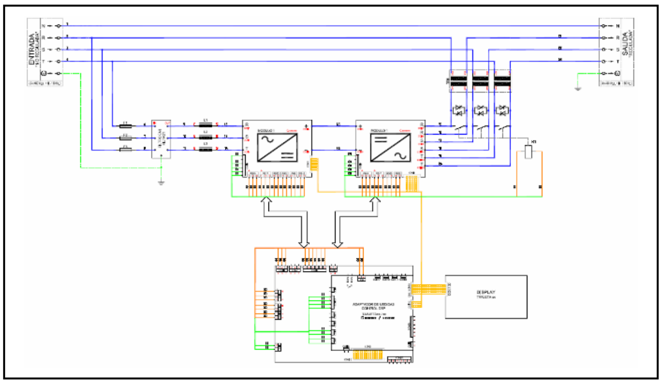

Figure 6. Topology of the SET-DVR.

The first deployed units have demonstrated to be successful in real industrial sites. A parallelable 300 kVA unit has been developed for low voltage (LV) 3x400 V grids.

The designed topology offers the following disturbances compensation capabilities:

- Voltage dips and swells.
- Voltage variations.
- Voltage distortion.
- Voltage flicker.
- Voltage unbalance.
- Some level of transient overvoltages.

The master unit is shown in Fig. 7. Higher power units can be built by paralleling slave units to the master one up to 10 or more units. Additionally, the proposed topology allows building custom-made solutions for medium voltage (MV) by changing the booster transformer.

Figure 7. SET DVR 300 KVA.

The proposed system has the following main features:

- No battery or alternative energy storage required, minimizing maintenance cost and increasing reliability.
- Continuous voltage regulation within the ± 0.5%.
- Compensation of long lasting dips (-50% up to 30 sec).
- Avoids relays and brushes.
- Time response less than 3 milliseconds.
- Capable to operate with industrial regenerative loads (e.g. four-quadrant converter).
- Improves the voltage distortion.
- Flicker compensation.
- Non stop of process operation in case of failure.
- Easy to parallel additional equipment.
- Independent phase compensation.
- Voltage balancing capability.
- Balanced and unbalanced dip compensation.
- Automatic Bypass
- Efficiency 97.5% for LV and 98.5% for MV.
- Overload capacity: 150% during 1 second.
- Dips logging and system monitoring.

V. SET-DVR OPERATION

A. Voltage Dips Compensation Capability

Fig. 8 shows the compensation capabilities of the system. A sample dip compensation (5 cycles) is represented in Fig. 9.

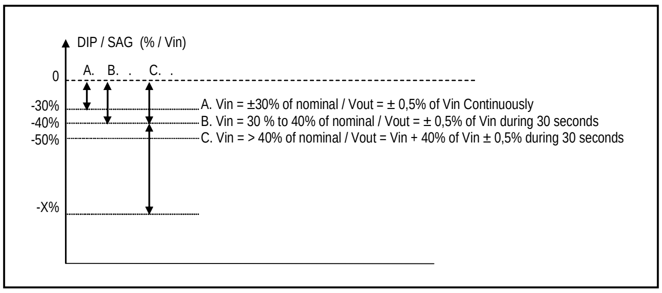

Figure 8. SET-DVR dips compensation capabilities.

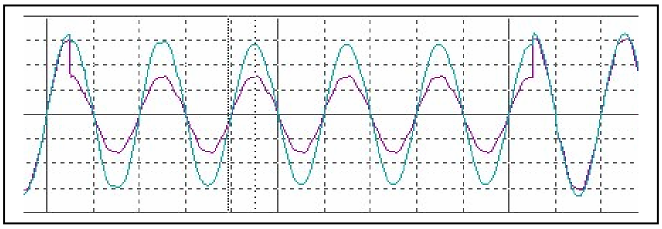

Figure 9. Compensation sample for a 40% voltage dip.

Contrary to what it might be thought the behaviour of the SETDVR over the mains is not to drop the voltage down during the sag, but even to restore it during the fault or even to elevate it, as it will be demonstrated in the following example. Fig. 10 shows a simplified model to demostrate the behaviour of the SETDVR during the sag and the voltage effect on the mains.

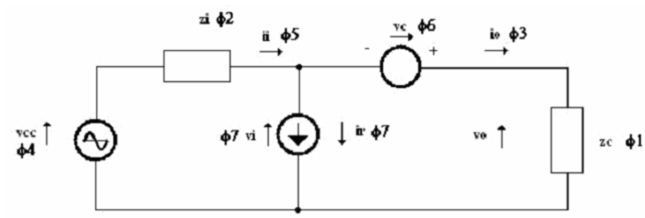

Figure 10. Simplified Modelo f the SETDVR connected to a mains thought a transformer of the same power of the SET DVR

v_{cc} is the shortcircuit voltage transformed to the secondary of the transformer that is powering the SETDVR; z_i is the equivalent impedance of the same transformer translated to the secondary; v_i is the input voltage to the SET DVR also shared by other loads connected to the output transformer; v_o is the SETDVR output voltage that is obviously maintained stable before and during the sag; io is the SETDVR output current; i_r is the active rectifier of the SETDVR that is capable to maintain the voltage and the current with the same phase; v_c is the compensation voltage of the series with v_i continuously keeping vo within the voltage regulation percentage of ± 0.5%.

Fig. 11 also depicts the current phases Φ_i . z_i and z_c together with their phases represent the input and output impedances.

As plot in vector diagram of Fig. 11, the load connected to the SETDVR has power factor close to 1, the current is in advance to the voltage having a capacitive behaviour and therefore it raises the voltage.

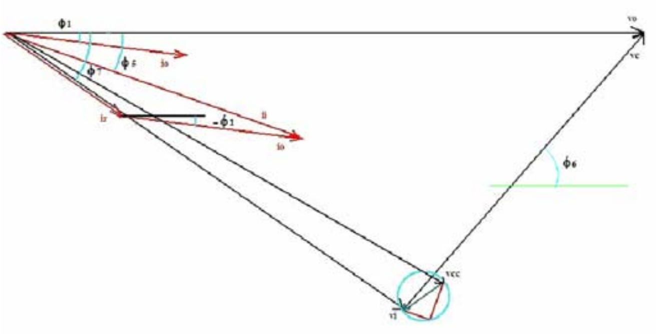

Figure 11. Input Voltage to SET DVR (Vcc) behaviour during the sag.

It can be observed that for a single phase sag fault, a voltage drop comes together with negative phase shift since the mains impedance would normaly be inductive. Therefore, assuming that the argument of v_n is 0 it results in:

$$vcc = \frac{vn\ Rcc}{Z_l\, e^{(\phi_l I)} + Rcc} \tag{1}$$

$$\{\beta = \frac{vcc}{vn}, \alpha = \frac{Rcc}{Z_l}\} \tag{2}$$

$$\beta\sim = \frac{-\sqrt{2\cos(2\phi_l + 2\phi4) + 2}\ \sin(2\phi4) - \sqrt{2\cos(2\phi_l + 2\phi4) + 2}\ \sin(2\phi_l)}{-\sin(3\phi_l) + \sin(\phi_l) - \sin(\phi_l + 2\phi4) - \sin(\phi_l - 2\phi4)} \tag{3}$$

Fig. 12 plots β values versus Φ values.

$$\phi4 = -\arctan\left(\frac{\sin(\phi_l)\,(\cos(\phi_l)\,\beta\sim - \sqrt{\cos(\phi_l)^2\,\beta\sim^2 + 1 - \beta\sim^2})}{-\beta\sim + \cos(\phi_l)^2\,\beta\sim - \cos(\phi_l)\sqrt{\cos(\phi_l)^2\,\beta\sim^2 + 1 - \beta\sim^2}}\right) \tag{4}$$

From Fig. 11 it can be derived that:

$$(5)\quad ii\sim e^{(\phi5\, I)} = ir\sim e^{(\phi7\, I)} + io\sim e^{(\phi1\, I)}$$

$$(6)\quad vc\sim e^{(\phi6\, I)} = vo\sim - vi\sim e^{(\phi7\, I)}$$

$$(7)\quad vi\sim e^{(\phi7\, I)} = vcc\sim e^{(\phi4\, I)} - zi\sim e^{(\phi2\, I)}(ir\sim e^{(\phi7\, I)} + io\sim e^{(\phi1\, I)})$$

Equations (5), (6) and (7) can be decomposed into real and imaginary components, and toghether with energy conservation principle as follows lead into 7 equations:

$$(8)\quad vi\sim ir\sim = io\sim \cos(\phi1)\, vo\sim - io\sim vi\sim \cos(-\phi1 + \phi7)$$

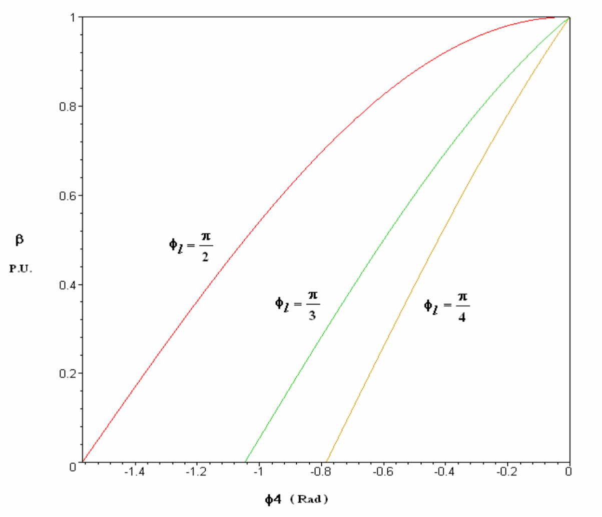

Figure 12. β versus Φ

Those 7 ecuations finally result in,

$$\{ii\cos(\phi5) = ir\cos(\phi7) + io\cos(\phi1),\ ii\sin(\phi5) = ir\sin(\phi7) + io\sin(\phi1),\ vc\cos(\phi6) = vo - vi\cos(\phi7)\} \tag{9}$$

$$\{vc\sin(\phi6) = -vi\sin(\phi7),\ vi\, ir = -io\,(-\cos(\phi1)\, vo + vi\cos(-\phi1 + \phi7))\} \tag{10}$$

$$\{vi\cos(\phi7) = vcc\cos(\phi4) - zi\, ir\cos(\phi2 + \phi7) - zi\, io\cos(\phi2 + \phi1),\ vi\sin(\phi7) = vcc\sin(\phi4) - zi\, ir\sin(\phi2 + \phi7) - zi\, io\sin(\phi2 + \phi1)\} \tag{11}$$

where the variables to determine are

$$\{ii,\ ir,\ \phi5,\ \phi7,\ vc,\ vi,\ \phi6\}$$

for the values, $\{\phi_l = 1.427996661, \beta\sim = 0.6\}$

It equals, $\phi4 = -0.7921078143$

and for the following variables values,

$$\{vo = 230,\ vcc = 138.0,\ zi = 0.1840,\ io = 100,\ \phi1 = 0,\ \phi2 = 1.4279967,\ \phi4 = -0.7921078143\}$$

$$\{vc\sin(\phi6) = -1.\ vi\sin(\phi7),\ ii\cos(\phi5) = ir\cos(\phi7) + 100.,\ ii\sin(\phi5) = ir\sin(\phi7),\ vc\cos(\phi6) = 230. - 1.\ vi\cos(\phi7),\ vi\, ir = 23000. - 100.\ vi\cos(\phi7),\ vi\sin(\phi7) = -116.4459816 - 0.1840000000\ ir\sin(1.427996661 + \phi7),\ vi\cos(\phi7) = 94.30521852 - 0.1840000000\ ir\cos(1.427996661 + \phi7)\}$$

that solving numerically result in,

$$\{\phi6 = 0.6802657902, \phi7 = -1.018292556, vc = 197.3878311, vi = 145.8587422, ii = 179.1947795, \phi5 = -0.5233044519, ir = 105.204800\}$$

Notice that a shortcircuit voltage is 138V over the nominal 230V results in 145.8V at the transformer output. Notice also that the impedance of the transformer is inductive with an argument of Π/2.2

As a conclusion the input voltage at the SETDVR is raised even though the module of the input impedance is 0.184Ω. The power processed by the SETDVR is 230*100=23000VA that is similar to the one transformer with a 8% voltage drop with a Π/2.2 argument value and 23000VA of nominal value.

Finally Fig. 13 and Fig. 14 show a simulation and the voltage and current values during the fault:

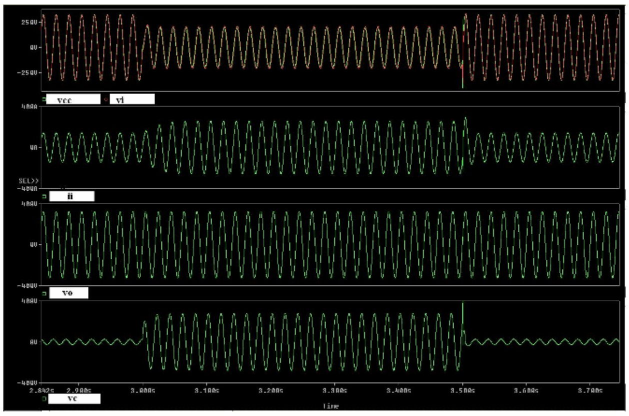

Figure 13. vcc, vi, ii, vo and vc simulation values.

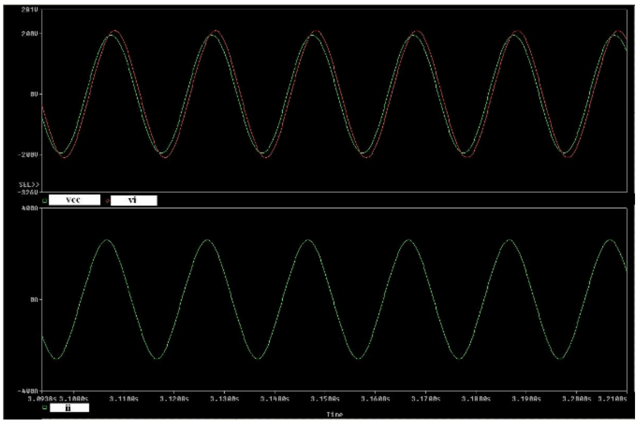

Figure 14. vcc, vi and ii simulation values..

Likewise, diferent fault types have been analysed resulting in an equivalent behaviour to the above sample. As a conclusion the SETDVR effect over the output voltage of the transformer normally powering and its neighbourging load do not fault to lower values. Contrary the capacitive behaviour confronted to the phase shift of the inductive values of the transformer help to mantain or ecen slighty elevate the voltage.

B. *Voltage Regulation*

The designed topology looked also at the possibility to mitigate other power quality problems at the same time, as flicker, slow and fast regulation problems, voltage distortion and some level of transient overvoltages. Finally the SET-DVR has demonstrated to become effective for all these problems with a high stabilization accuracy and very fast response, typically less than 3 milliseconds.

C. *Voltage Unbalance Compensation*

Due to the independent phase compensation capability as well as the bidirectional energy flow control operation, this equipment can balance and equalize three phase unbalanced systems, both during transients and continuously.

D. *Voltage Flicker*

Due to the continuous operation and its accuracy and fast response the system also solves the flicker problem.

E. *Overvoltage*

Its capability to respond for 2 to 3 ms sub-cycle transients together with complementary MOV equipped as standard offers a high level of overvoltage protection both for very fast and fast transients (e.g. capacitor's bank switching).

VI. MONITORING

Both devices have a disturbance monitoring system. The logging systems is a user friendly interface using web server technology. Fig. 10 shows the appearance of the alarm logging function.

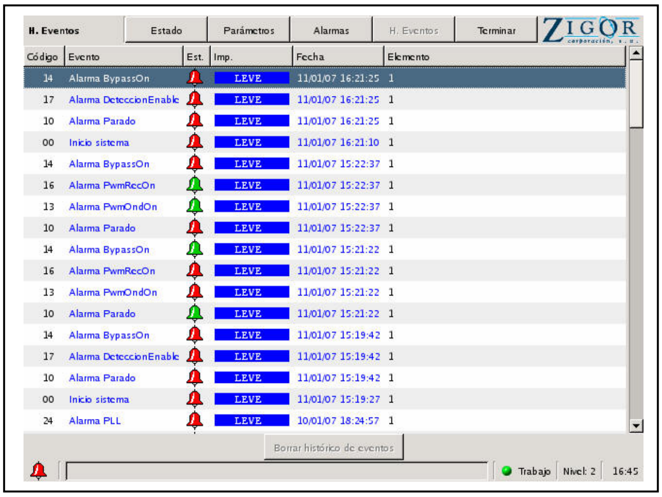

Figure 15. Monitoring system.

VII. CONCLUSIONS

When talking of power quality solution, it existed a gap concerning industrial environment requirements. The innovation introduced with SEPEC and SET-DVR systems offers an excellent option for industrial proccesses protection.

SEPEC has proven to be a cost-effective immunization equipment against interruptions for those customers whose high power protection needs (ranging from 200 kVA to 1200 kVA) were unaffordable with existing UPS technology.

SET-DVR offers an important advantage which is the lack of energy storage components leading into maintenance cost elimination and reliability raise for the complete system. Because the energy flow could be reversed throughout the booster transformer, this equipment achieves high efficiency as well as overvoltage protection capability. Finally the proposed topology allows building custom-made systems for any voltage level.

Both solutions have been validated in a variety of industrial facilities including ceramics, plastics and polymers processing, paper manufacturing or pumping stations. The choice of the most convenient solution will depend on several factors, depending on the feeder, the requirements of the process or the investment.

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