Update on Energy Storage Based Power Quality Applications in South Africa

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***Abstract*-- Although South Africa is termed a high-energy intensity country, the sheer size of its power network and the sophisticated needs of some consumers still means that Power Quality has to receive serious attention.**

Eskom has taken a lead in this area through the development of a series of static power converters with a wide range of functionality. These converters can interface with any type of external energy source to provide the type of autonomy and quality specified by the user (Eskom's Q_uPS philosophy).

This paper presents the preliminary results of Eskom's laboratory trials and early commercial demonstrations of various applications of energy storage based Q_uPS technology.

I. Introduction

THE story of Eskom's involvement in Power Quality really has two beginnings, neither of which can claim total precedence. Firstly, Eskom's Research management has a strong focus on conducting research that not only provides benefits to the utility, but that also has a good possibility of fostering South African industry. Secondly, and independently of this ideal, South Africa's National Electricity Regulator (NER), in concert with the Electricity Suppliers Liaison Committee (ESLC), commissioned the development of a rationalised national specification for the measurement and classification of power disturbances. This specification is called NRS048 [4] locally, and has many similarities with the international IEEE 519 and IEC 1000 Specifications.

The two concepts came together when Eskom funded a program of research that was targeted at making use of components that are readily available and that could be configured in a way that would provide a multi-function approach to the various power disturbances defined in NRS048, or at least as many of them as possible. It was realised early on that some of the disturbances would require some form of external energy storage in order to compensate for the disturbances that were of more than momentary duration. However, work on the energy storage aspect was deferred until the power electronics aspects had been addressed.

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Eskom contracted the conceptual and engineering design to the University of Stellenbosch's Department of Electrical and Electronic Engineering. Among the basic requirements was the need to have a versatile programming capability so as to combat the different disturbances likely to be encountered in each end-use application. The challenge was to eliminate the two classical deficiencies of the dual conversion series-connected UPS: poor efficiency due to having to rectify and invert the full load power continuously, and the poor harmonic distortion occurring at the supply point.

The basic design of the new device combines the high speed switching capability and low losses of the present range of Insulated Gate Bipolar Transistors (IGBTs) with a programmable digital controller so as to have full control of the compensating waveforms and phase angles. An isolating thyristor is connected in series so that the load and the supply can be separated as soon as a disturbance is detected, whereupon the power electronics will inject the appropriate compensation [1],[2],[3].

There is nothing in the design that is especially worth protecting by patent. The secret of success lies within the design-in capability of the digital controller. This is programmed for each individual application and will need to take into account:

- The characteristics of the particular load,
- The type, or types, of compensation required, and
- The nature and support characteristics of the external energy source.

Thus was conceived and born the Q_uPS, a range of devices that can provide all the functions of a traditional UPS, but without the shortcomings. The interest in energy storage technologies was to follow soon thereafter.

II. The Q_UPS Configuration with Storage and Generation

The diagrams below (Fig. 1, Fig. 2) show the basic building blocks of the Q_uPS configured in a real system where the critical load (CL) and non-critical load (NCL) have been separated. Transfer between the mains supply and standby-generators takes place by switching mechanical switches (MS1 and MS2). Flywheel energy storage systems (Fig. 2) require an additional converter (converter 2) to interface the variable-frequency ac output of flywheel machine with the dc link of the main Q_uPS converter (converter 1).

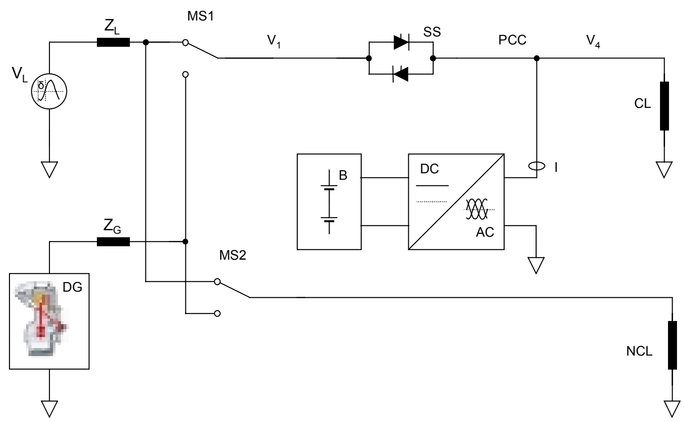

Fig. 1: Q_uPS with battery energy storage and diesel generator

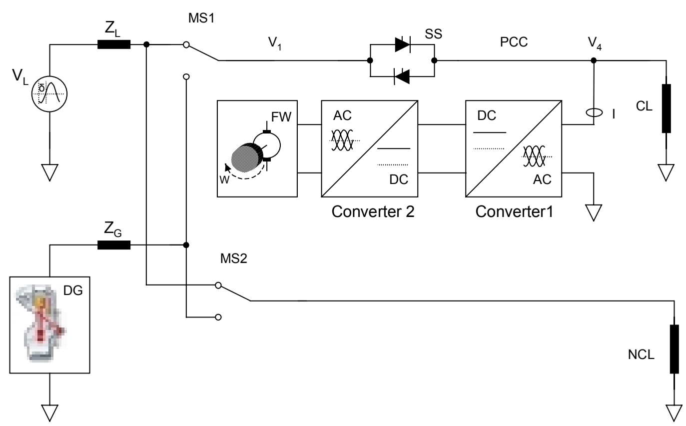

Fig. 2: Q_uPS with flywheel energy storage and diesel generator

In the diagrams the Q_uPS is configured in parallel with the load, although it can easily be configured in series if long-term ride through support is not required. Examples of series injected compensation would include power factor correction, voltage regulation and removal of unwanted harmonic distortion. Eskom's first field applications have so far been shunt connected and this paper will therefore concentrate on that configuration.

A series of laboratory models based on the Q_uPS concept has been made at University of Stellenbosch ranging in capability from 45 kVA up to 2 MVA. It was decided quite early on to make the 250 kVA version the first model to bring to market. While this represents an inevitable compromise, it has been found that it is feasible to configure up to eight 250 kVA units in parallel (i.e. total capability of 2 MVA) while remaining under the control of one master digital controller. Furthermore, the 250 kVA unit could still prove marginally cost competitive even with a customer's load as low as 100 kVA.

Fig. 3: Eskom's 250 kVA Q_uPS

Accordingly the first (prototype) model to be built was rated at 250 kVA, and this is still in service at the University's laboratory, where it is used for integration with the various candidate energy storage devices and for "lab scale" tests. After satisfactory proof of concept trials, the decision was made to build the first two units for field application, and partners were sought to host the field trials.

III. Sentech as First Customer

As it happens, the engineering branch of Sentech, the leading signal distributor for broadcast services in South Africa, is host for the first two commercial field trials. Sentech has 220 transmitting stations countrywide, and is faced with serious challenges. Principally, their choice of sites has to take into account the primary need to achieve satisfactory broadcast coverage and consequently the selected sites are usually in remote locations and with poor accessibility. This typically results in their being at the end of the line for their mains supply. They are therefore likely to experience a high incidence of power disturbances, aggravated by the frequency of lightning strikes for which South Africa is notorious. The standard solution to this would be the standby diesel generator, and this is indeed Sentech's philosophy. However, the high pump price of diesel and the fuel transport costs make this an expensive option. As an indication of local diesel generation expenses, standalone operation costs approximately \$0.12/kWh and standby operation up to \$0.30/kWh or more. Any opportunity to reduce the costs associated with the number and duration of diesel start-ups is worth investigating. In addition, the output amplifiers of the TV transmitters use thermionic valves, and these have been found to be vulnerable to even momentary mains supply dips, and replacement costs are high.

A. Kameeldrif trial

The first commercial trial of the Q_uPS was installed in October 1999 at Sentech's Kameeldrif station, which serves the Pretoria area. This site is at 1660 metres altitude and the access road has an 800 m climb over the final 3 km. There are 6 TV channels and 10 radio channels, and approximately 6.75 million viewers/listeners. The average number of voltage dips alone is 30 per month. Depending on how close the elapsed time is between dips, this could represent nearly 200 separate diesel starts per year, ignoring longer-term outages. Assuming a minimum run time of 25 minutes per dip-induced start (to reduce short-run diesel engine wear and tear), about 650 litres of fuel will have been used each month, just to compensate for an accumulated dip duration of probably less than 10 seconds.

Fig. 4: Photograph of the Kameeldrif site

As the load at Kameeldrif for the TV transmitters is 200–250 kW, the supplies to the radio and TV transmitters are separated at the distribution boards, with only the latter being protected by the Q_uPS. In this trial the energy storage consists of a five minute lead acid battery. This provides sufficient capability to ride through all the momentary dips, and to set the start time for the diesel generators at 6 seconds after an outage has been detected. This allows sufficient time for the auto-recloser sequences of the line protection circuitry to be completed in the event of a short disturbance without having to start the standby generators.

Fig. 5 below shows (on a NRS048 dip window chart) the number of incidences successfully mitigated during a two-month period of the Kameeldrif trial of 15 months. It is worth noting that the Q_uPS compensated for all the disturbances logged. Already the radio channel operators are expecting the same treatment.

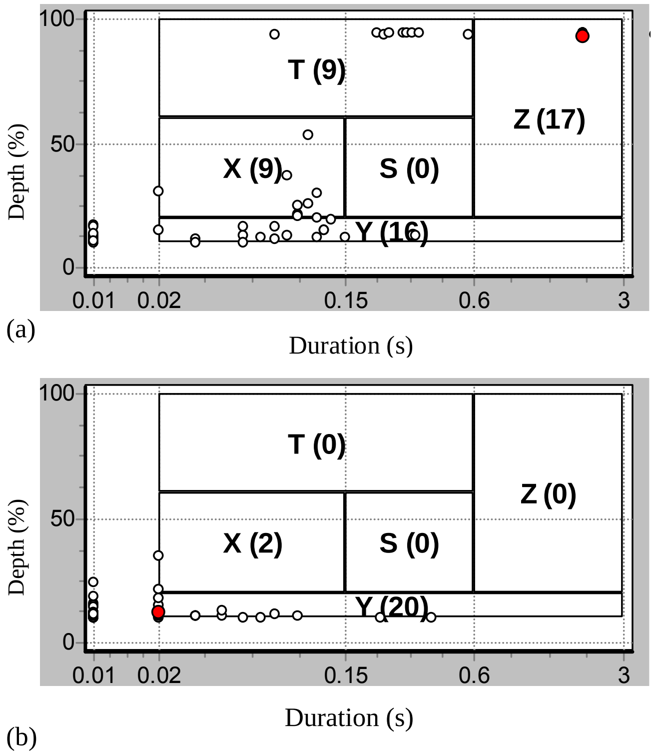

Fig. 5: NRS048 Dip windows of Q_uPS *(a)* input and *(b)* output

Lead acid batteries were chosen for this trial because of their availability and their low initial cost. Battery condition is being monitored, and only after their first replacement will it be possible to derive an estimate of the life cycle costs. As they are housed in an air conditioned part of the building, they can probably be expected to last longer than would be typical for many other sites.

With the success of the Q_uPS in the first trial assured, Eskom became braver in its approach to the energy storage option and so high speed flywheel technology is being used for the second trial. Integration of the flywheel energy storage with the Q_uPS was successfully achieved at University of Stellenbosch in July 2000. This was followed by a course of operator training before the system was deployed in the field.

B. Middelburg Trial

The site for the second field trial is Sentech's Middelburg station, which has 5 TV channels and 10 radio channels, and serves approximately 625 000 viewers/listeners. The Middelburg site is also approximately 1600 metres above sea level, but accessibility is not a problem here.

Fig. 6: Photograph of the Middelburg site

In this case some aspects of the energy storage device are the complete converse of those for lead acid batteries. The capital cost is high, while the expected maintenance intervals (and of course O & M costs) are designed to be considerably lower. While some routine maintenance will be required for the vacuum pumps, the bearing technology is maintenance-free for the lifetime of the device (nominally 20 years). The energy storage capability of the flywheel system in use is rated at 200 kW for 60 seconds (12 MJ) before its protection operates and isolates it from the DC bus. The power consumption in idle mode is 1200 W, far less that the penalty incurred by a dual-conversion technology. Recharge time could theoretically be the same (60 seconds), but the rating of the breakers at the main board needs to be taken into account, so as not to cause an overload when supplying full current to both the station load and the flywheel charger.

Installation of the flywheel-based system started in August 2000 and the system went live in November 2000. There has been a reasonable amount of learning involved, and the lessons learned will be useful for the future. Initially, some reconfiguration between the protected and unprotected loads at the distribution boards was needed, as the current drawn for the protected load was running too close to the design maximum. Subsequently, there were some phase unbalance issues that needed to be addressed. Essentially the load has a fairly high proportion of single-phase (mainly auxiliary) circuits and these are not evenly distributed between the phases. Eskom has realised that this effect will not be restricted to transmitter stations, and so future versions of the Q_uPS will have this factor designed out.

IV. WAVEFORMS ILLUSTRATING Q_uPS OPERATION

An indication of the versatility of the digital controller of the Q_uPS is shown in the oscilloscope traces below. Fig. 7 indicates the performance when riding through a dip (100% in depth and 2 seconds in duration). The speed of full power delivery and the comparison between the "before and after" voltage levels in Fig. 8 show the good match between the flywheel or battery energy storage device and the response of the Q_uPS. In the case of a long-term outage in which the standby generators were fired up the traces are exactly the same. Fig. 9 shows the voltage support provided from the energy storage, and the handing over of the load from energy storage to the generators or mains supply under software control once synchronisation has been obtained.

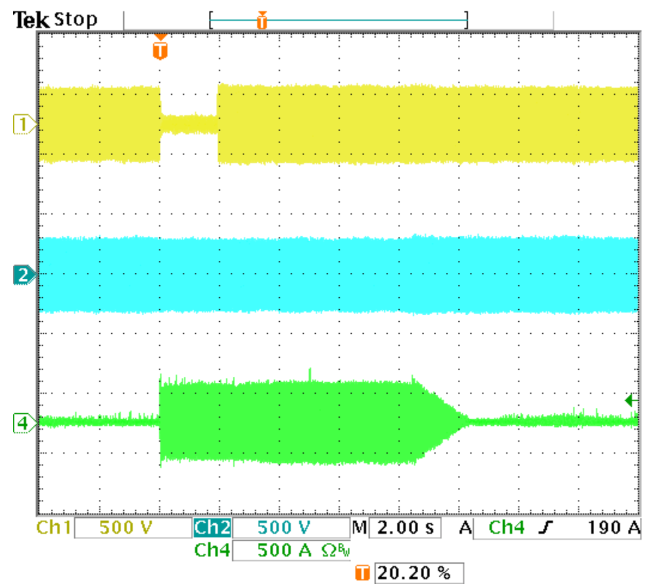

Fig. 7: Scope trace showing performance during a 100%, 2s mains dip; channel 1: mains, channel 2: load voltage, channel 3: injected current

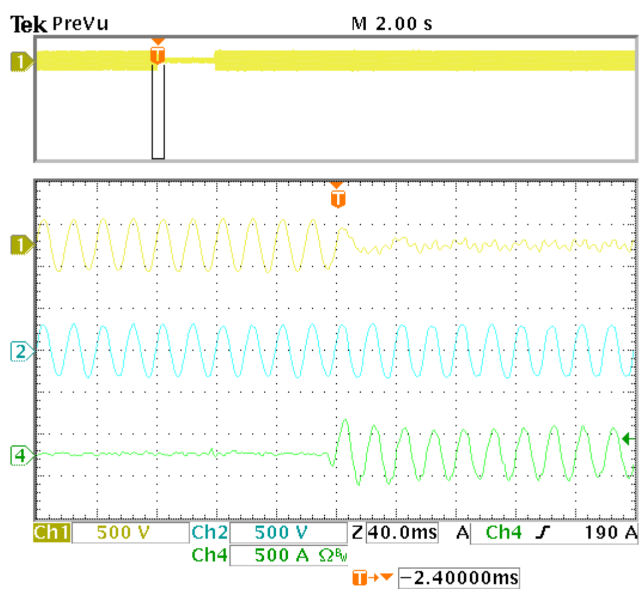

Fig. 8: Scope trace zoomed in at start of dip

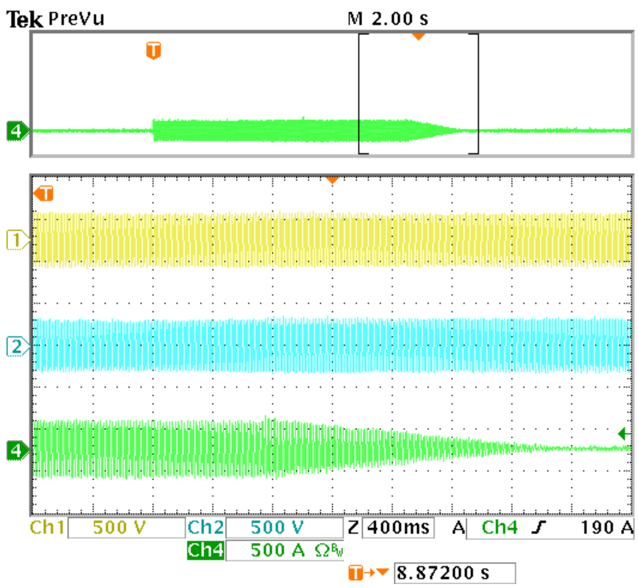

Fig. 9: Scope trace zoomed in at turn-back to utility or stand-by generator dip

V. Conclusions

Eskom's experience to date has shown that it is indeed feasible to combine flywheel energy storage with a power electronics device such as the Q_uPS for application in the field. It has further demonstrated that it is possible to bring in standby generators under control of the multi-purpose digital controller to provide long term power protection.

However, while Eskom has learned much from the Sentech trials, in both cases the standby generators had already been installed. It was thus not possible to have been involved in a full system power quality design for a greenfield situation. It is hoped to address this aspect soon.

VI. Future work

The next step in Eskom's research program involves investigation into regenerative fuel cell technology. The regenerative fuel cell (or redox flow cell as it is also called) effectively has as much energy storage capacity as the electrolyte tanks will allow. Until more is known about the cost reduction trend for this technology, Eskom is making the assumption that redox flow cells will find their niche in the alleviation of diesel fuel costs in applications where the power quality scenario has a high incidence of longer term outages. If the energy storage device can ride out fairly long outages, say up to two hours, then it should be possible to reduce the rating of the standby generators significantly, and the fuel costs will show a corresponding reduction. Of course a strategy would need to be in place to manage the risk for very long outages. Due to the lighter duty cycle of the standby generators, the full system should have a longer ccalendar lifetime, and thus the user will have a better idea of the total life cycle costs of his power protection approach. Because the electrodes of the redox flow cell are unaffected by the chemical reaction, its lifetime is expected to be much longer than that of the lead acid battery (say 20 years).

In the redox flow cell context, Eskom has embarked on a program of trials with a redox battery of 200kW, 2-hour (1.44GJ) capability. As in the previous trials, integration trials will take place at the University of Stellenbosch, again using the Q_uPS as the power conversion device. Follow-on field trials are presently planned to provide peaking power at a remote gold mine where the demand profile is becoming both higher and peakier and where the only option at present is to install more standalone generating capacity. If the load factor of the existing generating sets can be improved and the cost of a new set can be avoided until the planned grid extension is in place, the consumer should have lower electricity costs.

It is hoped to be able to report on the results of this work at a subsequent conference.

Although Eskom has a modest research portfolio on fuel cell technology, this has yet to address power quality issues. The simple reasoning behind this is that prospective suppliers appear to be concentrating on other market sectors (automotive, standalone residential, distributed generation in particular), and we have been unable to obtain any offers for trials. Hence our fuel cell research is directed at future supply side options, with an interesting sideline in membrane technology research. Again we are hopeful that suppliers will approach us with an offer to co-operate in trials for power quality applications.

VII. References

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[2] S. Eckroad, "UPS Substation, evaluation, conceptual design and generic specification," EPRI report TR-111091, September 1999.

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[4] *NRS 048, Electricity Supply - Quality of Supply*, South African Bureau of Standards, Pretoria, 1996.