

# Powering telecommunications network interfaces using photovoltaic cells and supercapacitors.

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**Abstract** New and emerging telecommunications access networks may require network termination units (NTUs) to be back-up powered, especially for telephony service provision. The multiplicity of NTUs, located at or near customers' premises, dictates both low capital and operational costs. Powering an NTU with photovoltaic cells and supercapacitors is expected to achieve a low life-cycle cost. This paper introduces the requirements for NTU powering, then develops photovoltaic cell and supercapacitor component models and investigates their application to powering an NTU.

## 1. Introduction

Some new telecommunications access networks, such as hybrid-fibre coax (HFC), fibre-to-the-home (FTTH) and wireless networks, require network termination units (NTUs) to provide an interface between the network and the customer. NTUs are typically situated at the customer's premise and consume a relatively small amount of power (ie. <5W). In addition, some services have a grade-of-service requirement that dictates the need for back-up power to the NTU. A number of technical options are available to provide a power source to the NTU, and to provide back-up power.

Power for an NTU can be sourced either from the network, from the customer's premise, local to the NTU, or a hybrid of these sources. In addition, back-up power can be provided remotely (ie. co-located with the source), or locally within the NTU.

Sourcing power from the network is not an option for FTTH and wireless networks. For HFC, an additional lead-in copper pair and a power passing tap are typically required. Unfortunately for HFC, noise ingress from the power lead-in cable can degrade the network's upstream noise performance. For the copper-pair access network, a new line-interface card (LIC) is typically required. Unfortunately for the copper-pair network, power distribution can lead to network corrosion and safety concerns.

Sourcing power from the customer side of the NTU raises many issues such as ownership/responsibility, power bill responsibility, maintenance access and safety. Where the NTU provides a plain-old-telephony-service (POTS), there is a community expectation that the customer does not have to provide such a power source. In contrast the community expectation for some services, such as modems and cordless phones, is that the customer provides mains power and is also responsible for any back-up. As such, sourcing power from the customer side of the NTU is unlikely to lead to a single generic solution where pre-existing community expectations are entrenched.

A local source of power is most conveniently supplied from solar photovoltaic (PV) cells. PV powering is attractive for NTU's mounted external to the customer's premise, with cells attached to the face of the NTU enclosure.

Back-up time requirements for services such as telephony can exceed 8 hours. Batteries are the back-up technology of choice, as they are a mature, proven product. However the operational and maintenance cost of batteries deployed in large numbers in uncontrolled environments is likely to make this option unsupportable. An alternative storage device is a supercapacitor, which requires no maintenance but is the subject of continuing research and development. The present performance of supercapacitors is considered good enough to allow valid technical investigation of their use in telecommunications power systems.

This paper develops a power system concept based on photovoltaic cells as a power source, and supercapacitors as an energy store. The models and analysis in this paper are intended to aid in future assessment of an appropriate NTU power system.

## 2. Component models for design

Models of a photovoltaic array/cell and a supercapacitor are developed in this section to assist in power system design and optimisation. The popular PSpice simulation platform is used for the investigations in this paper.

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### Photovoltaic array/cell model

The photovoltaic (PV) array model described in [1] generates a voltage-current curve for different levels of solar insolation and temperature, and includes the effects of parasitic device resistances. The model has been shown to be accurate to within a few percent [2]. The PV model expression for the terminal current  $I_{PV}$ , and voltage  $V_{PV}$  is:

$$I_{PV} = I_{SC} [1 - C1(\exp^{((V_{PV} - V_{Edelta})/C3) - 1})] + I(Gdelta) - V_{PV}/R_P \quad (1)$$

where these terms have been described previously in [1]. The terms  $I(Gdelta)$  and  $V(Edelta)$  are the translation generators:

$$I(Gdelta) = -\alpha \cdot L \cdot \Delta T - I_{SC} \cdot (L-1) \quad (2)$$

$$V(Edelta) = -\beta \cdot \Delta T - R_S \cdot I(Gdelta) \quad (3)$$

and:

$$C1 = 1/(\exp^{(1/C2)} - 1) \quad (4)$$

$$C2 = (V_{MP}/V_{OC} - 1) / \ln(1 - I_{MP}/I_{SC}) \quad (5)$$

$$C3 = C2 \cdot V_{OC} \quad (6)$$

$V_{OC}$  = open-circuit voltage

$I_{SC}$  = short-circuit current

$V_{MP}$  = maximum power point voltage

$I_{MP}$  = maximum power point current

$R_S$  = equivalent series resistance

$R_P$  = equivalent parallel resistance

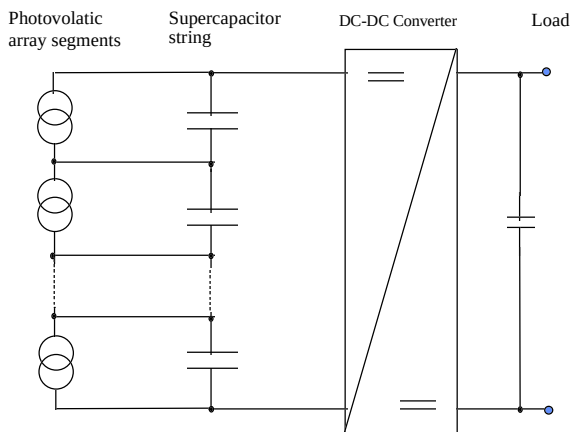
$\Delta T$  = temperature differential (relative to 25°C)

$L$  = normalised insolation level (relative to 1 full sun, ie. 1kW/m<sup>2</sup>)

$\alpha$  = temperature coefficient of  $I_{SC}$  (Amps/°C)

$\beta$  = temperature coefficient of  $V_{OC}$  (Volts/°C)

The curve described by equation (1) is translated to different insolation and temperature levels using equations (2) and (3). Parameter values are dependant on PV cell technology.



**Fig 1. A power system topology based on photovoltaic cells and supercapacitors.**

### Supercapacitor model

The supercapacitor model has been derived from measured characteristics of commercially available 470 Farad components. The model is a simple series resistor-capacitor network ( $C_C = 470F$  &  $R_{CS} = 2.6m\Omega$ ), with an extra resistor ( $R_{CP} = 2k\Omega$ ) in parallel with the capacitor  $C_C$  to model self-discharge. The measured self-discharge rate of a fully charged supercapacitor was reasonably linear down to about 70% of full voltage (~3 days), but reduced significantly at lower levels. The linear portion of the self discharge is modelled by  $R_{CP}$ .

### 3. Power system topology investigations

#### Power System Concept

A power system concept suitable for powering NTUs and based on photovoltaic cells and supercapacitors is presented in this section. The power system topology is shown in Figure 1 and has the following attributes:

- each supercapacitor component is individually charged by a photovoltaic array segment,
- the voltage-limited characteristic of each photovoltaic array segment is matched to the maximum voltage rating  $V_{Cmax}$  of the supercapacitor ( $\approx 3V$ ),
- a string connection of supercapacitors delivers a high input voltage to the dc-dc converter supplying the load, allowing the dc-dc converter to achieve operation over a wide input voltage range and with high efficiency.

#### Configurations

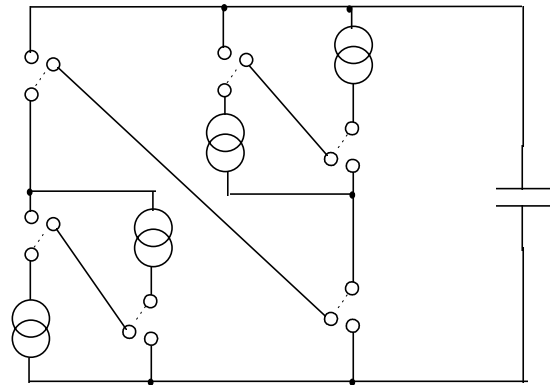
In order to investigate the likely practical performance of this power system topology, four PV array configurations are investigated.

*Configuration a):*

where each PV array segment has  $V_{OC} < V_{Cmax}$ .

*Configuration b):*

where each PV array segment has its output voltage clamped to  $V_{CLAMP}$ , where  $V_{CLAMP} = V_{Cmax}$ .



**Fig 2. Circuit schematic of Configuration c).**

*Configuration c):*

where each PV array segment is divided into four switched sub-segments, as shown in Figure 2. Switching is controlled to maximise charging efficiency. Each sub-segment has its output voltage clamped to  $V_{CLAMP}$ , where  $V_{CLAMP} = V_{Cmax}$ .

*Configuration d):*

where each PV array segment is connected to a supercapacitor through a dc-dc conversion stage incorporating a maximum power point tracker.

### Simple Charging Investigation

The performance difference between these four configurations a) - d) was investigated by charging a supercapacitor under full sun conditions. Simulation conditions and parameter values are:

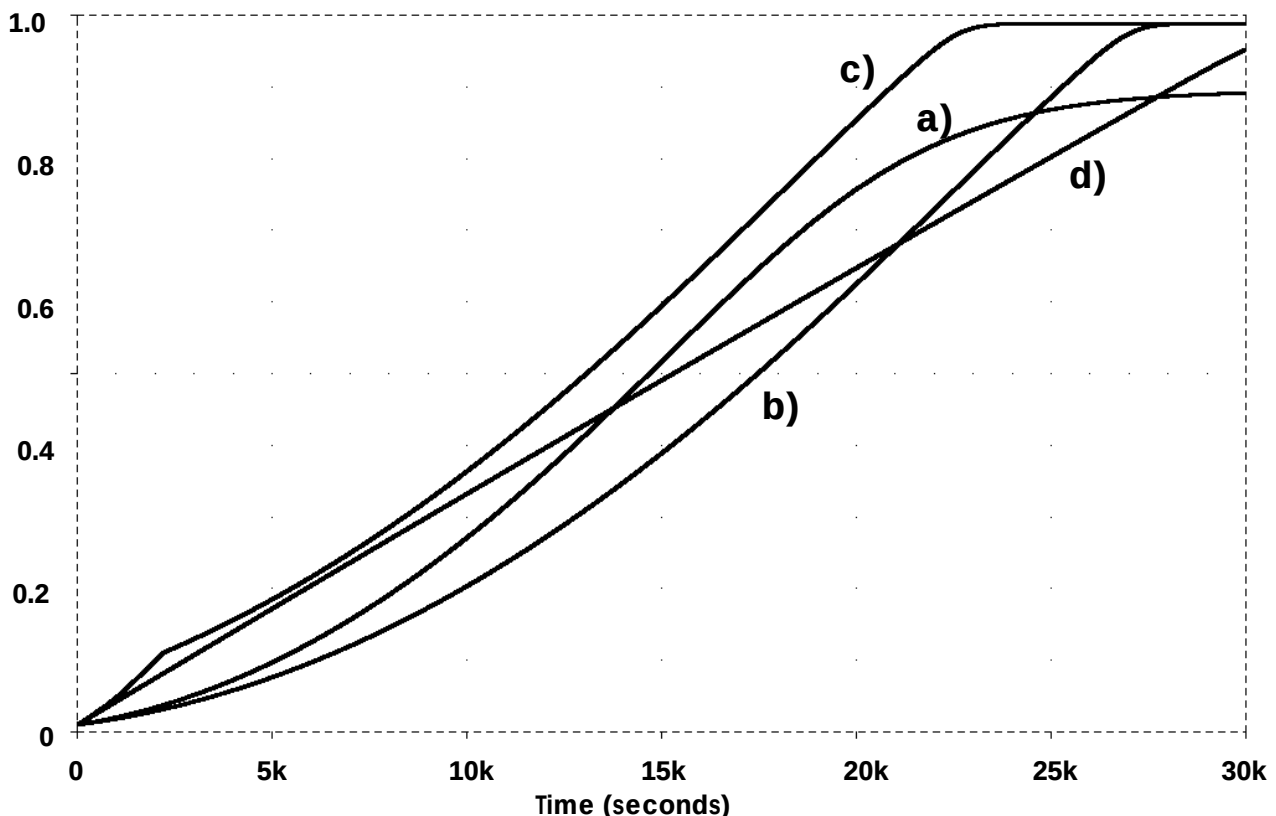
|                                                 |                                            |
|-------------------------------------------------|--------------------------------------------|
| $L=1$ (ie. full sun)                            | $\Delta T=0$ (ie. $T=25^{\circ}\text{C}$ ) |
| $V_{OC} = 0.57 \text{ VPC}$<br>(volts per cell) | $I_{SC} = 60\text{mA}$                     |
| $V_{MP} = 0.43 \text{ VPC}$                     | $I_{MP} = 53.4\text{mA}$                   |
| $R_S = 1\text{m}\Omega$                         | $R_P = 1\text{M}\Omega$                    |
| $\alpha = 1\text{mA}/^{\circ}\text{C}$          | $\beta = 1\text{mVPC}/^{\circ}\text{C}$    |
| $V_{CLAMP} = 3\text{V}$                         | No load connected                          |

The voltage clamp used in configurations b) and c) consists of a 3V zener diode. The efficiency of the dc-dc conversion stage in configuration d) is set at a practical level of 60% which is constant for all input levels. The number of cells in each PV segment depends on the configuration: a) has 5 cells, b) has 6 cells, c) has 6 cells, and d) has 5 cells (but can have any number of cells). To normalise the results, the short-circuit current for configurations b) and c) was scaled such that the maximum power for all configurations was the same (ie.  $I_{SC}=50\text{mA}$ ).

The simulated increase in energy in the supercapacitor as a function of time for the four configurations is shown in Figure 3. The charging time of configuration a) is faster than b) due to a higher  $I_{SC}$ , however configuration a) only charges to 90% of maximum due to its  $V_{OC}$  being lower than the maximum supercapacitor voltage of 3V. The higher  $V_{OC}$  of configuration b) allows the supercapacitor to be charged to 100% (but not greater than 100% due to the clamp).

The charging time of configuration c) is significantly better than configurations a), b) and d). The switched sub-segments in configuration c) optimise the charging current at low supercapacitor voltages.

### Normalised energy stored in supercapacitor



**Fig 3. Simulated increase in energy stored in supercapacitor with time of the four photovoltaic array configurations a) to d), for a simple charging profile.**

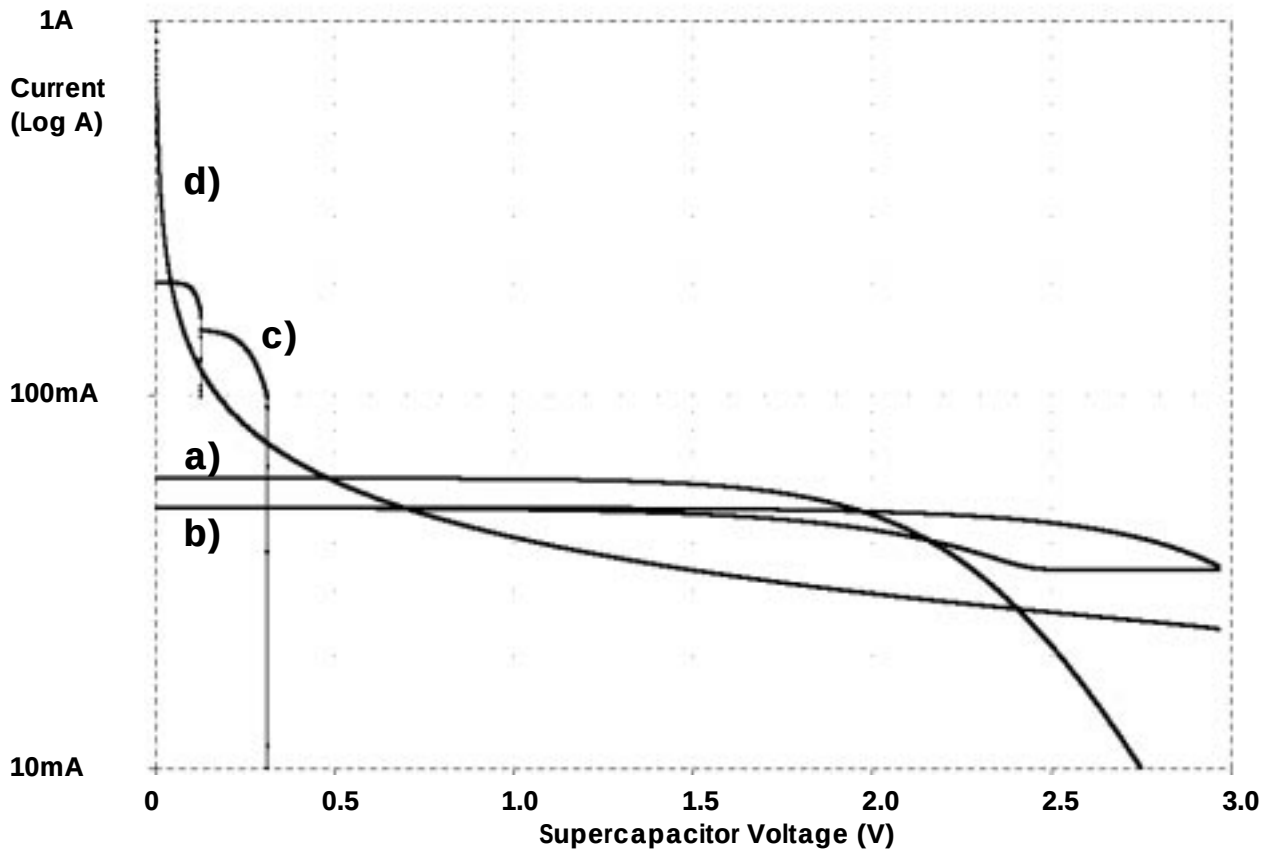


Fig 4. Simulated array current as a function of supercapacitor voltage during charging.

The charging performance of configuration d) is initially nearly as good as configuration c), however the performance reduces significantly as the supercapacitor approaches a fully charged state. The charging performance of configuration d) is severely limited by the conversion efficiency of the dc-dc converter and maximum power point tracker.

Figure 4 shows the supercapacitor charging current as a function of supercapacitor voltage. This figure details the complex variation of charging current and indicates that actual system performance will depend on the typical range over which the supercapacitor voltage varies.

#### Advanced Charging Investigation

The power system concept presented in this section can be investigated under conditions approaching those typically experienced by an NTU. A solar powered NTU would experience diurnal changes in insolation and temperature, as well as a load that has a constant power characteristic [3]. These characteristics can be modeled, and simulation analysis can be used to indicate power system performance.

Configuration b) was investigated by simulation using both temperature and insolation diurnal profiles, and a constant power load. The diurnal temperature and insolation profiles are shown in Figure 5. Figure 6 shows the voltage variation over a 2 day period for a 470F supercapacitor with a load of 20mW. Figure 6 also shows array current and load current (which varies

inversely with supercapacitor voltage due to the constant power characteristic).

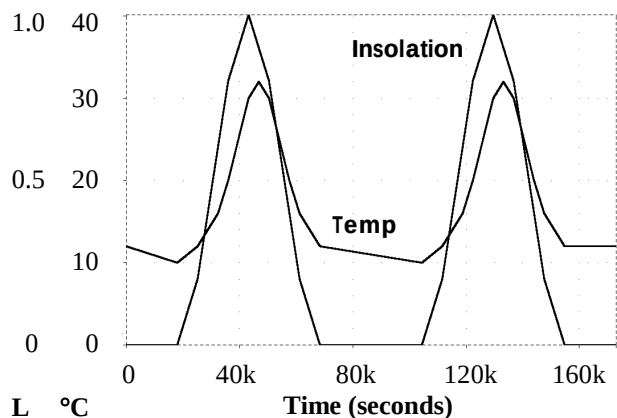


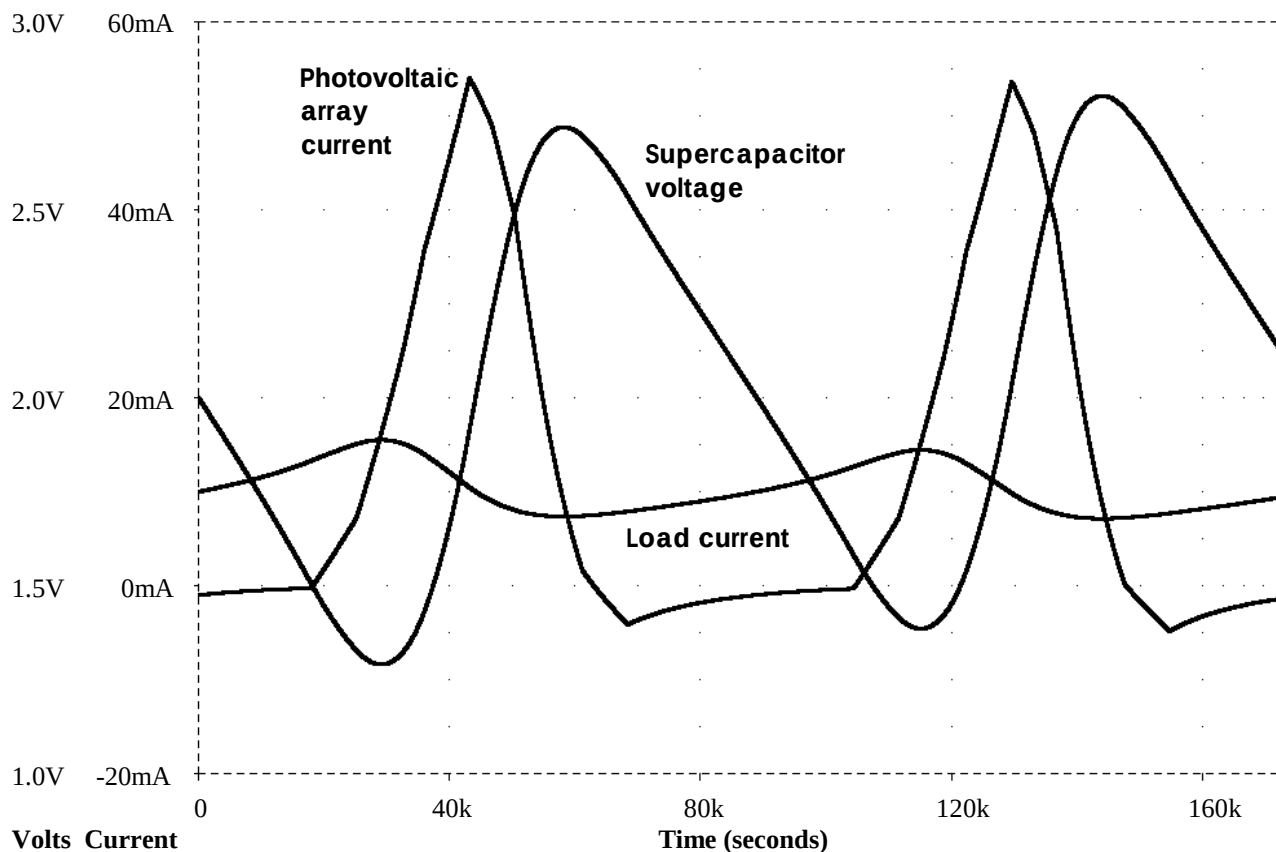
Fig 5. Diurnal insolation and temperature profiles.

#### 4. Power System Design Discussion

##### Configurations

Configuration a) has a circuit simplicity that provides inherent high reliability, as there are a minimal number of power system components. Power systems placed in an uncontrolled environment where service would be relatively expensive may benefit from this optimum reliability.

Configuration b) requires a minor increase in the number of power system components, but has the



**Fig 6. Variation of supercapacitor voltage, array current and load current over 2 day period with a 20mW load.**

advantage of allowing the supercapacitor to store the maximum amount of energy when fully charged. This advantage optimises cost, where supercapacitor cost is a large portion of power system cost.

Configuration c) requires a moderate increase in the number of power system components, but has the advantage of allowing the supercapacitor to charge more rapidly from a discharged state. This advantage may optimise cost, however this is difficult to assess as it depends on component costs, system design and environmental conditions.

Configuration d) requires a significant increase in the number of power system components, however performance is dependent on conversion efficiency. The converter cost may be a large portion of power system cost.

#### **Photovoltaic Array**

Reverse current flow through the array can occur at night due to the IV characteristic of the PV cell. This reverse current may need to be blocked, depending on magnitude. A series diode or relay make suitable blocking devices. Careful design is required to choose a solution that represents a minimum power loss. No attempt was made in the advanced charging investigation to inhibit reverse current flow through the array, with the simulation in Figure 6 showing a slight negative load current at night.

#### **System Sizing**

It is enlightening to appreciate the physical size of the PV array and the supercapacitor needed to supply a given load. In the advanced charging investigation, a load of 20mW was supported by a 6 cell PV array segment with a 50mA  $I_{sc}$ , and a 470F 3V supercapacitor.

Commercial HFC telephony NTUs consume (down to) 0.5W average. This load level could be supported by 30 such array segments and supercapacitors in a string using the topology shown in Figure 1. The total PV area would be about 60 cm<sup>2</sup> (ie. about 3" square) assuming encapsulated 10% efficient cells. The total supercapacitor volume would be about 1,000 cm<sup>3</sup> (ie. about 1 litre) using currently available supercapacitors.

The physical characteristics of the PV array and the supercapacitors appear to be acceptable when compared with a nominal NTU enclosure of a few litres volume (ie. 10x10x20cm).

In addition to size and volume, the cost of these power system components is also an important factor. An estimated total array cost is about AUSD\$100, given the multiplicity of segment terminations. An estimated total supercapacitor cost is about AUSD\$3,000. At the present time, cost and volume efficiency of supercapacitor components are changing rapidly as sales increase and technology advances. This technology holds significant promise for powering NTU and other "remote"

telecommunications devices due to its simplicity and operating lifetime.

## 5. Conclusion

Generic NTU powering requirements have been described in this paper and a power system concept has been developed based on photovoltaic cells and supercapacitors. Of primary importance with this power system is the optimisation of the interface between the photovoltaic energy source and the supercapacitor energy storage. The charging efficiency of four configurations was investigated, and their design issues discussed.

Simulation results show appropriate design techniques and circuit configurations can significantly improve the energy transfer efficiency between the photovoltaic array and the supercapacitor.

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