Switched Intelligent Grid Networking Systems

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***Abstract*--Switched Intelligent Grid Networking Systems (SIGNS) [31] is the result of research, analysis and development of an alternative process for controlling end-user electrical power quality, as well as transients on the incoming electricity supply grid. In the past power quality issues associated with the grid network were usually generated by the connected loads. This has changed in today's grid system with embedded intermittent renewable energy being included on the energy profile. The research demonstrated that it is possible to control end-user electrical power quality through the addition of battery storage at the user end of the grid and a switching device, forming an intelligent buffer between the electrical grid supply and the load. The function of the device is to select the most appropriate energy source to effectively absorb a proportion of any surges and transients, whilst offering a path for augmented alternative energy.**

***Index Terms*— inverters, power grids, power quality, switching circuits.**

Introduction

The concept of SIGNS is built on a harvest storage model where energy is collected over a period of time, stored and then used as required whilst allowing the storage medium to absorb peaks and surges in power. The complexity of maintaining power quality over the entire national grid, regardless of load and end-user responsibility has seen the development and inclusion onto the grid of numerous types of Static Compensators (STAT), which are reactive by nature [20]. Energy loss and power quality issues are generated by activity on the grid. Moving a proportion of the power quality responsibility to the consumer could effectively reduce the pressure on the grid, reduce loss and reduce peak loading concerns. In Queensland it is estimated that 10% of the multibillion dollar expenditure on grid infrastructure caters for loads that are present for less than 1% of the time [26]. One possible solution is to enable the generator and end user, to share responsibility, through a system that would complement the power generators' efforts to maintain power quality.

Power quality definition [27] can be defined as; *"Any power quality manifested in voltage, current, or frequency deviations that results in failure or mis-operation of a customer's equipment or electrical power system quality."*

A. Design Rationale

The intelligent system would need to have the capacity to:

- remove peak loading as well as transients,
- add autonomy through domestic energy storage capable of feeding onto the grid as well as adding autonomy,
- correct end user power factor whilst filtering harmonics and
- augment renewable energy onto the grid.

To this end, the research introduces the development of SIGNS, the concepts, ideals, practical considerations and applications.

The introduction of grid commutated feed-in inverters onto the electricity grid is a relatively new science and the development of these inverters is still very much in its infancy. SIGNS offers the possibility that the inverter may be developed to be part of the solution by acting as a partial Distribution Static Compensator (DSTATCOM) and installed as part of the consumer's energy system.

II. Background

Australia has over 850,000 km of power lines [24] with 16 distribution networks of which 80% are located in rural areas. The Australian National Electricity Market (NEM) [5], came into being in 1998 providing electricity to a wholesale market covering Queensland, New South Wales, Australian Capital Territory, Victoria and South Australia. In 2005 Tasmania joined the market with Basslink, connecting the island to the mainland. NEM is the longest interconnected distribution network in the world with a distance of over 5000 km between the furthest points in the network [15]. The challenge of operating a spot market of generators with the dynamic capacity to satisfy demand is the responsibility of the Australian Energy Market Operator (AEMO), a group formulated in 2009 [4]. Although the NEM network is the longest electrical network in the world, its load and distribution density is relatively light, often with many kilometres between customers. The interconnection of the grid means that the overall system current, harmonic distortion and power factor, will affect all consumers to a greater or lesser degree.

A. Line Efficency

Power transmission is the process of transporting the electrical energy from the power station to substations, normally at high voltage to reduce line losses. Distribution is the process of bringing the transmitted supply, down to usable voltages and distributing to consumers. The net power loss is the difference between the generated energy and billed energy.

$$Line\ effeciency\ \mu = \frac{power\ recieved\ \ consumers}{power\ delivered\ system} \times 100 \quad (1)$$

With five different generation networks involved in the national grid, there is a real challenge in maintaining frequency stability, voltage regulation and power factor, within defined limits. Each of the generator networks, have grown up over the past 100 years, on a needs basis and without the view of being connected to a national grid. Consequently there are operational differences, and heightened complexity relating to the interconnection of the networks. These are compounded by the inclusion of feed-in generators, such as photovoltaic (PV) grid systems, initiated as a part of the Mandatory Renewable Energy Target (MRET) [1].

The greater the distance electrical energy is transported, the greater the energy against load loss. Transmission at higher voltages increases corona discharge [14], but reduces current and cable heat loss (joule loss) bought about by the current and resistance of the cable. Corona discharge occurs when the potential of a conductor is high enough to cause the air around the conductor to ionise creating a leakage path, whereas joule loss is the heating effect of current passing through a conductor. Heating energy loss can be expressed by the formula;

$$Heating\ energy\ loss = I^2R \quad (2)$$

Where:

I = current

R = resistance

The resistance of the conductor is affected by temperature, the resistivity of the material, cross-sectional area, length and the skin effect factor.

The skin effect factor occurs because on a DC distribution conductor the current flows uniformly through the conductor, whereas with an AC current, the current tends to flow on the outer surfaces of the conductor. At 50 Hz, the AC resistance of the conductor can be approximated by multiplying the DC cable resistance by 1.02.

B. Supply Line Impedance

For simplicity the following analysis considers a single phase supply only. Resistors consume real power, inductors consume reactive power, whilst capacitors generate reactive power. Therefore in a balanced network, where current is in phase with the voltage, the capacitive reactive power generated, must equal the reactive power consumed, unless the circuit itself is purely resistive, in which case, neither reactive components exist.

Where the load is constant, the volt drop can be corrected by increasing the source voltage to allow for this volt drop. Where the load fluctuates, the problem becomes more complex, with source voltage needing to be constantly changed, if a constant output voltage is to be maintained. The supply line impedance (Z) can be approximated by (3), where X_L is the inductive reactance (4) and X_C is the capacitive reactance (5).

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad (3)$$

$$X_L = 2\pi f L \quad (4)$$

$$X_C = \frac{1}{2\pi f C} \quad (5)$$

In (3), R is the resistance of the conductors, in (4) L is the network inductance, and in (5) C is the network capacitance. The supply line impedance is the cause of volt drop and rapid fluctuating loads and the main cause of voltage sags or dips. For example, an induction motor starting direct online, such as a commonly used domestic refrigerator, has a typical start curve as shown in Fig. 1. On starting a motor may draw up to 5 to 6 times the run current (I), causing a volt drop over the impedance of the supply line, given by (6).

$$Volt\ drop = I \times Z \quad (6)$$

Poor power factor decreases transmission efficiency and increases the current required to deliver a given output power and hence increases the heating energy loss.

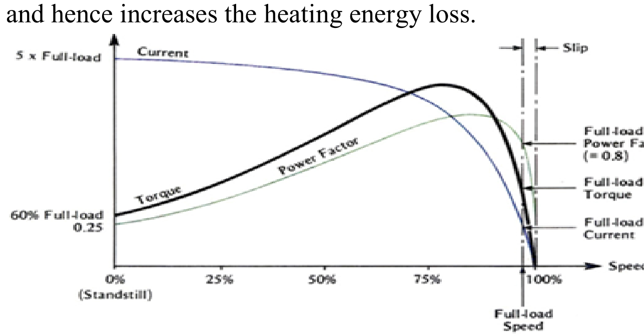

Fig. 1 Typical start curve

C. Increased Transmission Complexity

The problems of maintaining power quality is further exacerbated by the inclusion of uncontrolled third party generators, such as grid connected PV systems. As at December 2013, 22% of domestic dwellings in Queensland were fitted with grid connected PV systems giving a total generation capacity of more than 986 MW. The greater proportion of the load on the generation system is caused by domestic consumers whom, as the research has shown, use the least amount of energy between the hours of 9 am and 3:30 pm. The lucrative feed-in tariffs offered in the past has seen many opt for a PV system that is oversized in terms of their instantaneous daytime light loads. Consequently in suburbs where there is a large number of grid connect systems in place many are going into fault mode due to over voltage.

The graph in Fig. 2, shows that at the time most of the energy generated by the grid connected system occurred was

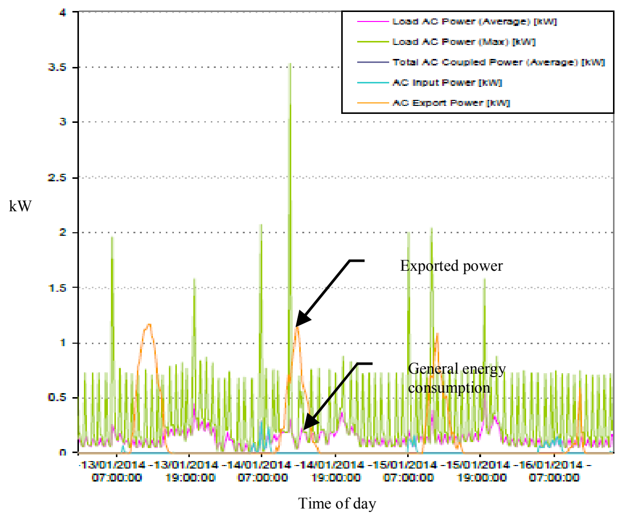

Fig. 2 Instantaneous power graphed over a number of days

when the domestic load was at its lowest, meaning the greater proportion of the energy generated is exported onto the grid.

Power Quality Elements and Typical Loads

Voltage fluctuations are short term variations in voltage, generally due to the nature of the connected load. As the load current increases the supply voltage falls, the amount depends upon the impedance of the network.

1) Voltage flicker

Voltage flicker is a short term random voltage variation, which may be less than 10% of the voltage.

2) Voltage sag or dip

Voltage sag or dip is usually between 10% and 90% of the supply voltage and may be present for periods of half a cycle to a minute. Common causes of sag or dip are motor or machines such as welders and/or faults on the grid.

3) Voltage swell

Voltage swell is where the supply voltage reaches between 110% and 180% of supply and may be present for periods of half cycles to at times in excess of a minute.

4) Voltage transients

Voltage transients are large unidirectional spikes or transients, present on the supply grid.

5) Harmonic distortion

Harmonic distortion is a distortion of the sinusoidal wave shape that may affect some appliances and may even cause burnouts, due to sub or circulating currents. Harmonic distortion may preclude some circuit protection devices from operating.

III. Hypotheses. and Stages of Research

The focus of the research was on the following four stages of development, and are the benchmarks to demonstrate the viability of buffering the grid's electricity supply with SIGNS storage, and an inverter coupling as well as augmenting renewable energy components into the supply. They form the foundation of a Virtual Standalone System VSS, which is a system that is capable of operating, without dependence on the grid supply, for a period of time and can be fuelled by either the grid or renewable energy sources. The tariffs used in the analysis are those currently in place with one of the available energy retailers in Queensland.

A. Stage 1 Buffer Model

In this stage of modeling the load is connected to the grid via an inverter, SIGNS, battery and battery charger. The battery is sized to carry the energy requirements during peak energy costing, 4pm – 8pm.

1) Objectives

- Identify comparative losses, battery charger loss, battery round trip efficiency, and inverter efficiency
- Define cost comparison using different cost per kWh
- Financial status using net present value (NPV)
- Identify limitations

2) Findings

The loss of efficiency through this model was ≈ 30%. The reduction in energy cost, using an off peak tariff ≈ 37%.

The buffer model at this stage of development shows that it is possible to collect energy over a period to supply an end user load limiting surges and peak loading and line voltage disturbance The foremost limitation identified, was the size of load that could be connected. The net present cost (NPC) over 10 years and the limitation on types of loads present questions on the viability of such systems. Improved efficiency is critical for such a system to become a working part of the AC supply network.

B. Stage 2 Modeling Introducing Charge Hysteresis

1) Objectives

- Investigate the prospect of increased system efficiency, through switching the battery charger off, when the charger is operating at low efficiency and allowing a greater battery depth of discharge.

This stage introduced hysteresis, allowing the battery to discharge to a predetermined level, before switching on the battery charger. Then switching the charger off when the battery reached float. This enabled the battery charger to operate for longer periods at optimal efficiency. This mode increased the system efficiency by almost 5%.

C. *Stage 3 Augmenting Renewable Energy*

1) *Objectives*

- Explore the viability of augmented energy input on the buffer model with PV input coupled to the grid side of the system without feeding energy onto the grid.
- Evaluate the system's financial viability.

The key element in this stage was monitoring the battery charger's energy requirement from the grid and switching on a grid connected inverter to generate as much of the energy requirement without exceeding it. This was achieved via a multiplexed circuit connecting strings to the grid connected inverter mimicking a D-STATCOM concept as illustrated in the single line diagram (SLD) Fig. 3.

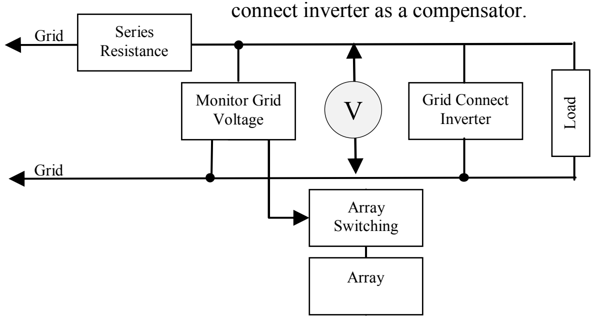

Fig.3 D-SATCOM mimic SLD

The load is the battery charger. A Latronics PV Edge inverter was used for this exercise because of its low PV input voltage (between 50 and 100 V). The significance of this is that 250 W, PV modules could be switched in, in sequence and out depending upon the requirements of the battery charger. The power monitor circuit used a simple current transformer (CT) rectified and filtered and feed to a comparator which enabled either load power or line voltage to be monitored and the array switched accordingly. This demonstrated the buffer model capacity to assist with maintaining grid voltage levels or offsetting energy consumption. The single greatest limitation being the grid connect inverter's time delay in commutating at first switch on and with varying levels of PV input power.

D. *Stage 4 Modeling a Virtual Standalone*

1) *Objectives*

- Evaluate the effects of over-sizing the array, to effectively remove a proportion of the daytime load as well using battery storage to offset peak loading.
- To investigate the viability of loads switching between a battery supported inverter and the grid.
- To investigate the effects on appliances being switched between supplies without synchronization and the ability of an inverter to absorb the start and surge current of the loads before switching to the grid.
- To evaluate the financial viability including a virtual standalone system as a part of the grid supply.

The aim of this stage of modeling was to address the limitation of previous stages of development and increase the renewable input to offset a greater proportion of the load without increasing the storage capacity.

The first step of this stage involved sizing the array such that batteries when the array was in full sunlight would charge at their maximum rate without the need for any grid input and only switching the grid battery charger on when the battery voltage fell below a minimum set period, for a period. The set level was 24.8 V.

Fig. 4 displays a sample end user energy requirement (blue) against peak sun hours (PSH) (red) and suggests that an array may be able to carry the day time load as well as charge batteries for use at times when the level of irradiation is low and the household energy demand is high. The battery storage capacity would only need to have the capacity to carry the hours outside of PSH. The energy requirement from the grid could be accessed at low demand times.

The second step, involved developing a circuit that would switch the load to the grid when the power requirements exceeded the capacity of the inverter. A time delay of a few seconds enables the standalone inverter to absorb a portion of startup surges. The inverter used was a Latronics 24 V, DC,

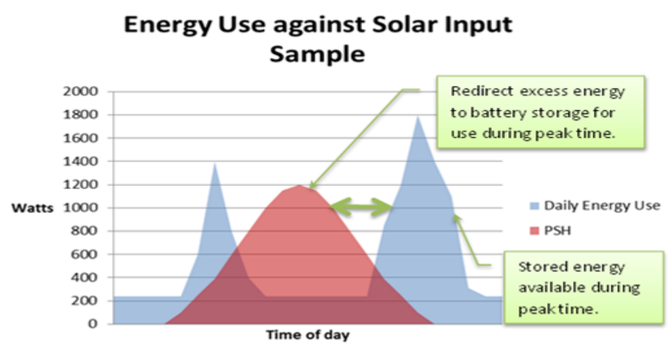

Fig. 4 Possible energy harvest

1800 W inverter, with a surge capacity for 3 seconds at 5200 W. The circuit was designed such that when a connected load exceeds the maximum surge power a priority interrupt is generated, switching the load immediately to the grid. An auto changeover switch manufactured by Latronics, introduced up to a 12 ms delay in switching from the inverter to the grid. The switching delay is the delay inherent with mechanical switching as demanded by the Australian Standards. Nevertheless, the main control component of this exercise was battery voltage.

Battery voltage monitoring revealed that battery voltage fell below 24.8 V for a short period each day. A closer look showed that a voltage drop occurred around 7 am most days, causing the unit to switch to the grid for approximately 20 minutes, as shown in Fig. 5. Whilst there is insufficient evidence to show that this would occur every day, it does demonstrate that with minimal storage capacity, it is possible to be a virtual standalone.

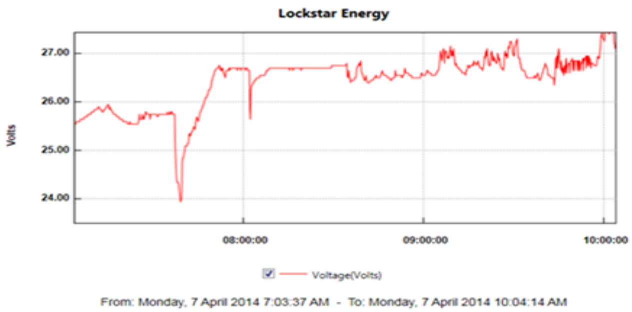

Fig. 5 Daily battery voltage fluctuations

The experimentation battery storage system used Valve Regulated Lead Acid (VRLA) batterie,s where the life expectancy is directly related to the operational daily depth of discharge. Typically, for maximum life expectancy, daily discharge should not exceed 30% of battery capacity. Nevertheless a number of battery manufacturers are taking up the challenge and offering VRLA batteries with a daily depth of discharge of up to 50% of capacity and a cycle life exceeding 3800 cycles. The unit developed during the experimentation was based on both hard wired logic for stability and programmable logic for flexibility utilising commonly available components and a low cost solution.

E. Net Present Value (NPV)

The NPV calculations are based on an inflation rate of 3% and a discount rate of 8%.

For the purpose of setting comparative bench marks, the Net Present Value (NPV) was calculated and evaluated against a grid connected system of the same size. The cash flow for a grid connected system, showed a payback in 10.5 years and a positive cash flow of $4,500 in 20 years.

Whereas the SIGNS virtual standalone cash flow showed a payback of approximately 8.5 years and a positive cash flow of $37,000 in 20 years.

IV. Conclusion

The SIGNS system modelling demonstrates that a harvest model is capable as offering a buffer against grid disturbance and power quality. A SIGNS buffer system may offer a number of advantages, such as:

- Autonomy from power outages
- Reduction in greenhouse emissions through lower dependence on coal fired power stations
- May remove surges and harmonics from the grid, however, further research is required in this area.
- Lower energy bills
- Giving a system cost much lower than a conventional standalone system with battery recurring costs much lower

V. Limitations

The introduction of the SIGNS virtual standalone system concluded a number of limitations, including:

- may generate transients on the grid,
- increased maintenance,
- increased establishment costs and
- no energy offset during inclement weather.

Further research is required to verify these findings, nevertheless the research has demonstrated that greater flexibility and lower demand at peak times can be achieved when the end user becomes partly responsible for the end user power quality.

Acknowledgment

The first author thanks Dr. Richard Burton, his industry supervisor not only for his professional assistance but also for his patients and good humour when all direction seemed lost.

Alex Thorogood also acknowledges the assistance of Chris Thorogood, his wife and boss, who remains the most amazing person that he has ever had the good fortune to have met. Thanks for being prepared to live in an experiment.

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