Technology Choices for an Evolving Power System

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Abstract

Electrification of processes and transition towards 100% renewable generation is considered instrumental for achievement of a low emission future and this can be fuelled by enabling technologies. New Zealand and Australia, like many other countries, are grappling with achieving this goal while transitioning from a legacy electrical network, with the constraints it imposes, by making incremental enhancements. The facilitating technologies; for instance power electronic converters and digital systems (which include a combination of control systems, distributed sensors, communication network and mathematical models) introduce the necessary flexibility and controllability within the power system [23-24]. There are a number of technology choices available so as to engineer an effective transition with scarce resources. This paper will analyse some of the alternative technologies and solutions considering the performance at the point of connection (including low inertia power systems), designing for efficiency and reliability [22-25]. The alternatives will include energy sources and storage; AC and DC transmission; aggregated and distributed controls.

Introduction

The term "sustainability" is expressed as the ability to continue a specific behaviour indefinitely. This concept presents significant challenges in resource variability and constrained conditions. The long-term knock-on impact on the environment, society and economy are far from desirable. World Energy Council (WEC) has identified the three often conflicting goals of energy sustainability - energy security (economic), energy equity (social) and environmental sustainability; as the 'energy trilemma' [1]. Accordingly, transition to a low emission future will require a holistic approach and a multi-faceted solution, engaging scientific, engineering, economic, and social/societal knowledge (Figure 1). Electrification of processes that use non-renewable energy and electricity sourced from renewable energy, are considered as some of the transition enablers. This paper identifies the characteristics of the established electric power system; impact of introduction of alternative renewable/sustainable resources and interfacing technologies; and the attributes of the portfolio of engineering solutions.

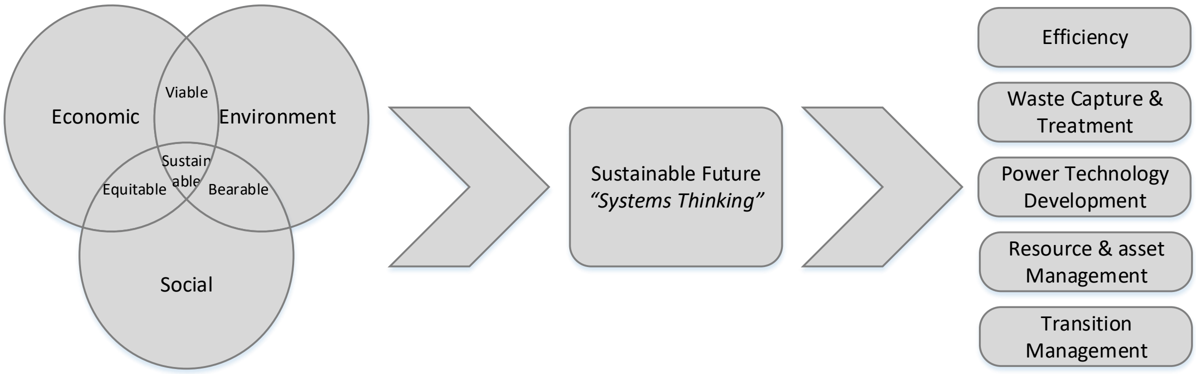


Figure 1 Trilemma and elements for sustainable transition – Energy & Electricity

Electric Power System – Origin and Evolution

Illumination being the original commercial application of electricity, in September 1882 T Edison established the first complete electric power system [2] with the generators located at the Pearl Street Station. This was a 110V DC system covering an area of roughly 1.5km radius. The expansion and extension of the DC system was restricted by the voltage drops due to the inherent resistance of the interconnection system.

Proliferation of the AC power system in late 1880s early 1890s, can primarily be attributed to the development of transformers by L Gaulard and J D Gibbs based on the principles of electromagnetic induction determined by M Faraday and J C Maxwell [2], enabling stepping up of AC voltage thus minimising transmission losses over long distances. The AC system further advanced through development of poly-phase systems by N Tesla.

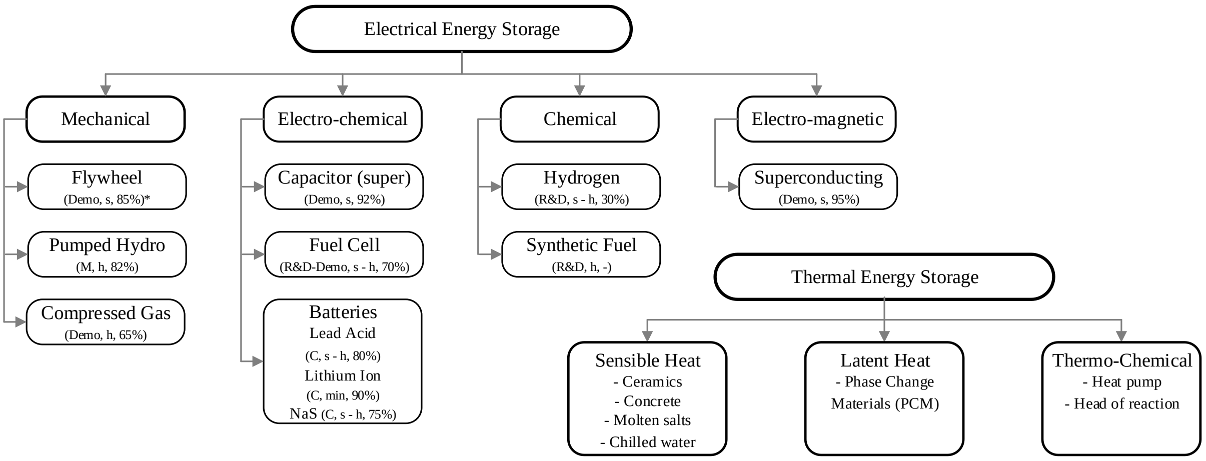
Apart from specific (LV/MV) applications, DC power system was shelved until the advent of mercury arc valves in early 1950s. Development of suitable power electronics devices, namely thyristors, in late 1960s has extended the use of DC. Line Commutated Converter (LCC) based High Voltage DC (HVDC) transmission became a techno-commercially attractive solution for bulk power transfer over long distances. It also enabled effective integration of asynchronous systems facilitating sharing of energy resources. Ongoing development of high power rating controllable devices such as IGBTs has led to the introduction of Voltage Source Converter (VSC) based HVDC option. This is widely used to integrate remote bulk generation from intermittent renewable energy sources (eg. wind, solar). Despite the obvious advantages associated with DC supply, presently the LV and MV DC power system installations are limited to distinctive applications. This slow uptake of DC at lower voltages can be attributed to the vast and established AC infrastructure; standardised commercial products and associated interfaces; and the need for specialised DC protection and isolation mechanisms involving forced extinction of DC current.

An electric power system comprises of energy sources, generators, converters, transformers, transmission and distribution medium, loads, and ancillary systems such as monitoring, control, protection and communication. Operation and stability is determined by the characteristics of its constituent elements, associated control and protection, power circuit configuration and interaction thereof. The following sections selectively assess some of the power system components and their contribution to a robust network design.

Energy Source & Storage

Energy is an essential commodity, supporting most operations and developments in the modern world. Energy can be broadly classified into primary and secondary forms. Primary energy sources are regarded as those obtained through extraction or capture, with or without a refining process, before the energy contained in it can be converted into heat or mechanical work (e.g. flowing water, coal, natural gas, solar, tidal, wind energy, biomass etc.) [4]. Secondary energy forms also known as “energy carriers”, occur as a result of the transformation of primary energy using conversion processes (e.g. petrol, diesel, electricity, biofuel, heat, work etc.) [4].

Storage or inventory is an essential element of any supply chain and there is sufficient familiarity around the storage process for energy in the solid, liquid or gaseous state. Certain forms of primary energy (e.g. solar, tidal, wind etc.) can chiefly be stored by first converting in to secondary energy forms such as electricity or heat, both necessitating further conversion to enable storage. Figure 2 identifies some of the associated energy storage technologies that can be converted back to electricity or heat on-demand. Excess electricity can be stored in the form of a product, where the process represents a variable and controllable demand.



Notes:
*(Maturity, Discharge time, ≈ Efficiency)
Maturity: M - Mature, C – Commercial, Demo - Demonstrator, R&D – Research & Development
Discharge time at rated power: s - seconds, min - minutes, h - hours

Figure 2 Energy storage technologies classification [4 - 7]

Energy storage within an electric power system provides, stability, reliability and resilience in the face of disturbances, intermittence of supply or demand (Figure 3). Technology choice, design and location should be optimised considering the composition of the power system including load and the available resources. Diversity in the energy storage system can minimise risk of scarcity in the supply chain. Figure 4 identifies the composition of the installed (≈ 188MW [3]) global electricity storage as of December 2018. Only 2% of the identified storage is clearly converter interfaced. Depending on the configuration of the generators associated with the Pumped Hydro Storage (PHG) the remaining storage has the potential of offering rotational inertia in addition to electricity.

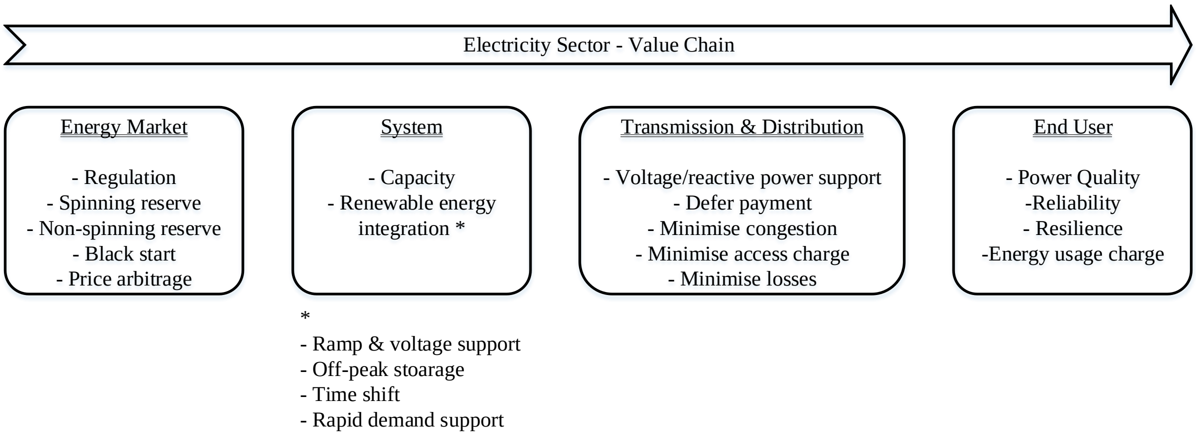


Figure 3 Energy storage applications in electric power system [6]

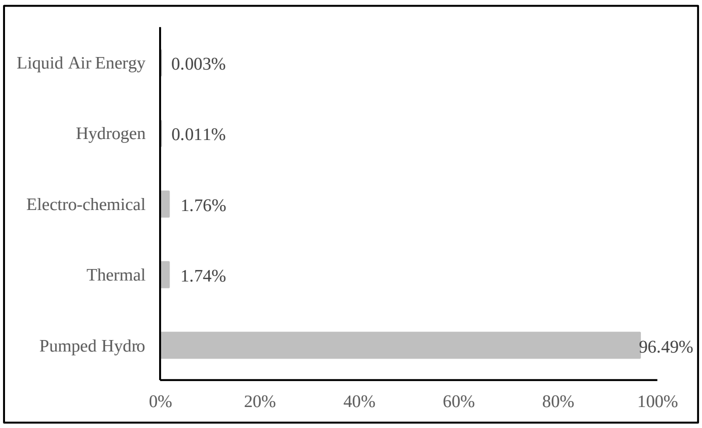


Figure 4 Composition of installed electricity storage as of December 2018 [3]

Electricity Generation

At present, electricity is primarily sourced from clustered synchronous generators, which convert rotational mechanical power, typically derived from flowing liquid (water) or gas (steam, heated gas etc.), into electricity through electromagnetic induction. Table 1 represents the composition of the global electricity generation. Significant proportion of the synchronous generation outside New Zealand utilises non-renewable energy source.

Of ≈ 6.5 TW installed generation capacity [9], around 0.2TW is interfaced with the network through HVDC [12, 13] consisting of 0.015TW of VSC HVDC. In the absence of the data related to utilisation of various assets and expected albeit limited overlap with the data presented in Table 1, it can be approximated that an additional 3% and overall < 9% of the generation is at present interfaced with the AC system through converters [8 - 14], some localised.

In the future, globally the proportion of synchronous generation with respect to partly or fully converter interfaced generation is expected to reduce due to:

- move towards use of intermittent renewable energy sources (solar, wind etc.) considering resource constraints as well as environmental sustainability
- increase in the demand of electricity due to electrification of load in order to minimise emission

Table 1 Electricity generation composition

Region	Synchronous	Converter Interfaced*	Renewable / Sustainable	Non - renewable
Global [8]	≈ 94%	≈ 6%	≈ 35%**	≈ 65%
New Zealand [10]	≈ 95%	≈ 5%	≈ 81%	≈ 19%
Australia [11]	≈ 92%	≈ 8%	≈ 16%	≈ 84%

* excludes HVDC

** Nuclear is considered a sustainable source

Power System Stability and Operation

“Power system stability” is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [16]. Stability of the power system is determined by the balance between the real and reactive power demand and supply; and damped interaction within the system. It is primarily characterised in terms of frequency, voltage and for a system comprising of synchronous machines, rotor angle. “Stability” and the associated concepts and services can be broadened to encompass converter interfaced storage, generation or load, i.e. the Converter Interfaced Technology (CIT). Unlike direct network connected machines, CIT does not inherently contribute to the inertia or the short circuit level of the power system. Performance of the network can be enhanced through converter control, implementation of stabilising hardware and use of distributed sensing and communication infrastructure.

Stability and Power Quality including CIT

“Rotor angle stability” refers to the ability of synchronous machines within an interconnected power system, to remain in synchronism after being subjected to a disturbance [16]. Both synchronising and damping torque components are key to maintaining or restoring equilibrium between the electromagnetic and the mechanical torque. Rotor angle stability can be enhanced by, appropriate design and co-ordination of Power System Stabiliser (PSS) control associated with synchronous generators and Power Oscillation Damping (POD) controllers associated with HVDC and Flexible AC Transmission System (FACTS) devices.

“Frequency stability” is characterised by the balance between generation and load, traditionally represented by the following equation [2]:

$$P_m - P_e = 2H.\,\overline{\omega}_e.\frac{d\overline{\omega}_e}{dt}$$

Where P_m and P_e represent the mechanical and electrical power respectively, H is the system inertia constant and $\overline{\omega}_e$ the per-unitised angular velocity.

“Inertia” reflects the natural inherent capability of rotating machines to store and inject their kinetic energy into the system as may be necessary [16]. Such a response mitigates the effects of an imbalance, but does not correct it. ENTSO E [17] refers to the reserves for frequency control and correction as the operating reserves, and classifies them as: Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR), and Replacement Reserves (RR).

A response equivalent to “inertia” can be triggered by control action through additional outer loop controllers for the CIT. The power mismatch can be balanced by changes in the stored energy, limited only by the storage capacity and the current rating of the converter. The CIT can be triggered by change in frequency, traditionally termed as Fast Frequency Containment (FFC) control or by monitoring Rate of Change of Frequency (RoCoF) representing synthetic inertia (SI) [18-21]. Relative to RoCoF based control, FFC is considered robust and effective [20].

“Voltage stability” is determined by the reactive power and voltage support provided through excitation control in generators and synchronous condensers, switched capacitor/reactor banks and tap-changer control. It can be enhanced by appropriate placement of FACTS devices within transmission [32] and distribution networks. Similarly, Distributed Energy Resources (DER) can be utilised to minimise voltage excursion within the distribution network.

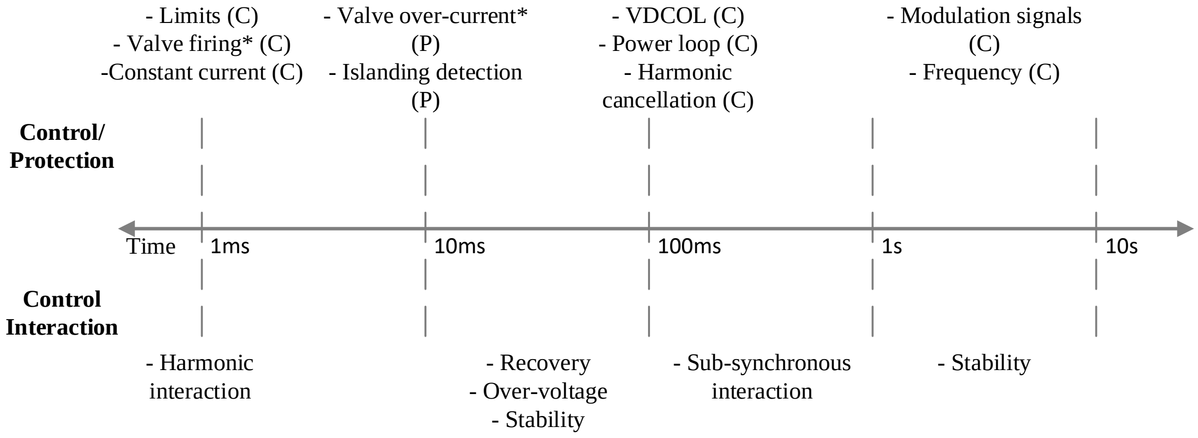
Single phase operation and associated pre-existing unbalance can be spatially and temporally exaggerated in the LV networks on introduction of DERs. Statistical network analysis can identify the capacity and boundary operating conditions of the infrastructure. Such analysis will inform decisions; e.g. incentivised operating modes for DER, smart sensor deployment, specialised distributed technologies (e.g. load balancers typical to railway applications [34, 35]) or infrastructure upgrade.

The conventional scheme of grid connected power converters, i.e. all LCC HVDC, most VSC HVDC schemes terminating in established AC networks as well as typical VSC converter interfaced renewable generation, are synchronized to the measured grid voltage through a Phase Locked Loop (PLL). This is based on the assumption that the converters are embedded in a relatively strong network. Equations in Appendix A represent the static indices indicative of the “Network stability limits” for an LCC HVDC [26-28]. These static indices can characterise VSC HVDC interaction with the network [31] and may be adapted for other CIT. Understanding of the interaction can be further refined through application of quasi-static and dynamic methodologies. Minimising undesirable interaction (affecting stability and power quality) between the numerous CIT and existing resources of varying and sometimes unknown capability is key. This can be achieved through selective, co-ordinated and droop control [33].

Distributed & Aggregated Control – Role of Communication

Simplified aggregated control of distributed resources through communication in the form of electrical signals “ripple control” [36] superimposed on the standard main power signal is well established. Wired, and more recently digital fibre optic communication technology is applied for automatic operation (e.g. switching) of the power system. With rising penetration of DER, extensive use of communication including wireless technology is anticipated in order to optimise usage of resources [18] through aggregated control.

Figure 5 represents a generic timeline of converter actions and network interactions. Considering the relative speed of interaction, a balance is to be struck between distributed and aggregated control and protection. Localised/distributed primary control and protection with centralised/aggregated control for optimising steady-state operation is appropriate considering communication latency, data analysis delays, potential data errors and design for reliability and security. Application of distributed and aggregated protective control is demonstrated in the following text through two examples.



C – Control
P – Protection
VDCOL – Voltage dependent current order limit
* < Tens to hundreds µs for VSC technology

Figure 5 Typical timeline of converter actions and resulting interactions

Depending on the network configuration, reliable determination of islanding condition for CIT such as remote micro grids based on local measurements presents a number of challenges. It is time critical to be able to detect islanding condition and alter control and protection settings so as to ensure continued stable operation with minimum impact on the scheme rating. Application of distributed monitoring and priority communication determining islanded status can prevent instability within the islanded system. A fault within the telecommunication system coincident with an islanding event can be treated as a contingency scenario.

Aggregated remote generation connected to the AC system via CIT (HVDC) is required to withstand and recover from temporary disturbances within the receiving end AC grid. In such events, amongst other methods energy storage/spill mechanisms within the HVDC power circuit is applied. For a VSC HVDC scheme this may necessitate implementation of dynamic breaking systems (DBS). The excess energy is initially stored in the circuit capacitance raising the DC voltage which triggers the DBS [22]. The DBS operates as a controlled DC load, spilling the excess energy minimising DC voltage excursion. Its control is co-ordinated with the main converter DC voltage control. Furthermore, DBS can be externally triggered by the AC network operator through communication other emergency operating scenarios.

Conclusion

Numerous novel technologies and solutions are available, in order to enable transition of the electricity sector to a low emission future. Apart from the obvious challenge of ensuring an economically sustainable transition within the legacy infrastructure and market structure, several technical challenges arise with the evolving network. Understanding of the specific infrastructure requirements and use of optimisation techniques involving an understanding of the behaviour of new technologies will be key to ensure energy sustainability.

Intermittent nature of the renewable energy source necessitates use of efficient electricity storage. At present, electricity storage technology apart from PHS is immature, in most cases low energy density and/or discharge time. PHS has geographical restrictions and can have environmental implications. Energy sources and storage can be effectively co-ordinated within regions of geographical proximity for example Europe. Isolated nations such as New Zealand will require an independent and robust energy ecosystem.

Data consolidated in this publication identifies a significant gap globally in the introduction of renewable electricity as well as electrification of loads [37, 38]. Considering the available resources the renewable generation as well as most of the load (e.g. electric vehicles) are expected to be converter interfaced. Increased ingress of CIT and proportional reduction in synchronous generation will necessitate modelling and understanding of system interaction (dynamic as well as power quality), re-evaluation of the power system stability parameters and ancillary service requirements (reserve capacity and rating of assets) and an understanding of the capability of the existing infrastructure.

Rapidly evolving technologies (e.g. sensing, communication) and techniques (e.g. control algorithms) will necessitate consideration for backward compatibility or even open and modular design permitting system upgrades with minimum investment.

This is a significant paradigm shift and presents an exciting opportunity for a co-ordinated effort to develop the next generation electricity infrastructure.

Appendix A – HVDC Static Indices

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$$SCR = \frac{SCL_{min}}{P_d} \qquad ESCR = SCR - \frac{Q_c}{P_d}$$

$$QESCR = \frac{SCL_{min} - Q_c}{P_d + Q_d}$$

These indices are indicative of voltage and frequency stability, and reflect the effect of AC system impedance and inertia. Subsequent to a network disturbance, stable operation of LCC is expected so long as SCR is typically ≥ 2. With appropriate and co-ordinated control, the scheme can be designed for lower SCR.
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$$MIIF_{j,i} = \frac{\Delta V_j}{\Delta V_i} \qquad MIESCR_i = \frac{SCL_i - Q_{ci}}{P_{di} + \sum_j MIIF_{j,i} . P_{dj}}$$

Proximity indices reflecting interaction between two or more HVDC [30].
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$UIF_g = \frac{P_d}{MVA_g}\left[1 - \frac{SCL_g}{SCL}\right]^2$:

Torsional interaction between DC control and SCL represented by the corresponding generator. For LCC interaction is insignificant when UIFg < 0.1.
</td><td>

$f_{(res)} = f_1 . \sqrt{\frac{SCL}{Q_c}}$:

Indication of resonant frequency (low-order harmonics) at a specific SCL and shunt capacitive elements in use.
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where:

Symbol
SCR - Short circuit ratio
QESCR - Q effective short circuit ratio
ESCR - Effective short circuit ratio
SCL – Short Circuit Level
MVA – Apparent power
P – Real power
Q – Reactive power
f – Frequency
V – Voltage
MIIF – Multi-infeed interaction factor
MIESCR – Multi-infeed interaction ESCR

Subscript
c – Capacitive at PCC
res – resonance
1 – fundamental
d – converter rating/absorption
g – Generator
min – Minimum
i, j – bus numeration

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