APPLICATION OF HYBRID GENERATOR SYSTEM IN A SMART GRID

TAN Hang Kiang Ray, CHUA Hian Koon, TEH Siaw Peng, LIM Jun Rong, TAN Peng Jin

ABSTRACT

Diesel generators are used for powering emergency loads during a sustained grid outage. Their design utilisations are typically less than 70% of the rated capacities because of the need to conform to operational considerations such as system load variability and non-linearity, as well as to satisfy environment derating factors. However, it would be a significant capability achievement if the remaining 30% of the reserve potential could be unlocked in part or in full for operational use to enhance asset and space utilisation. Energy storage is known to be able to achieve economic advantages such as "peak shavings" and more efficient usage of renewable energy. This article explores how smart energy storage systems (ESS), by means of an inverter in parallel interface to a diesel generator, operating seamlessly in a hybrid system, could lead to a 28 percentage point increase of the generator's prime capacity, and result in better diesel generator capacity utilisation. The ESS can be configured to support load variability and allow diesel generator to operate more in constant power mode, thereby freeing up generators from load-following constraint. When the generator is decoupled from instantaneous load variability, the additional degree of freedom in the system allows it to operate closer to its rated capacity.

Keywords: diesel generator, smart grid, energy storage system, renewables, load variability, unlock generator capacity, optimisation with statistics, photovoltaic, battery, power network

INTRODUCTION

The main challenge in the redevelopment of electrical power infrastructure for military camps and bases is in providing dynamic engineering solutions that integrate with existing infrastructure and meet operational requirements in an optimal and cost-effective manner, both now and in the future. New hardware technologies and software control innovations are actively pursued and integrated into the overall engineering design to provide flexibility, enhance operational efficiency, reduce manpower requirement, conserve energy and optimise capital investment. The use of military microgrids in an attempt to expand infrastructure power capability and flexibility is one of the many electrical engineering innovation introduced.

DIESEL GENERATOR WITH SMART ENERGY STORAGE

The Idea

Diesel generators are important assets in a microgrid system that augment grid reliability. In a microgrid, multiple energy loads and supplies are interconnected within the grid boundary, and the system is capable of operating regardless of whether it is connected to the main power grid. Military base microgrids (Shih, Kong, Chia, & Ashwin, 2017) can be configured to operate in grid-connected mode most of the time, and only switch to islanded mode when there are disturbances in the main grid. While renewable sources such as solar and wind power are increasingly integrated into the grid, their power outputs are intermittent and influenced significantly by the season and weather, and can vary abruptly and frequently. When operating in islanded microgrid mode, diesel generators have to perform the complex act of supplying electric power to meet variable load demands, while maintaining grid reliability and stability in terms of voltage, frequency control and regulation (Zamora, & Srivastava, 2010). Diesel generators have mechanical parts that operate in constant rotation (in revolution per minute), generate constant air flow, and consequently require a large balance of plant for their auxiliary air flow and heat exchange requirement. Although advanced diesel generators are more power dense and energy efficient, the actual utilisation of the diesel generating power is typically lower than its optimal operating point. This is due to the need to keep a significant amount of spinning reserve to satisfy the load variability from the system loading, non-linear load and increasingly from the intermittent renewable energy feed-in. The diesel generators must be capable of dealing with huge surges and declines in the electrical load during load regulations, which result in strong mechanical and heat stresses.

The utilisation of a diesel generator over its active operation period, in terms of average generator load factor, is typically below 70% of the rated capacity with reference to the reciprocal engine unit's horsepower. The nature of the load profiles and surge current of motorised loads contribute to load variability, and they are the main factors to consider when designing a generator system. Traditionally, diesel generators are sized larger to cater for short duration of large power demands such as motor starting currents, but this was not ideal as the investments in real estate and balance of plant also grew accordingly. By design consideration, the 70% rated capacity upper bound of the loading is taken to be the generator's full load. As a result, the diesel generator system and resources are under-utilised, with about 20% to 30% of power capacity set aside for the initial load starting phase. This translates to higher amortised cost in terms of cost per kW and kW per hour over its design life.

As diesel engines are reciprocal mechanical assemblies that produce friction in operation, it is not ideal to employ larger reciprocating machines for the provision of spinning reserve in a microgrid due to energy losses, potential engine wear and tear and wet stacking issues. Wet stacking, which happens during low loads, is a phenomenon of a diesel engine dripping a thick, dark substance from exhaust pipes often known as stacks. This design methodology of loading the diesel generator up to 70% rated capacity leads to a snowball effect of untapped spinning reserve when larger microgrids are implemented, and the aggregated reserves could reach megawatt levels for a reasonably sized power network.

Therefore, the key idea is to explore alternative means to increase the utilisation of both existing and new diesel generator plants. If the diesel generator capacity utilisation could be raised from 70% to 90%, it could potentially unlock an additional 28 percentage point increase of its prime capacity.

The Innovation

Smart Energy Storage System (ESS) implemented via battery-inverter set-up as parallel power interface to a diesel generator was studied to unlock the reserve capacity potential. The ESS supports load variability as it responds to sudden load changes (Basak, Chowdhury, Halder Nee Dey, & Chowdhury, 2012) in an attempt to allow the diesel generator to operate in constant power mode, and in the process frees up the generators from a load-following constraint. When the diesel generator system is decoupled from instantaneous load variability, an additional degree of freedom is created and it is allowed to operate closer to its rated capacity. The diesel generator will be optimised as the reserved capacity can now be unlocked to enhance power production without affecting the balance of plant such as the building provisions for system air flow.

ENERGY STORAGE IN A SMART GRID

A smart grid allows the integration of different sources of energy to an electrical grid. It includes a variety of operational and energy measures including smart control of energy resources. A typical configuration, with the ESS as one of the key components as part of a larger network, can be seen in Figure 1.

A typical ESS configuration consists of a power conversion unit and an energy storage medium (battery) (Heo, Park, & Lee, 2016). The power conversion unit, usually an inverter, is used to convert alternating current (AC) – which can be from the power grid, generators and other distributed energy resources – to direct current (DC) and vice versa (Pogak, Prodanovic, & Green, 2007). The energy from the DC will be transformed electro-chemically and stored in a battery medium. Besides regulating system voltage and frequency, the inverter also reacts to instantaneous load variability through its switching and synchronising technology. Through this, the ESS safeguards the network's power quality and ensures the voltage and frequency will not fluctuate beyond operation limits. This enables the integration of renewable power sources such as solar energy with the microgrid. The energy generated by renewable power sources usually comes in intermittent forms, giving rise to issues of power assurance and stability, and may lead to wear and tear of generators in the microgrid. The ESS is able to respond to frequency and voltage changes more quickly than diesel generators and compensates adequately for the large amount of photovoltaic (PV) output intermittency. Figure 2 shows the ESS smoothening out the effects of intermittent PV output on the generator.

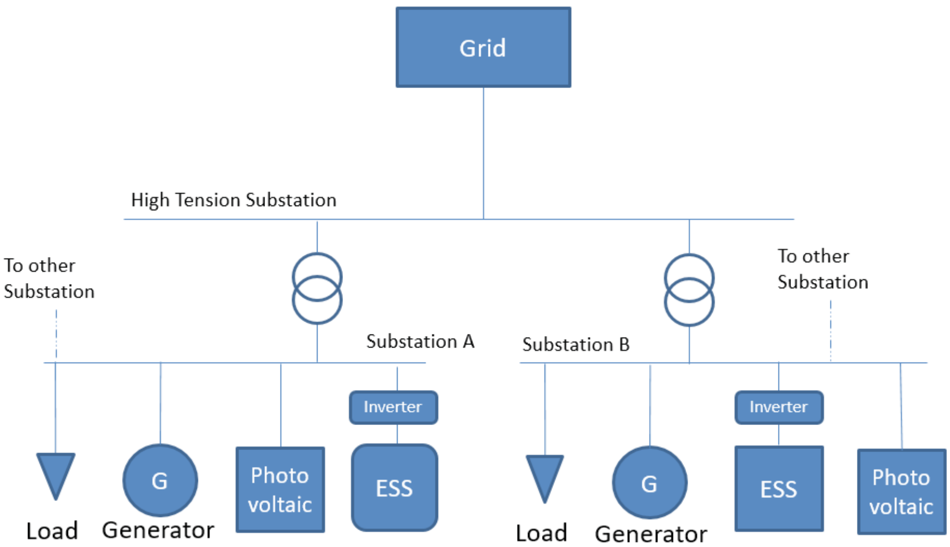

Figure 1. Smart grid

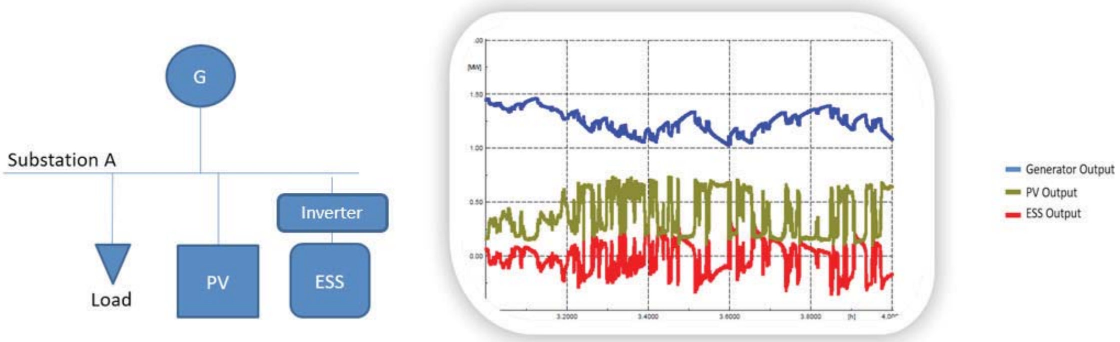

Figure 2. Microgrid with PV and ESS system, stable generator output

INCREASED DIESEL GENERATOR OPERATION CAPABILITY

The team's ultimate goal was to design an ESS to increase the diesel generator's operational capability. With results based on statistical means, the team proposed ESS support for diesel generators operating in microgrids with intermittent solar power sources. The main operational objective was to prevent a progressive power network collapse due to overloading (Yang, Xia, & Feng, 2010). The aim of the ESS was to unlock the proportion of generator reserve under ISO 8528 prime rating operation conditions, thereby powering up the microgrid system with an additional source of power.

The Impact

Two of the commonly defined ISO rating for diesel generator are used to perform the operation of power generation for microgrid system. The first prime operating mode provides a full load of up to 70% loading factor under variable loading conditions. Operating on a constant loading condition, the same diesel generator can provide a full load of up to 90% loading factor, which can be considered as being in a Constant Power (COP) operating mode (ISO, 2013). Under the variable loading conditions, the diesel generator also governs the voltage and frequency within a fixed limit upon loading deviations.

In this instance, the diesel generator accelerates its mechanical torque output to match any increase in load demand within a fixed time, stipulated under ISO 8528's transient response recovery. As a result, both the generator cooling circuit and maximum horsepower constraint limit the load factor to below 70% for variable loading under prime operating modes. For the constant power modes, the generator has a lower requirement for the regulation of voltage and frequency due to load variation. Here, the criteria for both the generator cooling circuits and horsepower reserves is less critical, and the full load is translated to a higher load factor of 90% for some diesel models.

OPTIMISING GENERATOR SYSTEM WITH ESS

The Implementation

To assess the performance of a diesel generator when paired with an ESS, a microgrid configuration was used (see Figure 3). The power system of the parallel ESS interfaced via modular power inverter with AC to DC conversion is illustrated in Figure 3. The parallel ESS increases the operational capability of the diesel generator in the microgrid under adverse conditions of rapid load variation and power overloading. The system comprises prime rated diesel generators as the main source of power. To achieve energy efficiency, the power inverter was made with a new silicon carbide technology for high power density and low switching losses when converting from AC to DC power. High performance, low loss power inverters provided the opportunity to incorporate modular active harmonics and power factor correction features, thereby reducing overall current heating losses.

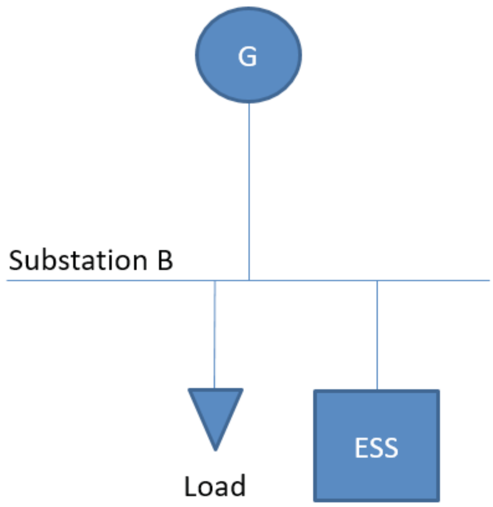

Figure 3. Hybrid generator system with ESS

Software simulation on the effects of the ESS on the generator was carried out using PowerFactory. The generator was sized at a prime rating of 150kW with a 100kWh energy storage system connected in parallel. The results shown in Figure 4 conclude that the use of ESS improved the utilisation of diesel generators by changing the operational mode from load varying to constant load. This mode of operation met the condition for the generator to be operated at higher loading (70% to 90%), which could be considered as unlocking 28 percentage point of the generator's prime capacity in potential operating power. The ESS took care of the fluctuations in load. The generator's output remained constant, and frequency and voltage of the system were maintained within 0.01 per unit.

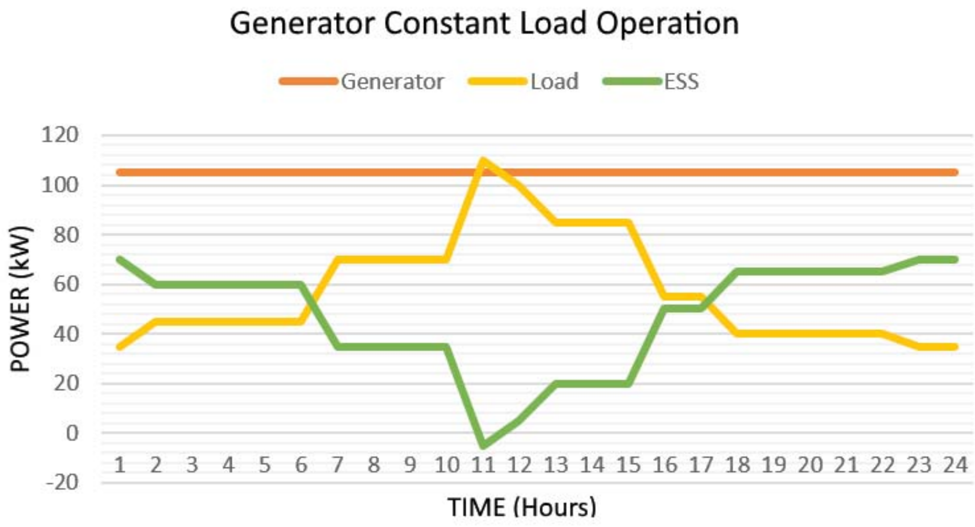

Figure 4. Results from simulation

SYSTEM LOAD PROFILE ANALYSIS

The Expected Results

The simulated load profile is illustrated in Figure 5.

The load profile from Figure 5 is processed and represented in normal distribution curves in Figure 6 below, showing the average load factor, μ=58kW with a standard deviation of 22.5kW. The confidence interval of 2σ is used in this paper for discussion and it predicts the likelihood of the real power in demand to be 58±45 kW over 95.0% of the time.

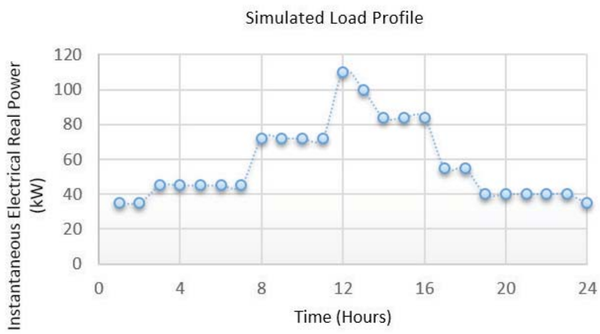

Figure 5. Simulated loading on the diesel generator

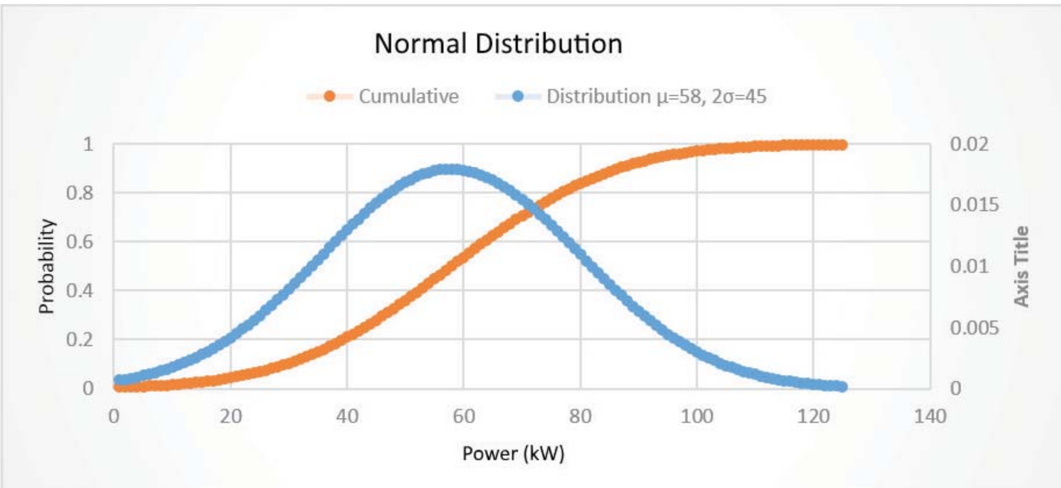

Figure 6. Simulated loading on the diesel generator with normal distribution
μ=58 kW, 2σ=45 kW

PROPOSED SYSTEM CONFIGURATIONS

The Implementation

In the proposed configurations shown in Figure 7, configuration 1 serves as a base reference. It is based on the normal set-up, which has a 188kVA diesel generator operating in prime mode with the capability to provide 105kW of average load factor, as well as an overload capability of 105±45 kW and up to a maximum of 2,520kWh energy production in 24 hours.

Configurations 2 and 3 are considered to be upgraded options. Under configuration 2, the diesel generator operates in COP instead of prime mode. The key difference is that the load variability is reduced to constant power mode. Under COP mode, the diesel generator is capable of providing higher average load factor at 135kW, without overload capability at 135kWh and up to a maximum of 3,240kWh energy production in 24 hours.

Configuration 3 attempts to combine the operation benefits of configurations 1 and 2, to give the maximum overloading capability and highest energy production over 24 hours. The diesel generator in configuration 3 is capable of providing a higher average load factor at 135kW, with an overload capability of 135±45 kW, and up to a maximum of 3,240kWh energy production in 24 hours. This configuration provides a good balance between overloading capability and maximises the energy production in terms of having a higher average load factor in 24 hours. The load profile from Figure 5 is also mapped onto the table for comparison purposes.

GENERATOR LOADING CAPABILITY CURVE

The Enhancement

The addition of ESS onto the 188kVA generator system provided additional power loading capability to serve a load within the 135±45 kW boundary (in green in Figure 8). In comparison with the normal set-up with 188kVA generator system at 105±45 kW (in blue in Figure 8), the loading capability has improved by 28 percentage point. The increase of loading capacity means that the electrical design could allow for more electrical peak loading to be safely added onto the diesel power system without violating ISO 8528 operating guidelines. Figure 8 illustrates the electrical loading in normal distribution, with the fraction of occurrence (in 24 hours) mapped on the vertical y-axis and power loading on the horizontal x-axis. The deployment of 188kVA generator with ESS saw the largest capability improvement (in green), over the original simulated 125kVA generator (in blue in Figure 8).

Specifications					Maximum rating in 24 hours	
S/N	**Generator Rating**	**Generator mode**	**Load Factor in kW**	**Load deviation in kW**	**Energy in kWh**	**Power in kW**
1.	188 kVA, normal set-up	Prime	105	45.0	2,520	150
2.	188 kVA, normal set-up	COP	135	10.0	3,240	135
3.	188 kVA+ ESS, hybrid set-up	COP	135	45.0	3,240	180
^	Load Profile (Figure 5)	-	58.0	45.0	1,392	103

Figure 7. System configuration for different diesel generator set-ups

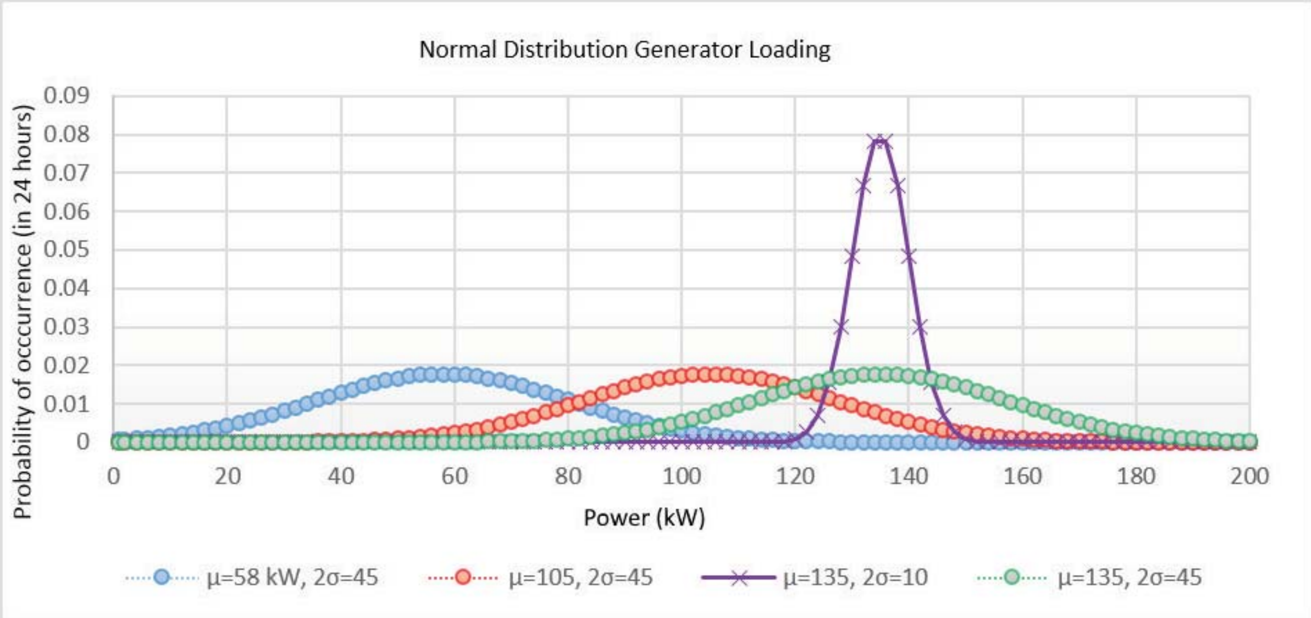

Figure 8. Normal distribution plot for generator loading curve for
(a) μ=58kW, 2σ=45, (b) μ=105, 2σ=45 (c) μ=135, 2σ=10 and (d) μ=135, 2σ=45

ENHANCE SOLAR PANEL PENETRATION

Additional Benefits

Higher solar power penetration and its variability risk bringing destabilising effects on the microgrid, as the sudden and inconsistent renewable energy production under cloudy conditions, could cause a corresponding variation in the power production of the diesel generator. The ESS guards the diesel generator against such variations by preventing the onset of conditions which could range from wet stacking, or the extreme destabilising condition where diesel generator operates in the region of zero power output.

CONCLUSION

Besides improving the utilisation of diesel generators, the use of ESS reduces the effects of load and solar power variability, which results in a more reliable smart grid. It also improves network stability by mitigating the effects of sudden changes in the electrical loading that could result from the starting of large electrical loads or sudden changes in the supply of renewable energy. In addition, it changes the fundamental operations such that AC electrical energy from diesel generator can now be stored. By allowing energy to be stored in ESS, the load-following constraint of diesel generator with system loads is decoupled and therefore, an additional degree of freedom is created. This freedom in the system allows the diesel generator's reserve capacity to be unlocked and serve a higher constant power load, leading to a 28 percentage point increase in the generator's prime capacity. A more demanding system load that is higher in peak loading can thus be better managed to prevent the occurrence of over and under loading with a confidence interval of 95.0%.

This smart ESS-driven diesel generator innovation is an unconventional, out-of-the-box design approach to reinvent and derive entirely new competitive advantages that would support future and dynamic needs of military microgrids. It has been achieved through a comprehensive understanding of advanced power technologies and niche applications of microgrid power infrastructure for camps and bases.

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BIOGRAPHY

TAN Hang Kiang Ray is a Manager (Building and Infrastructure) spearheading the development of technical competency and building up the expertise in the area of secured, operation energy solutions for protective infrastructures. He is a Singapore Certified Energy Manager Professional accredited under the Institution of Engineers Singapore to perform energy audit for large energy users. Ray seeks to bring new, resilient, highly survivable, innovative and sustainable power technology solutions to enhance operational efficiency. In 2015, Ray initiated the microgrid development technology roadmap and developed data-driven energy storage implementation plan under specialised sub-areas. He graduated with a Bachelor of Engineering (Electrical and Electronic Engineering) degree from Nanyang Technology University (NTU) in 2007.

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