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A Novel Voltage Stability and Quality Index Demonstrated on a Low Voltage Distribution Network with Multifunctional Energy Storage Systems

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Abstract

This work examines the effect of energy storage systems (ESSs) operation on the voltage stability and quality of the local power system. The variation of these two voltage dimensions is expressed in a collective manner by the novel voltage stability and quality index (*VSQI*). For the calculation of the *VSQI*, a complete voltage stability curve is required, and the coordinates associated with voltage stability and quality are identified. The distance between the abovementioned coordinates, that collectively indicates the effect of ESSs operation on the two voltage dimensions, is represented by the *VSQI*. The process for *VSQI* identification is repeated for each operating scenario, with the studied cases including grid operation prior to ESSs utilisation, grid support performed by a community level ESS, and grid operation with distributed ESSs. The ESSs are powered by renewable energy sources (RESs), and a future scenario of 70% photovoltaic (PV) penetration was examined. Other ESSs applications presented in this work, include time-shifting of the energy produced by RESs, peak load shaving, and reducing the loading levels of transmission lines and of the substation transformer. The above stack of ESSs applications, highlights the multifunctional role of ESSs as support to the grid. A real low voltage (LV) distribution network located in south-east Queensland, Australia was employed for the study.

Keywords: voltage stability and quality index; energy storage; low voltage network; photovoltaic energy.

1 Introduction

1.1 Drivers and impediments to increased renewable energy in the grid

Various health, environmental, and cost related drivers has led to an exponential growth in the use of RESs in the electricity grid over the past decade. The global installed capacity of RESs (excluding hydropower) in 2006 reached 207 GW, while in 2016, the installed capacity has increased to 883 GW according to the international renewable energy agency [1]. In terms of RESs global share in the energy mix, in 2006 the share was in the region of 3%, in 2015 it became 7%, and it is anticipated to reach a value proximate to 20% by 2035 [2].

Reducing fossil fuels combustion for electricity generation, and replacing conventional fuel with renewable energy, aids the battle of climate change [3, 4], and contributes to the Paris agreement for less than 2 °C of temperature increase compared to preindustrial levels [5]. Further, renewable energy promotes public health by reducing particulate concentration in the air [3, 6]. The efforts towards a more environmental friendly energy production are supported by declining costs and the increasing efficiencies of RESs [2, 7]. For example, the mean cost of a 5kW PV system has reduced from AUD\$2.06/Watt to AUD\$1.33/Watt between 2012 and 2016 [7].

The abovementioned drivers serve the purpose of further deployment of RESs, however, higher levels of renewable energy in the grid challenge the secure, qualitative, and economic grid operation. Symptoms introduced to the grid by the presence of RESs, include voltage rise problems [8-10], overloading of grid components such as transmission lines and transformers [11, 12], frequency excursion/suppression [13, 14], and increased spinning reserves [15, 16]. Further, the increased spinning reserve requirement, to be used as a backup, in the case of sudden loss of renewable generation, decreases the efficiency of the thermal units that serve as reserves, because these units operate at non-optimum levels, in order to have the margin to ramp up or down, depending on the dispatch commands they receive [17].

1.2 Literature review on RESs integration strategies

1.2.1 Demand side management

By applying the principle of demand side management (DSM), the authors in [18], demonstrated that the impact of high levels of PV penetration on the grid operation can be mitigated. In [18] are utilised, air-condition units of customers within the LV network for voltage regulation purposes, both during hours of excessive PV generation (i.e., in the morning), and at times with high load demand (i.e., at night). The abovementioned control strategy is often called virtual energy storage system (VESS), with the turning on of loads to be considered as charging of the ESS, and the turning off of loads, to be regarded as ESS discharging

[18]. In general, the DSM method arises multiple questions about its applicability. For example, the physical presence of heavy loads in the feeder, may not sum the necessary power to counteract the PV impact. Further, residential customers are hesitant to allow the distribution network service provider (DNSP) to control their domestic loads due to limited cost incentives and reduced self-control of their appliances. The work in [19] suggests, that not only high economic incentives are required to motivate electricity users to participate in DSM, but also economic penalties may be considered, when electricity customers deviate from the curtailment prompts provided by the electrical utility. The authors of the present work deem, that an alternative to the DSM practice should be followed, that aids the daily routine of electricity customers.

1.2.2 Power curtailment

Power curtailment is another solution able to mitigate the overvoltage caused by excessive PV generation. Two ways of power curtailment are examined in the work reported in [20]. Firstly, droop-based PV inverters would reduce their power output when overvoltage is anticipated. Because the overvoltage phenomena are more intense at terminals of the feeder that are placed remotely of the substation transformer, the first curtailment method presented in [20], reduces the output power of the PV inverters that are situated at the remote terminals. Regarding the inverters proximate to the substation transformer, their participation to power curtailment is negligible. This first strategy, succeeded in overvoltage prevention, however it was unfair to electricity customers at the end of the feeder, because the power reduction of their rooftop PV installations, was greater than the power reduction of the PV installations proximate to the transformer. A second, more equitable power curtailment method is demonstrated in [20], where a more even power reduction is realised. According to the later method, the power to be curtailed is shared equally, among the PV inverters that exist in the LV network. A demerit of the second method is that more energy is curtailed in total at feeder level, to achieve the same voltage regulation, that was achieved by less energy curtailment, when only the PV inverters situated at the end of the feeder were involved in the curtailment process. The authors of this paper have focused their study scope on maximising the injection of renewable energy into the grid rather than truncating it, therefore PV power curtailment exceeds the scope of the present work.

1.2.3 Tap changer transformers

The aim in [21], is to identify the maximum penetration level distributed generation (DG) units can reach in Canada, when either the on-load or the off-load tap changing mechanism of the substation transformer is utilised. A typical Canadian network is employed for the studies, with the identified DG penetration limit, to be equal to the thermal limit of the feeder. The studies indicated that utilisation of both on-load and off-load tap changing mechanisms maintained the voltage within the legitimate limits, for the higher DG penetration. A conclusion of the study was that the on-load and off-load tap changing mechanisms can only be used in

cases where the thermal limits of the grid components (e.g., transmission lines or the substation transformer) are not violated. In cases where the loading limit of the grid equipment is exceeded (e.g., critical transmission line overloading), because the tap changing mechanism only regulates voltage, the voltage rise problem would be mitigated, while the overloading of the grid equipment would be sustained or even exacerbated.

1.2.4 Solar inverters

Utilisation of the reactive power capability of solar inverters helps achieve higher PV penetration levels in the grid [22, 23]. The dispatch commands of the inverters, are generated by employing various types of droop characteristics. For example, for the droop in [22], the reactive power dispatch command depends on the extent of the terminal voltage deviation from its nominal value. Further, the droop characteristic in [22] maintains two slopes. The first slope presents reduced steepness and it is used to restore voltage rise up to 3%. The second and steeper slope of the droop characteristic, is considered for voltage rise levels, greater than 3% and up to 10% of the nominal voltage. The droop characteristic introduced by the authors in [23], controls the reactive power of the solar inverter, not only based on the terminal voltage at the point of common coupling (PCC) of the inverter, but also it considers the PV power generation, that through the solar inverter it is converted into AC, and in turn it is injected into the grid at the PCC. Both of the works in [22, 23] demonstrate that solar inverters can be used to mitigate the voltage rise at the feeder terminals, however, this is achieved by the solar inverters absorbing reactive power from the grid. For the reactive power to reach and be absorbed by the solar inverters, it has to flow through the substation transformer and transmission lines up to the point where the solar inverters are situated. This means that the loading of the substation transformer and transmission lines is further increased, because the reactive power must flow through those components, to reach the solar inverters. Thereby, the method that employs solar inverters to facilitate higher PV integration, is only applicable when terminal voltages are the only parameters that are violated. In the case where both terminal voltages and transmission lines loading are violated, the reactive power absorption by the PV inverters will mitigate the voltage rise, however it will exacerbate the overloading of the grid components.

1.3 Literature review on ESSs facilitating RESs integration and other grid applications

1.3.1 ESSs for voltage stability improvement

The effect of DGs and ESSs on the steady-state voltage stability is explored in [24-26]. The focus of the work in [24], is on the placement and sizing of DG units. The system under study, is a rural distribution network, with candidate buses for DGs placement, to be considered the ones that present higher voltage sensitivity to power variation. The work in [24] indicates, that integration of DGs positively affects the voltage stability of the system. Similar positive effects, by the presence of DG units on the stability of the system are also

presented in [25], where in that work, the beneficial role of DG units on system losses is also captured. The work first presented in [25], that only examined DGs, was extended in [26], to also include one ESS per PV installation, while voltage stability enhancement and energy loss reduction as the objectives of the work, remained invariant. These studies demonstrate the positive effect of DG units and ESSs on voltage stability, however, the loading of the critical transmission lines and the reduction of the peak load at night hours, is not considered in [24-26]. Further, the mathematical formulation introduced by the authors in [25, 26], is only applicable to radial grid arrangements, since for the calculation of losses for example, the analytical expression requires to consider the total of the buses that are included in the power-flow path. In case of a radial grid, the identification of those buses is a feasible task. Conversely, in the case of a grid model with a more complex arrangement (i.e., loop or mesh) that resembles grids in practice, because the power-flow path changes at each power-flow execution, the utilisation of an analytical expression such as that described in [25, 26] is impracticable.

1.3.2 ESSs regulate frequency and provide spinning reserve

Replacing thermal generators by an ESS, to perform frequency regulation (i.e., primary reserve) and spinning reserve (i.e., secondary reserve), results in regulating the system frequency at the fastest possible speed and with the minimum amount of energy utilised for that purpose [27]. In the work presented in [28], it is demonstrated that because of the fast acting nature of a battery-based ESS (with absence of mechanical inertia), periods of frequency excursion are minimised with the ESS to absorb energy faster than the response to over-frequency that can be provided by thermal generators, that follow the automatic generation control (AGC) signal. The fastest response of the ESS, is also indicated in the case of under-frequency, where the fast-acting storage, restores the system frequency faster than generators with mechanical inertia [28]. In addition, the period where generators operate at part load (to be ready for frequency regulation up/down and spinning reserve) is minimised, an action that positively affects operating costs, since fuel consumption is minimised. An ESS, is effective on frequency regulation not only in the case of rapid load variations that lead to frequency excursions/suppressions, but it is also a competitive solution to smooth out fluctuations that originate from the output power of wind turbines. In [29], the ESS response is coordinated with the operation of the permanent magnet synchronous generator (PMSG) wind turbine. In that work it is indicated, that for various penetration levels of wind energy, the system frequency is restored to the nominal value 11.5 to 13 seconds faster than other frequency regulation methods.

1.3.3 ESSs improve line losses and perform voltage regulation

The authors in [30], formulated an optimisation problem, that minimised the cost of the energy storage units as well as the line losses, while the voltage was maintained at all times within the allowable range. The

optimisation was applied to a practical LV network in Italy that maintained a radial arrangement, while two ESSs were considered for grid support. The method proposed by the authors, succeeded in indicating that the terminal voltages were improved with ESSs utilisation, while the line losses were also reduced as compared to the amount of losses prior to ESSs becoming operational. Although the authors in [30] showcased ESSs capability to perform voltage regulation, the ESSs capability to enhance the voltage stability of the electricity grid was not covered in the study. One ESS per PV installation is considered in the work reported in [31], with the control proposed by the authors to realise voltage regulation. A limitation of the control method proposed in [31], is that it requires the ESS situated at the last bus of the power-flow path per branch, to be identified and treated as the virtual leader, which would be impracticable to implement on electricity grids that maintain complex arrangements such as mesh and loop grid arrangements. Voltage regulation was the objective of the control method presented in [32]. The authors in [32] successfully mitigated both the voltage rise problem in the morning, and the voltage drop in the evening, however, neither the loading of the transmission lines and the effect of ESSs on voltage stability is presented.

1.3.4 ESSs for congestion relief

The authors in [33], adopted the concept of virtual power plants (VPPs), where a PV power plant and a battery-based ESS were considered as one VPP, and in total three VPPs were available to be dispatched. At times during the day, where the DNSP anticipated congestion to occur, due to excessive generation of renewable energy, the VPPs were engaged and successfully prevented the exceedance of the thermal limits of the two critical transmission lines. An alternative to the engagement of the three VPPs to relieve the congestion, was to curtail renewable generation (a practice that is followed in [34]). The authors in [33] were definitely in favour of dispatching the available VPP, rather than to curtail the renewable energy. The work carried out in [33], demonstrated that the VPP concept is effective on congestion relief, yet, there are other ESSs applications that were not explored, such as peak load shaving, voltage support in the evening, and the effect of ESSs on voltage stability.

In [35], the high volume of solar energy present in the IEEE benchmark grid, resulted in the overloading of two transmission lines and voltage rise. To alleviate the above operational symptoms, the authors employed three ESSs with fixed placement and sizing. The control strategy included, division of the benchmark radial grid into areas, where one ESS was assigned to one area. The voltage rise and congestion phenomena were mitigated, by dispatching the local ESS in the area where it was located. In turn, the dispatch solutions for each of the three areas were combined, and if the three individual solutions led to one feasible dispatch solution for the entire grid, then this solution was adopted. The control method proposed in [35], alleviated congestion and voltage rise problems, however, the traditional dispatching method that dispatches all three ESSs simultaneously, and identifies the power-flow for the entire grid, produced better mitigation of the

voltage rise problem. In terms of congestion relief, the results were similar between the traditional dispatching method and the method proposed by the authors. Furthermore, the work in [35] presented no results or discussion related to peak shaving and voltage support in the evening.

1.3.5 ESSs function for load levelling

The authors in [36, 37] demonstrated the load levelling capability of an ESS that is connected at medium voltage level. The dispatch strategy includes the generation of a control signal, that represents the expected power at the substation transformer throughout the day, after the ESS has been dispatched. The generated control signal presents very little variation (almost a straight line) throughout the day. This almost invariant power through the substation transformer, is achieved by equalising the charging and the discharging phases of the ESS. The control strategy introduced by [36, 37], harnessed the ESS capabilities to perform load levelling, however, this study did not consider the voltage stability benefits that could be provided concurrently with other ESS applications.

1.4 Research contribution

- A new mathematical formulation is introduced that collectively considers both voltage stability and quality parameters for the local power system.
- Going beyond prior studies, the paper demonstrates the role of ESSs for a comprehensive aggregation of applications, namely, RESs shifting, voltage stability enhancement, voltage regulation, congestion relief, and peak load shaving.
- Two different ESSs deployment options (i.e. community level ESS and distributed ESSs at selected terminals of the LV network) are presented and compared in terms of compensation capability and cost.
- Most reported studies utilise radial grid models to demonstrate aggregated ESSs applications. A practical grid model that maintains a complex loop arrangement is used in the present work to demonstrate the capability of ESSs to perform multiple applications. Herein developed formulations and control methods that generate ESSs dispatch commands are more robust and generalizable.

2 Problem formulation

The overarching goal of this project was to demonstrate the multifunctional role of ESSs within an active distribution network (ADN) to facilitate higher RESs deployment and achieve the objectives of a number of grid applications. The two core research project objectives were:

- To introduce a novel formulation of a *VSQI* that collectively considers the variation of both voltage stability and quality, with the introduction of ESSs.
- To examine and compare distributed and community level ESSs deployment options within a real-life looped grid arrangement, in terms of their capacity for voltage stability and quality, RESs shifting, peak load shaving, and reducing loading levels of transmission lines and of the substation transformer.

The objectives were achieved considering the below study scope.

- A real-life LV distribution network, that maintains a complex arrangement was utilised for simulations.
- Three-phase balanced power-flow was performed.
- The information of the real-life LV distribution network, as well as the dataset of the load profiles, were made available to the authors by the local DNSP [38].
- Measured data of solar irradiation and ambient temperature, for the same region where the LV network is located were imported into the PV panel model analysed in [39-41], for the derivation of the PV generation time-series.
- The three grid operational constraints, namely terminal voltages, transmission lines loading, and substation transformer loading were examined.
- The developed control method that generates the ESSs dispatch commands was designed to be suitable for all common grid arrangements (e.g., radial, mesh, loop, etc.).

To examine the effect of ESSs operation on voltage stability and quality, and to demonstrate the multifunctional role of ESSs, that support the grid operation and allow higher PV penetration levels to be achieved, the following scenarios were explored with (W) or without (WO) ESSs.

- Solely load
- Load with 9.12% PV (reference value)
- Load with 70% PV – WO ESSs
- Load with 70% PV – W CL ESS
- Load with 70% PV – W DIST ESSs

Eq. (1) was used to determine the level of PV penetration (PV_{pen}) [42]. Variable $E_{PV,pa}$ is the total energy produced by the rooftop PV installations that exist in the LV network per annum (pa). Variable $E_{load,pa}$ represents the annual total energy demand from the loads that exist in the LV network. The energy-based definition of PV_{pen} was used in this study since it reflects the actual power produced by the PV installations over the one-year period, rather than using standard test condition (STC) values.

$$PV_{pen} = \frac{E_{PV,pa}}{E_{load,pa}} \quad (1)$$

3 Control operation

3.1 Storage units dispatch commands generated by variable droop control

Accurate ESSs dispatch commands were generated by employing the variable droop (VD) control principle. As illustrated in Fig. 1, the VD control adapts the slope of the droop characteristic on an hourly basis, until the

minimum power per ESS is identified, that results in a sound grid operation for each operating point. VD control eliminates excessive compensation that is prevalent for fixed droop (FD) control.

- VD characteristics – ESS1
- VD characteristics – ESS2
- VD characteristics – ESS3

Fig. 1. VD control characteristics formulation for distributed ESSs.

As shown in Fig. 1, each ESS operates under its own VD control, where the dispatch commands of the ESSs, $P_{ESS_\chi}(d,t)$, $\chi \in [1\ 3]$, for each day, d , of the year and hour, t , of the day, are a function of the power surplus, $SRP(d,t)$, at the substation transformer. In this work, where three ESSs have been strategically placed to perform grid support, the column vector that contains the ESSs dispatch commands, $\mathbf{P}(d,t)$, is described by Eq. (2). Regarding the formulation of the droop characteristics illustrated in Fig. 1, see Eq. (3).

$$\mathbf{P}(d,t) = \begin{bmatrix} P_{ESS_1}(d,t) \\ P_{ESS_2}(d,t) \\ P_{ESS_3}(d,t) \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} SRP(d,t) \\ SRP(d,t) \\ SRP(d,t) \end{bmatrix} = \begin{bmatrix} a_{ESS_1}(d,t) & 0 & 0 \\ 0 & a_{ESS_2}(d,t) & 0 \\ 0 & 0 & a_{ESS_3}(d,t) \end{bmatrix} \cdot \begin{bmatrix} P_{ESS_1}(d,t) \\ P_{ESS_2}(d,t) \\ P_{ESS_3}(d,t) \end{bmatrix} + \begin{bmatrix} SRP_{\min,ESS_1}(d,t) \\ SRP_{\min,ESS_2}(d,t) \\ SRP_{\min,ESS_3}(d,t) \end{bmatrix} \quad (3)$$

Regarding $SRP_{\max}(d)$, it is the maximum surplus of the day, and it represents the most adverse operating state a droop characteristic could handle, because it combines the highest PV generation over the day with the lowest morning load. $SRP_{\max}(d)$, along with the ESSs dispatch commands at $SRP_{\max}(d)$, formulated as $(\mathbf{X}(d), SRP_{\max}(d))$, define the first of the two points, required by a droop characteristic. As detailed in Eq. (4), $\mathbf{X}(d)$ contains the dispatch command per ESS at $SRP_{\max}(d)$.

$$\mathbf{X}(d) = \begin{bmatrix} P_{ESS_1,SRP_{\max}}(d) \\ P_{ESS_2,SRP_{\max}}(d) \\ P_{ESS_3,SRP_{\max}}(d) \end{bmatrix} \quad (4)$$

For the derivation of the ESSs dispatch commands at $SRP_{\max}(d)$, that are shown in Eq. (4), the distance between the ESS and the substation transformer, r_{ESS_χ} , is taken into consideration, according to Eq. (5).

$$P_{ESS_{\chi},SRP_{\max}}^{\diamond} = \left(\frac{r_{ESS_{\chi}}}{r} \right) \cdot P_{red} \quad (5)$$

Equation (5) expresses the power reduction to the compensation of $SRP_{\max}(d)$, $P_{ESS_{\chi},SRP_{\max}}^{\diamond}$, depending on the distance between the ESS and the substation transformer. Where for each $r = 150 \text{ m}$ the ESS is placed away from the substation transformer, its contribution to the compensation of $SRP_{\max}(d)$ is reduced by $P_{red} = 5 \text{ kW}$.

Eventually, the three $P_{ESS_{\chi},SRP_{\max}}(d)$ that fill the column vector $X(d)$, are obtained by Eq. (6). Where in Eq. (6), $P_{ESS,SRP_{\max}}(d)$ is the compensation an ESS placed at zero distance from the substation transformer would provide, and $P_{ESS_{\chi},SRP_{\max}}^{\diamond}$ is given by Eq. (5).

$$P_{ESS_{\chi},SRP_{\max}}(d) = P_{ESS,SRP_{\max}}(d) + P_{ESS_{\chi},SRP_{\max}}^{\diamond} \quad (6)$$

$SRP_{\min,ESS_{\chi}}(d,t)$ needs to be positioned on the y-axis according to the droop formulation in Fig. 1; this value represents the second point of the droop characteristic. The variation of the position of $SRP_{\min,ESS_{\chi}}(d,t)$ on the y-axis, changes the slope of the droop characteristic, $a_{ESS_{\chi}}(d,t)$, that in turn considerably affects the generated dispatch command in response to the expected $SRP(d,t)$.

The range of values that can be obtained by $SRP_{\min,ESS_{\chi}}(d,t)$, depends on the distance between the ESS and the substation transformer. Typical $SRP_{\min,ESS_{\chi}}(d,t)$ values as they were used in this work, are provided in Fig. 2, which illustrates that the closer the ESS is placed to the substation transformer, the lower the $SRP_{\min,ESS_{\chi}}(d,t)$ value.

Placing the second point of the droop characteristic (i.e., $SRP_{\min,ESS_{\chi}}(d,t)$) at a lower point on the y-axis, means that a steeper slope will be adopted by the droop, this results in the generation of an ESS dispatch command of higher value. Dispatch commands of higher values for the ESSs closer to the substation transformer (e.g., terminal 31 of the case study LV network analysed in Chapter 5) and of lower values, for the storage units placed remotely (e.g., terminal 50 of the case study LV network analysed in Chapter 5) are aligned with the loading conditions of the grid.

Fig. 2. $SRP_{\min,ESS_x}(d,t)$ variation as a function of distance.

Specifically, lower loading levels are anticipated at the remote ends of the LV network, due to the existence of a small number of loads and PV installations. Thereby, an ESS dispatch command of lower value, would successfully achieve the control aim. Conversely, the loading conditions in the vicinity of the substation transformer, are many times greater than the loading conditions at the network ends. This is because the power from the total of the areas of the grid, merges at the substation transformer. Thereby, for an ESS placed in the vicinity of the substation transformer to be effective in providing grid support, a dispatch command of higher value is required.

The green line in Fig. 2, indicates the average values of $SRP_{\min,ESS_x}(d,t)$, depending on the distance between the ESS and the substation transformer, with the distance to be denoted as r_{ESS_x} . The average $SRP_{\min,ESS_x}(d,t)$ (i.e., $SRP_{\min,ESS_x}^{AVG}$) is approximated by Eq. (7), where apart from the variable r_{ESS_x} , another three constants are utilised (i.e., a , b , and c), that are adapted to the electricity grid under examination. The values of the parameters utilised in this work were identified as $a=0.82$, $b=26.8$, and $c=63$. The previous constants were obtained by fitting a curve onto the green curve presented in Fig. 2, with Eq. (7) and the three

constants mentioned above to reproduce the green line of Fig. 2 for any r_{ESS_χ} value. The curve fit process was realised by importing Fig. 2 into the curve fit tool (CFT) available in MATLAB [43].

$$SRP_{\min, ESS_\chi}^{AVG} = \frac{(a \cdot r_{ESS_\chi}) + b}{r_{ESS_\chi} + c} \quad (7)$$

Eq. (3) is rearranged to Eq. (8), and the two points that have been identified – the first point per droop is given by $(X(d), SRP_{\max}(d))$ and the second point per droop results from Eq. (7) and by letting $SRP_{\min, ESS_\chi}(d, t) = SRP_{\min, ESS_\chi}^{AVG}$ – are substituted into this formula. By utilising the above two points, the right side of Eq. (8) is known, therefore the slope (i.e., $a_{ESS_\chi}(d, t)$) of the characteristic, formed by the above two points is identified.

$$\begin{bmatrix} a_{ESS_1}(d, t) \\ a_{ESS_2}(d, t) \\ a_{ESS_3}(d, t) \end{bmatrix} = \begin{bmatrix} SRP_{\max}(d) - SRP_{\min, ESS_1}(d, t) & 0 & 0 \\ 0 & SRP_{\max}(d) - SRP_{\min, ESS_2}(d, t) & 0 \\ 0 & 0 & SRP_{\max}(d) - SRP_{\min, ESS_3}(d, t) \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{P_{ESS_1, SRP_{\max}}(d)} \\ \frac{1}{P_{ESS_2, SRP_{\max}}(d)} \\ \frac{1}{P_{ESS_3, SRP_{\max}}(d)} \end{bmatrix} \quad (8)$$

The values of $SRP_{\min, ESS_\chi}(d, t)$ and $a_{ESS_\chi}(d, t)$ resulting from Eq. (7) and Eq. (8), along with the expected $SRP(d, t)$ value, are substituted into Eq. (9). This yields the ESSs dispatch commands, that fill the column vector $\mathbf{P}(d, t)$ described by Eq. (2) and illustrated in Fig. 1.

$$\begin{bmatrix} P_{ESS_1}(d, t) \\ P_{ESS_2}(d, t) \\ P_{ESS_3}(d, t) \end{bmatrix} = \begin{bmatrix} SRP(d, t) - SRP_{\min, ESS_1}(d, t) & 0 & 0 \\ 0 & SRP(d, t) - SRP_{\min, ESS_2}(d, t) & 0 \\ 0 & 0 & SRP(d, t) - SRP_{\min, ESS_3}(d, t) \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{a_{ESS_1}(d, t)} \\ \frac{1}{a_{ESS_2}(d, t)} \\ \frac{1}{a_{ESS_3}(d, t)} \end{bmatrix} \quad (9)$$

3.2 Storage units supplying energy to the grid

To facilitate the grid operation in the evening, particularly between 6 pm (t_1) and 12 am (t_2), the strategically placed storage units discharge energy into the grid, the energy they absorbed during periods of excessive PV generation. The abovementioned shifting of energy, facilitates the grid operation in numerous ways. For example, the loading of transmission lines and of the substation transformer is reduced, the terminal voltages are improved, and the stability of the electricity grid is enhanced. To effectively distribute in the evening the energy absorbed by the ESSs in the morning, in order to perform the abovementioned applications, the expected load demand, $L_D(d, t)$, is considered. The load demand over the period bounded between t_1 and t_2 , is substituted into Eq. (10), for identification of an hourly weight, $w(d, t)$, that directs more energy towards hours of high load demand where grid support is essential.

$$w(d, t) = \frac{L_D(d, t)}{\sum_{t_1}^{t_2} L_D(d, t)} \quad (10)$$

The total energy charged by each ESS during periods of excessive PV generation, $E_{C, ESS_x}(d)$, is kept within the column vector $\mathbf{E}_C(d)$, presented by Eq. (11).

$$\mathbf{E}_C(d) = \begin{bmatrix} E_{C, ESS_1}(d) \\ E_{C, ESS_2}(d) \\ E_{C, ESS_3}(d) \end{bmatrix} \quad (11)$$

After the end of the charging period, where each of the elements of $\mathbf{E}_C(d)$ has obtained a value, and with the evening weights known by Eq. (10), the ESSs dispatch commands prior to conversion losses (PCL), $P_{ESS_x}^{PCL}(d, t)$, are identified by Eq. (12). Please note that ESSs are treated as generators where a negative sign for $E_{C, ESS_x}(d)$ indicates the charging operation. Therefore, to determine $P_{ESS_x}^{PCL}(d, t)$ an absolute value is placed at $E_{C, ESS_x}(d)$, indicating the discharging operation represented by $P_{ESS_x}^{PCL}(d, t)$.

$$\begin{bmatrix} P_{ESS_1}^{PCL}(d,t) \\ P_{ESS_2}^{PCL}(d,t) \\ P_{ESS_3}^{PCL}(d,t) \end{bmatrix} = \begin{bmatrix} |E_{C,ESS_1}(d)| \\ |E_{C,ESS_2}(d)| \\ |E_{C,ESS_3}(d)| \end{bmatrix} \cdot w(d,t) \quad (12)$$

The roundtrip efficiency, n_{rt} , per ESS reaches 88% for Li-ion battery technology [44]. Therefore, the energy that leaves the battery and through the power conditioning unit (PCU) reaches the terminal where the ESS is connected at, is reduced by taking into consideration the discharging efficiency, n_d , as it is described by Eq. (13).

$$\begin{bmatrix} P_{ESS_1}(d,t) \\ P_{ESS_2}(d,t) \\ P_{ESS_3}(d,t) \end{bmatrix} = \begin{bmatrix} P_{ESS_1}^{PCL}(d,t) \\ P_{ESS_2}^{PCL}(d,t) \\ P_{ESS_3}^{PCL}(d,t) \end{bmatrix} \cdot n_d \quad (13)$$

4 Joint voltage stability and quality consideration

Voltage stability analysis has been extensively researched in the literature [24-26]. The voltage stability margin, is the distance between the current operating state, and the last operating state where the power-flow method converges. The process includes stressing the system by progressively increasing the load (S_{L_D}). A stress factor (k) performs the above, by increasing the total load active (P_{L_D}) and reactive (Q_{L_D}) power demand, according to the formulation in Eq. (14).

$$S_{L_D} = k \cdot P_{L_D}(d,t) + j k \cdot Q_{L_D}(d,t) \quad (14)$$

Equation (14) can be examined considering two conditions that are provided in Eq. (15). When $k=1$, S_{L_D} corresponds to the operating state of which the quality and stability are explored. For example, this operating state could be the 6th of December 2013 (i.e., d), at 8 pm (i.e., t). The second occasion is when k obtains a range of non-negative values, that are also other than 1. When k receives non-negative values, a power sweep is performed, from zero up to the last point where power-flow convergence is achieved. This last operating point of the system, in voltage terms, is the system's stability limit and it is the vertex of the voltage stability curve shown in Fig. 3.

$$S_{L_d} = \begin{cases} k=1 \rightarrow S_{L_d} = S_{L_d}(d,t) \\ k \neq 1; k \in \square_{\geq 0} \rightarrow S_{L_d} \neq S_{L_d}(d,t) \text{ or } S_{L_d}(d,t) < S_{L_d} < S_{L_d}(d,t) \end{cases} \quad (15)$$

To ascertain the effect of ESSs operation on voltage stability and quality, two voltage stability curves are presented in Fig. 3. The curves are obtained by performing two power sweeps. In the case where more than one ESS supports the grid operation, sequential power sweeps are performed.

Fig. 3. $VSQI$ formulation utilising voltage stability curves and the Pythagorean theorem.

This process involves adding one ESS per power sweep with the goal to record how each ESS influences the total voltage stability and quality variation. The first voltage stability curve shown in Fig. 3, is recorded in the absence of grid support units. The second power sweep is performed, when a community level ESS supports the grid operation. Each of the above cases forms a triangle, with the peaks of the triangle related to voltage

quality (vq) and voltage stability (vs), in the case of grid operation in the absence of grid support units (0), to be denoted as (x_0^{vq}, y_0^{vq}) and (x_0^{vs}, y_0^{vs}) . When a community level ESS supports the grid operation, the peaks of the triangle, that are used to ascertain the variation of voltage quality and stability, are defined as (x_1^{vq}, y_1^{vq}) and (x_1^{vs}, y_1^{vs}) . By observing the voltage stability curves in Fig. 3, it can be seen that the voltage quality is improved, with the voltage of the critical terminal to be elevated, from y_0^{vq} to y_1^{vq} . The same observation applies to the voltage stability, where the stability limit of x_0^{vs} , is replaced by the greater voltage stability limit of x_1^{vs} .

In this work, the two dimensions of voltage stability and voltage quality, are unified into one parameter for the first time in the literature. This parameter, is the novel voltage stability and quality index, $VSQI$, that provides an insight into the voltage-related dimensions of the power system, aiding the design and running of the electricity grid. The $VSQI$ can be used to assess the qualitative and secure operation of a future (e.g., next 10 minutes) operating state of the power system. For example, the system operator by comparing the $VSQI$ value prior to and after grid support units (e.g., ESSs) engagement, could decide whether it would be helpful for the grid, to add ESSs to the forthcoming unit commitment. For the calculation of the $VSQI$, the peaks of the triangles, as they were identified in the above paragraphs are utilised, along with the well-known Pythagorean theorem [45]. As it is shown in Fig. 3, the more power an ESS injects into the grid in the evening, the higher the voltage stability and the better the voltage quality. This improvement, is represented by the longer c side and b side of the triangle, which also results in a longer a side or hypotenuse of the triangle. By utilising the Pythagorean theorem [45], applied to the voltage stability curves and the resulting triangles that are formed, the $VSQI$ is identified according to Eq. (16).

$$VSQI_{\varepsilon} = \sqrt{(x_{\varepsilon}^{vs} - x_{\varepsilon}^{vq})^2 + (y_{\varepsilon}^{vs} - y_{\varepsilon}^{vq})^2}, \quad \varepsilon \in [0 \ 1] \text{ or } \varepsilon \in [0 \ 3] \quad (16)$$

When the $VSQI$ is identified in the case of a community level ESS, ε belongs to $[0 \ 1]$, with 0 represents the case of no grid support, and 1 indicates the operation of a community level ESS. Conversely, in the case where more than one ESSs support the grid operation, for example when three ESSs (i.e., $\varepsilon \in [0 \ 3]$) support the grid, $\varepsilon = 1$ means that only one of the three ESSs is operational. When the first and the second ESSs operate together, then $\varepsilon = 2$, and finally when all the three ESSs are dispatched then $\varepsilon = 3$. The $VSQI$ for each of the above circumstances has been determined for the case study.

5 Case study

The electricity grid presented in Fig. 4, serves as a trial network for the local DNSP [38]. Therefore, it has been used in this work as a case study, to demonstrate the *VSQI* formulation and the multifunctional role of ESSs. The LV network illustrated in Fig. 4, is a representative case of urban LV networks in Queensland Australia that predominantly maintain resistive behaviour. The total length of the transmission lines is identified at 1.7 km. 0.92 km maintain R_1/X_1 ratios >1 (i.e., 2.32, 1.44, 4.58), 0.37 km present R_1/X_1 ratios <1 (i.e., 0.92, 0.8), while the various line types of short length totalling 0.41 km, contribute to the resistive behaviour of the grid. Regarding the substation transformer impedance, it equals to 4%.

Fig. 4. Practical LV electricity grid in Queensland, Australia.

Research work related to the case study LV network has been reported [46]. This study determined that for ESS placement, the lowest ESS cost, $C_{ESS}(d)$, solution was to place the ESS at terminal 40. ESS placement at terminal 40, is associated with \$199,906 of capital cost, made of 87.84 kW of rated power, and 395.48 kWh of rated energy.

Measured load profiles acquired from the electricity grid of Fig. 4, were made available to the authors by the local DNSP [38]. The total load demand for the one-year period ranging from autumn 2013 to summer 2013-2014, denoted as $E_{load,pa}$, reached the value of 1,038,539 kWh. Recorded values of solar irradiation and ambient temperature, matching the load profiles availability period (i.e., from autumn 2013 to summer 2013-2014), are available in [47]. These values were imported into the PV panel model described in [39-41], for the generation of the PV production profiles, for each of the PV installations indicated in Fig. 4. The total energy produced during the one-year period by the PV installations, called $E_{PV,pa}$, was identified at 94,693 kWh. By

substituting $E_{load,pa}$ and $E_{PV,pa}$ as given above, into Eq. (1), the reference case PV penetration level (i.e. 9.12%) was obtained.

Full year simulations were executed, prior to ESSs engagement, in order to identify the critical grid parameters. The examined grid parameters include loading of transmission lines, $TL_i(d,t)$, $i \in [1\ 64]$ with $TL_i(d,t) \leq 100\%$, variation of terminal voltages, $V_j(d,t)$, $j \in [1\ 54]$ with $0.94\ pu \leq V_j(d,t) \leq 1.06\ pu$ [48], and loading of the substation transformer, $TR_1(d,t)$ with $TR_1(d,t) \leq 100\%$. The one-year simulations have revealed that the transmission line with the highest loading, thereby the critical one, was $TL_{38}(d,t)$. Further it was found, that the voltage at terminal 50, $V_{50}(d,t)$, presented the highest deviations from unity compared to the rest, and also violated the legitimate voltage limits.

The above two findings in terms of critical grid parameters are hardly surprising. This is because, $TL_{38}(d,t)$ is placed downstream of the substation transformer, as it can be observed in Fig. 4, therefore it serves a large portion of the grid and handles the associated loading. Regarding $V_{50}(d,t)$, which is the critical grid parameter in voltage terms, terminal 50 is the most remote terminal that exists in the LV network, with a distance of 461.08 m from the substation transformer. Distance has a detrimental effect on voltage; the longer the distance from the substation transformer the higher the impedance (i.e., $Z_l = R_l + jX_l$) of the transmission line, that in turn increases the voltage drop. According to Eq. (17) [49], the higher the resistance and the reactance of the line, R_l and X_l , that increases with the length of the line, the more voltage variation occurs between terminal 1 and 2, $\Delta V_{12}(d,t)$.

$$\Delta V_{12}(d,t) = \frac{P_{1,2}(d,t) \cdot R_l + Q_{1,2}(d,t) \cdot X_l}{V_1(d,t)} \quad (17)$$

Where in Eq. (17), $P_{1,2}(d,t)$ and $Q_{1,2}(d,t)$ are the active and reactive components of the power-flow between terminal 1 and 2. Further, $V_1(d,t)$, is the voltage of terminal 1.

The second factor that can cause higher voltage drop, is the increased number of terminals with loads, that are placed between the substation transformer (beginning of power-flow path) and terminal 50 (end of power-flow path). This is formulated by Eq. (18) [49, 50], where the more terminals (and more loads connected to each of them) are added to the power-flow path, the higher the total voltage drop, $\Sigma \Delta V(d,t)$, on the last terminal of the power-flow path. Where in Eq. (18), $\Delta V_{1,2}(d,t)$ is the first voltage drop within the power-flow path, and $\Delta V_{n-1,n}(d,t)$ is the last voltage drop within the power-flow path.

$$\Sigma \Delta V(d,t) \approx \Delta V_{1,2}(d,t) \pm \Delta V_{2,3}(d,t) \pm \Delta V_{n-1,n}(d,t) \quad (18)$$

The longer the transmission line, the higher the values of R_l and X_l , thereby the numerator of Eq. (17) increases, resulting in increased voltage variation (drop or rise). From Eq. (18), it is clear that the more terminals (and the corresponding loads) are included in the power-flow path, the higher the total voltage drop (i.e., $\Sigma \Delta V(d,t)$) that occurs on the last terminal. The above two observations confirm that the most remote terminal is often the one that suffers from the highest voltage variations (drop or rise). This is aligned with the simulation results, that indicate terminal 50 as the most critical terminal in voltage terms.

Having identified the critical grid parameters namely $TL_{38}(d,t)$ and $V_{50}(d,t)$, and by also taking into account the lowest cost solution yielded from the preliminary research work reported in [46] for the trial electricity grid of Fig. 4, the strategic placement of the ESSs is defined as follows.

- ESS(1) is placed at terminal 31
- ESS(2) operates from terminal 40
- ESS(3) serves from terminal 50

6 Results and discussion

6.1 Capital costs of distributed and community level ESSs

The total capital cost in the case of distributed ESSs, is provided in Table 1. This table shows that the total rated power and energy of all three ESSs situated at the critical terminals of the electricity grid, reached 83.10 kW and 363.40 kWh, respectively. The three distributed ESSs had a total capital cost of \$193,370.

Table 1. Capital cost in the case of distributed ESSs.

Pole	$ P_{MAX} $ (kW)	$ E_c $ (kWh)	$ E_{MAX} $ (kWh)	$ C_{ESS} $ (\$)
T(31)	36.60	149.65	187.06	94,619
T(40)	30.00	95.61	119.52	65,724
T(50)	16.50	45.45	56.82	33,028
Total	83.10	290.71	363.40	193,370

The prior research work associated with the same LV network [46], revealed that the lowest cost solution for placement and sizing of a community level ESS, was to place it at terminal 40. This solution exhibited 87.84 kW of rated power, 395.48 kWh of rated energy, and had a total cost of \$199,906.

By comparing the rated power and energy requirements, of the two energy storage arrangements examined in this work, it can be seen that the distributed ESSs case was more cost-effective than the single community level ESS. Specifically, the overall sizing requirements for the distributed ESSs, were reduced by 4.74 kW for rated power and by 32.08 kWh for rated energy. This saving led to a capital cost reduction identified at \$6,536. This improvement was due to the ESSs being distributed among the critical terminals of the electricity grid, therefore the power absorbed/injected by the ESSs, had an immediate effect on the critical grid parameters.

To compare the cost that yielded by placing the ESSs at terminals 31, 40, and 50, more placement solutions have been explored, and they are appended in Section 8.1. In general, the explored scenarios indicate that the closer the ESSs are placed to the critical terminals of the grid, the lower the ESSs cost is. This occurs because less power is required to be administered by the ESSs that are connected directly at the critical terminals, compared to the higher power absorbed/injected by the ESSs that are placed a long way from the critical terminals, while the control aim that is to maintain a secure grid operation at all times remains invariant for all placement scenarios.

6.2 Applications and grid support of distributed and community level ESSs

The results presented in this section correspond to the worst day of the entire one-year dataset, that is the 6th of December 2013. On that day, the highest solar irradiation was recorded [47], that led to the highest grid disturbance as a result of high PV generation. The highest grid disturbance was assessed using the critical grid parameters $TL_{38}(d,t)$, $V_{50}(d,t)$ and $TR_1(d,t)$. It should be noted that the total of the grid parameters were monitored throughout the simulations. The complete numerical solution of the control that is introduced in Chapter 3 is provided in the Appendix. Particularly, Section 8.3 fully formulates the VD characteristics that were used to generate the ESSs dispatch commands, during hours of excessive PV generation (i.e., in the morning). Regarding Section 8.4, it provides the total of the numbers that led to the ESSs dispatch commands during the peak load period (i.e., in the evening).

Low PV penetration levels are beneficial for the grid, without the requirement for additional grid support. Specifically in Fig. 5, for the baseline PV penetration level of 9.12%, it can be seen that the loading of $TL_{38}(d,t)$ was reduced during hours of PV generation (i.e., 6 am to 6 pm). The same observation is also extended to the loading of $TR_1(d,t)$; Fig. 7 illustrates that the loading levels of the substation transformer are diminished over the daylight period. The critical terminal voltage in the absence of PV power, maintained the values of 0.96 pu – 0.97 pu during the period 8 am to 2 pm (Fig. 6). In the same figure it can be seen that for the baseline PV penetration level of 9.12%, the voltage during the same period ranged from 0.97 pu to 0.986 pu, which is an improvement considering that the voltage moved closer to the unity.

Fig. 5 and Fig. 7 indicate that for 70% PV penetration in the absence of ESSs, the loading limits of the grid components have been severely violated, with the loading of the critical transmission line at 12 pm reaching 144%, and the loading of the substation transformer identified at 101.5%. Voltage rise phenomena are also observed in Fig. 6, where $V_{50}(d,t)$ equals to 1.079 pu at 12 pm, a value that considerably exceeds the statutory upper voltage limit of 1.06 pu.

In Fig. 5 to Fig. 7, it can be seen that when the community level ESS supports the grid operation, the total of the critical grid parameters are maintained either on the upper limit or well-below it. For example, the loading levels of $TL_{38}(d,t)$ were maintained at 100% between 9-10 am and 12-2 pm (Fig. 5). During the same period, $V_{50}(d,t)$ reached values ranging from 1.053 pu to 1.06 pu (Fig. 6). For example at 1 pm, $V_{50}(d,t)$ was 1.057 pu when the community level ESS was operational. The voltage value of 1.057 pu, represents a secure grid operation in voltage terms, however it is associated with overcompensation. Single event overcompensation (i.e., if it occurs only once), only increases the rated power of the ESS, but repetitive overcompensation also increases the rated energy of the ESS.

Fig. 5. Critical transmission line loading.

Distributed ESSs at the critical terminals also achieved sound grid operation at all times. However, distributed ESSs have the benefit of eliminating overcompensation. Specifically in Fig. 5, for the excessive PV generation period between 9 am and 2 pm, the loading of $TL_{38}(d,t)$ was maintained at 100%, which is similar to the case of the single community level ESS. In terms of critical terminal voltage, between 10 am and 1 pm (Fig. 6); where the upper limit of $V_{50}(d,t)$ was violated for the case of no grid support, the critical terminal voltage was regulated at 1.06 pu for the case of distributed ESSs. This signifies overcompensation elimination when distributed ESSs supported the grid operation. This is achieved, because of the power sharing between the distributed storage units, with the ESSs placed at terminals 31 and 40 to handle the largest amount of power that maintains the voltage in the vicinity of 1.06 pu, while the ESS placed at terminal 50 is dispatched, with less power, to regulate $V_{50}(d,t)$ exactly at 1.06 pu. Indicative of the above control strategy, are the values of $SRP_{\min,ESS_x}(d,t)$ (Fig. 2).

Fig. 6. Critical terminal voltage profile.

The ESS placed at terminal 31 (i.e., ESS_1) obtains low $SRP_{\min,ESS_1}(d,t)$ values, that lead to a steeper slope of the droop characteristic of ESS_1 and higher power dispatch commands. ESSs placed remotely from the substation transformer, such as the ESS placed at terminal 50 (i.e., ESS_3), received high $SRP_{\min,ESS_3}(d,t)$ values. The high $SRP_{\min,ESS_3}(d,t)$ values, produce droop characteristics of reduced slope that generate dispatch commands of low power. In Table 1, the rated power and energy of the ESS placed at terminal 31 (i.e., closer to the substation transformer) are 36.60 kW and 187.06 kWh, respectively. These rated values are higher than the sizing requirement of the ESS placed at terminal 50 (i.e., longer distance from the substation transformer) which is 16.50 kW for rated power and 56.82 kWh for rated energy. This indicates that ESS_1 handles more power than ESS_3 due to the steeper slopes of the droop characteristics that were used to generate the dispatch commands of ESS_1 .

Fig. 7. Substation transformer loading.

The RESs shifting operation of the ESSs that can be seen in Fig. 7 prevented $TR_1(d,t)$ from overloading. Particularly, the loading of $TR_1(d,t)$ prior to ESSs engagement was 101.5% at 12 pm, while when the ESSs shifted energy from morning to night, the loading of the substation transformer was kept at 77.3% at 12 pm, a value that is well-below the thermal limit of the device. The loading of the substation transformer during the peak load (i.e., at 8 pm) was 78.8% prior to ESSs deployment, as a result of load demand. RESs shifting application performed by the ESSs, enabled this peak loading on the substation transformer to be reduced to 63.3%. In other LV networks where transformer loadings are much closer to their capacity limits, ESSs deployment offers an alternative to transformer sizing upgrades.

Terminal voltages also benefit when ESSs discharge into the grid in the evening, and absorb energy in the morning. To illustrate this benefit, $V_{s0}(d,t)$ reached 0.93 pu at 8 pm for the case of no ESSs (Fig. 6). Conversely, when the ESSs injected power into the grid at peak load (i.e., at 8 pm), the critical terminal voltage improved to 0.942 pu, thereby positioning the critical terminal voltage and thus the total of the terminal voltages that exist in the LV network within the allowable voltage range.

6.3 $VSQI$ for distributed and community level ESSs

Table 2 has been generated by applying the novel $VSQI$ formulation introduced earlier in this paper. This table provides the $VSQI$ values and the associated quality and stability coordinates on the Cartesian plane for the examined scenarios. In general, the more power the ESSs injected into the grid, the higher the $VSQI$ value, signifying that the voltage stability and quality of the power system has improved. The $VSQI$ was 3.244 for the baseline scenario of having no ESS deployment and for the peak load demand at 8 pm. When the first of the three distributed ESSs was dispatched, the $VSQI$ value increased to 3.270.

Table 2. Cartesian coordinates used for the calculation of $VSQI$ at 8 pm.

Scenarios	Cartesian coordinates		
	Voltage quality	Voltage stability	$VSQI$
WO ESS	(1, 0.9283)	(4.203, 0.414362)	3.244
W DIST ESS1	(1, 0.930667)	(4.230, 0.41943)	3.270
W DIST ESS1, ESS2	(1, 0.935524)	(4.298, 0.419764)	3.338
W DIST ESS1, ESS2, ESS3	(1, 0.941757)	(4.365, 0.416538)	3.406
W CL ESS	(1, 0.944123)	(4.4218, 0.414574)	3.462

The introduction of the single ESS lessened the stress on the grid, thereby improving voltage stability and quality. Further, the point of instability situated at the vertex of the voltage stability curve shown in Fig. 8

changes when the ESS is deployed; it moves from a value of $4.203k$ to $4.230k$ when the ESS has been deployed (Table 2). This finding highlights that the addition of only one ESS in the grid (3 ESSs preferred as per design) provides some voltage stability benefits. From Table 2, the vertices of $4.203k$ (i.e., WO ESS), $4.230k$ (i.e., ESS1 operational), $4.298k$ (i.e., ESS1, ESS2 operational) and $4.365k$ (i.e., ESS1, ESS2, ESS3 operational) demonstrate the degree of voltage stability improvement resulting from the increased power injection from the ESSs into the grid. The voltage stability improvement can also be visualised in Fig. 8, because the more ESSs are dispatched, the vertex of the stability curve is positioned farther from the operating state at 8 pm.

Both the voltage quality and stability improvement is jointly captured by the $VSQI$ values (Table 2). The $VSQI$ has a value of 3.244 (i.e., WO ESS), 3.270 (i.e., ESS1 operational), 3.338 (i.e., ESS1, ESS2 operational), and 3.406 (i.e., ESS1, ESS2, ESS3 operational) for the explored scenarios.

Fig. 8. Voltage stability curves for distributed ESSs.

Benefits similar to the distributed ESSs scenario were experienced when the grid was supported by a community level ESS (Fig. 9). In terms of voltage quality, from the coordinates of Table 2 that form the peaks of the triangles shown in Fig. 8 and Fig. 9, the critical terminal voltage for the loading conditions at 8 pm (i.e., $1 k$) reached 0.941757 pu, when all three ESSs were operational. When grid support was performed by a single community level ESS, the critical terminal voltage was further elevated at 0.944123 pu. For all ESSs deployment scenarios, the critical terminal voltage was maintained within the allowable range (i.e., $V_{50}(d, t) > 0.94$ pu); the voltage support provided by the single community level ESS was slightly greater.

Fig. 9. Voltage stability curves for community level ESS.

Regarding the system voltage stability, the vertex of the voltage stability curve for the case of distributed ESSs was reached at $4.365 k$ when all three ESSs were operational. This vertex value increased to $4.4218 k$ for the community level ESS. This indicates that the larger concentrated ESS maintained slightly better stability than the three distributed ESSs. This occurred because the centralised community level ESS absorbed more

energy in the morning (associated with the voltage overcompensation throughout the morning hours that was discussed in Section 6.2), that was returned to the grid in the evening. This higher amount of energy that was discharged into the grid by the community level ESS, was available at the expense of greater sizing requirement and higher cost compared to the distributed ESSs case. Slightly increased $VSQI$ values compared to the lowest cost solution are also recorded in Section 8.2. Similarly to the community level ESS case, the higher $VSQI$ values that yielded for the ESSs placements presented in Section 8.2, occurred because of the greater sizing requirements by the ESSs that in turn increased their capital costs.

As it was pointed out by the discussions in the present section, individual examination of voltage stability and quality the more ESSs are engaged, may be more complex, than studying the variation of the $VSQI$, which is a single parameter and integrates both voltage dimensions.

6.4 Power and energy profiles for distributed and community level ESSs

The variation of power and energy for each of the examined ESSs cases that supported the grid operation on the 6th of December 2013, is presented in Fig. 10 and Fig. 11, respectively.

Fig. 10. Power profiles in the case of distributed and community level ESSs.

Fig. 10 illustrates that the storage unit closer to the substation transformer (i.e., ESS1 – black line) receives higher value dispatch commands because it handles a larger amount of power. In terms of ESS3 (terminal 50), because this terminal is positioned at the longest distance from the substation transformer and the power-flow in that region (i.e., towards the end of the feeder) is reduced, the dispatch commands generated for ESS3 are associated with lower power. These observations (Fig. 10) derive from the droop characteristics of higher slopes that were used to generate the dispatch commands of ESS1, compared to the lower slopes of the droop characteristics that were employed for ESS3 dispatch commands generation. The range of slopes the droop characteristics may obtain, as a function of the distance between the storage unit and the substation transformer, can be found in Fig. 2. The dispatch commands of ESS1 that maintained higher values, resulted in higher energy (Fig. 11) absorbed from / injected to the grid, by the storage unit placed at terminal 31.

Fig. 11. Energy profiles in the case of distributed and community level ESSs.

In this study, the overall larger community level ESS improved voltage stability slightly more than the distributed ESSs case during the peak period. Understandably, the larger single ESS has the capacity to absorb and inject greater amounts of power during critical periods, when compared to the three distributed ESSs, but has higher capital cost implications.

7 Conclusions

This research work has introduced a new *VSQI* that jointly captures the variation of voltage stability and quality. The advantage of using the *VSQI*, rather than independent assessments of voltage quality and stability, is that it provides an integrated assessment of the voltage performance characteristics of the electricity grid. A practical grid model that maintains a complex loop arrangement and it exists in south-east Queensland was employed for the simulations. Key scenarios (among others) that shed light on the effect of ESSs operation on the two voltage dimensions of the local power system, include grid operation under high stress (i.e., peak load period at 8 pm) prior to ESSs engagement, and after the ESSs were engaged. Regarding voltage quality, the critical terminal voltage from 0.928 pu prior to ESSs engagement, was elevated at 0.941 pu after the ESSs were engaged. In terms of voltage stability, the last point of convergence of the power-flow method in the absence of ESSs, was $4.203 k$, while when the ESSs injected power into the grid, the vertex of the voltage stability curve, was reached at $4.365 k$, signifying a system that is placed a longer distance from the point of instability. The variation of the above two voltage dimensions was captured collectively by the novel *VSQI*, that from the value of 3.244 prior to ESSs engagement, it was increased to 3.406, after the ESSs were operational and injected power into the grid.

The abovementioned voltage improvements, are complementary to the RESs shifting application performed by the ESSs, because the energy the storage units injected into the grid at night, was generated by the local RESs in the morning. This cyclic ESSs operation of charging in the morning and discharging in the evening, allowed for 70% PV penetration to be achieved that is only possible when storage units support the grid operation. Further, the loading of grid components is benefited by the ESSs presence, since the excessive PV generation in the morning that would overload transmission lines and the substation transformer in the case of non-operational ESSs, is absorbed and kept by the storage units, to be directed to the grid when it is needed the most (i.e., at night). When the ESSs discharge power into the grid at night, shave the peak load. For example, the loading of the substation transformer at 8 pm reached the value of 78.8% prior to ESSs engagement, while when the ESSs injected power into grid, the loading level was reduced to 63.3% at 8 pm.

In terms of capital cost of the two ESSs deployment options that were explored in this work, it was found that the cost in the case of a community level ESS is \$199,906. Conversely, in the case of ESSs distributed among the critical terminals of the grid, the total cost reaches the value of \$193,370. It is noteworthy, that both ESSs arrangements maintain a secure grid operation at all times in the presence of 70% PV penetration,

however, the solution of distributed ESSs is more economical by \$6,536 because it is more effective. The higher effectiveness in the case of distributed ESSs, originates from the fact that the storage units are placed directly at the critical terminals of the grid, hence the effect on the critical grid parameters is immediate.

8 Appendix

8.1 Cost oriented sensitivity analysis for ESSs placement

Terminals 31, 40, and 50 are of special interest for the LV network illustrated in Fig. 4, as it was analysed in Chapter 5 of the present work. Briefly, terminal 31 is associated with $TL_{38}(d,t)$ that experiences overloading in the ESSs absence, the voltage at terminal 50 (i.e., $V_{50}(d,t)$) exhibits the highest deviations from the unity compared to the voltages of the rest of the terminals that exist in the LV network. Further, it was indicated in [46], that placing a community level ESS at terminal 40, results in the lowest ESS cost, while the total of the grid parameters are maintained within the statutory limits. Further to Fig. 4, the abovementioned critical terminals are specifically marked in Fig. 12.

To demonstrate the declining costs as the ESSs are placed closer to the critical terminals marked in Fig. 12, Table 3 has been created. This table presents eleven placements, sorted from highest cost to lowest cost. These placements have been examined by considering terminals with high dV/dP sensitivities, or terminals that control multiple power-flow paths.

Table 3 ESSs trial placements and the associated costs.

Examined placements	Placement terminals			C _{ESS} (\$)
	ESS1	ESS2	ESS3	
P1	2	5	15	Overloading
P2	34	11	21	Overloading
P3	53	27	23	276,066
P4	44	34	11	275,107
P5	50	26	21	271,377
P6	43	26	5	260,866
P7	45	28	12	256,645
P8	47	29	15	243,025
P9	50	44	39	213,427
P10	47	43	36	213,016
P11	31	40	50	193,370

P1 and P2 visualised in Fig. 12, constitute infeasible solutions, because they are placed after transmission line 38 (i.e., terminal 31 in Fig. 12), hence the ESSs are unable to prevent the overloading of the transmission line.

P3, and P6 to 8, because they maintain two of the three ESSs prior to transmission line 38, they succeed in maintaining a secure grid operation at all times. However due to the placement of the third ESS on the east side of the grid, that is remotely placed from the critical grid parameters, more power is utilised by the ESSs to achieve the control aim that is achieved with less power by the ESSs that are placed proximate to the critical grid parameters. This higher power requirement for each hour of operation, increases both the rated power and the rated energy of the ESSs, that in turn appoint P3, and P6 to 8 feasible solutions, but of higher cost compared to other placements that are proximate to the critical terminals.

Fig. 12 Examined ESSs placements 1.

In terms of P4 and P5 that are shown in Fig. 13, they are placements of high $\frac{dV}{dP}$ sensitive terminals. In the case where terminal voltages were the parameters that were most severely violated, these placements would have been competitive.

The ESSs dispatch commands, when the ESSs follow P9 and P10, significantly affect the power of the power-flow path, that commences from the substation transformer, and through terminals 31 and 40, reaches terminal 50 where is the end of the power-flow path. As it can be observed in Fig. 12, this power-flow path contains the total of the critical terminals, therefore the power managed by the ESSs, causes a significant impact on the critical grid parameters. Therefore P9 and P10, achieve the same control aim (that is to maintain a secure grid operation at all times) compared to P3 to P8, only when the ESSs follow P9 and P10, the aim is achieved with less power and energy, therefore P9 and P10 constitute lower cost solutions compared to the feasible but more costly solutions of P3 to P8.

With the ESSs being connected directly at the critical terminals of the LV network in P11, the power managed by the ESSs affects the most the critical grid parameters, therefore the control aim is achieved with less power and energy compared to any other placement. The lowest rated power and energy requirements of the storage units in P11, appoint P11 the lowest cost solution compared to the rest.

Fig. 13 Examined ESSs placements 2.

8.2 $VSQI$ development as a function of ESSs placement

The tables with the $VSQI$ values that are presented hereafter, are sorted from the highest $VSQI$ value to the lowest $VSQI$ value. When the ESSs are placed at terminals with high dV/dP sensitivity, a greater voltage stability and quality benefit occurs compared to the case of ESSs, seated at terminals with low dV/dP sensitivity.

For example, the highest $VSQI$ that equals to 3.635 was observed when the ESSs were placed at terminals 50, 26, and 21, with the numbers of voltage quality and stability that compose the $VSQI$, to be provided in Table 4. An ESSs placement of lower contribution to voltage quality and stability compared to the one examined above, is when the storage units are seated at terminals 47, 43, and 36. Table 9 supplies all the numerical values that were used to calculate the $VSQI$ that was identified at 3.517 for this placement. By comparing the two above placements it is observed that both enhance the voltage quality and stability of the grid compared to the case of grid operation with no support, because the $VSQI$ in the case of no support was identified at 3.244, as it can be observed in Table 2 of Section 6.3. The value of 3.244 for $VSQI$ in the case of no grid support, is lower compared to the $VSQI$ values for both of the cases examined above, representing the improved voltage quality and stability when the ESSs are operational and support the grid operation.

Table 4 Cartesian coordinates used for the calculation of $VSQI$ at 8 pm, for the ESSs placed at terminals 50, 26, 21.

ESS1	ESS2	ESS3	
Terminal 50	Terminal 26	Terminal 21	
Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	<i>VSQI</i>
W DIST ESS1	(1, 0.953471)	(4.457, 0.425339)	3.497
W DIST ESS1, ESS2	(1, 0.959818)	(4.550, 0.427379)	3.589
W DIST ESS1, ESS2, ESS3	(1, 0.960897)	(4.596, 0.424659)	3.635

Table 5 Cartesian coordinates used for the calculation of $VSQI$ at 8 pm, for the ESSs placed at terminals 50, 44, 39.

ESS1	ESS2	ESS3
Terminal 50	Terminal 44	Terminal 39

Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	<i>VSQI</i>
W DIST ESS1	(1, 0.935994)	(4.283, 0.420734)	3.323
W DIST ESS1, ESS2	(1, 0.944062)	(4.395, 0.417768)	3.435
W DIST ESS1, ESS2, ESS3	(1, 0.950520)	(4.491, 0.419192)	3.531

Table 6 Cartesian coordinates used for the calculation of *VSQI* at 8 pm, for the ESSs placed at terminals 45, 28, 12.

ESS1	ESS2	ESS3	
Terminal 45	Terminal 28	Terminal 12	
Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	<i>VSQI</i>
W DIST ESS1	(1, 0.943236)	(4.401, 0.417869)	3.441
W DIST ESS1, ESS2	(1, 0.948486)	(4.475, 0.415442)	3.515
W DIST ESS1, ESS2, ESS3	(1, 0.949214)	(4.488, 0.416524)	3.529

Table 7 Cartesian coordinates used for the calculation of *VSQI* at 8 pm, for the ESSs placed at terminals 53, 27, 23.

ESS1	ESS2	ESS3	
Terminal 53	Terminal 27	Terminal 23	
Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	<i>VSQI</i>
W DIST ESS1	(1, 0.938995)	(4.339, 0.416181)	3.380
W DIST ESS1, ESS2	(1, 0.946730)	(4.448, 0.416633)	3.488
W DIST ESS1, ESS2, ESS3	(1, 0.948527)	(4.483, 0.417852)	3.523

Table 8 Cartesian coordinates used for the calculation of *VSQI* at 8 pm, for the ESSs placed at terminals 43, 26, 5.

ESS1 Terminal 43	ESS2 Terminal 26	ESS3 Terminal 5
Scenarios	Cartesian coordinates	<i>VSQI</i>

	Voltage quality	Voltage stability	
W DIST ESS1	(1, 0.941353)	(4.380, 0.417803)	3.420
W DIST ESS1, ESS2	(1, 0.947591)	(4.470, 0.415058)	3.510
W DIST ESS1, ESS2, ESS3	(1, 0.948115)	(4.479, 0.416813)	3.519

Table 9 Cartesian coordinates used for the calculation of $VSQI$ at 8 pm, for the ESSs placed at terminals 47, 43, 36.

ESS1 Terminal 47	ESS2 Terminal 43	ESS3 Terminal 36	
Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	$VSQI$
W DIST ESS1	(1, 0.934304)	(4.277, 0.416464)	3.318
W DIST ESS1, ESS2	(1, 0.941985)	(4.383, 0.418180)	3.423
W DIST ESS1, ESS2, ESS3	(1, 0.948642)	(4.477, 0.417492)	3.517

Table 10 Cartesian coordinates used for the calculation of $VSQI$ at 8 pm, for the ESSs placed at terminals 47, 29, 15.

ESS1 Terminal 47	ESS2 Terminal 29	ESS3 Terminal 15	
Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	$VSQI$
W DIST ESS1	(1, 0.940320)	(4.351, 0.420477)	3.391
W DIST ESS1, ESS2	(1, 0.946113)	(4.428, 0.418768)	3.468
W DIST ESS1, ESS2, ESS3	(1, 0.947132)	(4.449, 0.417806)	3.489

Table 11 Cartesian coordinates used for the calculation of $VSQI$ at 8 pm, for the ESSs placed at terminals 44, 34, 11.

ESS1 Terminal 44	ESS2 Terminal 34	ESS3 Terminal 11	
Cartesian coordinates			
Scenarios	Voltage quality	Voltage stability	$VSQI$

W DIST ESS1	(1, 0.938267)	(4.339, 0.415189)	3.379
W DIST ESS1, ESS2	(1, 0.940718)	(4.369, 0.413448)	3.410
W DIST ESS1, ESS2, ESS3	(1, 0.941950)	(4.394, 0.417282)	3.434

8.3 VD characteristics numerical solution

The numerical solution of the VD characteristics that were used to generate the ESSs dispatch commands, when the ESSs were placed at terminals 31, 40, and 50, is provided in Table 12.

Table 12 VD characteristics numerical solution for the lowest cost placement.

ESS1 Terminal 31	ESS2 Terminal 40	ESS3 Terminal 50
$d = 281$		
$SRP_{\max}(d) = 325.62 \text{ kW}$		
$ P_{ESS,SRP_{\max}}(d) = 39.32 \text{ kW}, r_{ESS} = 0 \text{ m}$		
$r_{ESS_1} = 30 \text{ m}$	$r_{ESS_2} = 156.53 \text{ m}$	$r_{ESS_3} = 461.08 \text{ m}$
$P_{ESS_1,SRP_{\max}}^{\diamond} = 1.00 \text{ kW}$	$P_{ESS_2,SRP_{\max}}^{\diamond} = 5.2177 \text{ kW}$	$P_{ESS_3,SRP_{\max}}^{\diamond} = 15.3693 \text{ kW}$
$ P_{ESS_1,SRP_{\max}}(d) = 38.32 \text{ kW}$	$ P_{ESS_2,SRP_{\max}}(d) = 34.1023 \text{ kW}$	$ P_{ESS_3,SRP_{\max}}(d) = 23.9507 \text{ kW}$
$t = 9 \text{ am}$		
$SRP(d, t) = 220.2029 \text{ kW}$		
$SRP_{\min,ESS_1}(d, t) = 196.7244 \text{ kW}$	$a_{ESS_1}(d, t) = -3.3637$	$ P_{ESS_1}(d, t) = 6.98 \text{ kW}$
$t = 10 \text{ am}$		
$SRP(d, t) = 279.4552 \text{ kW}$		
$SRP_{\min,ESS_1}(d, t) = 192.8087 \text{ kW}$	$a_{ESS_1}(d, t) = -3.4658$	$ P_{ESS_1}(d, t) = 25.00 \text{ kW}$
$SRP_{\min,ESS_2}(d, t) = 212.2964 \text{ kW}$	$a_{ESS_2}(d, t) = -3.3230$	$ P_{ESS_2}(d, t) = 20.21 \text{ kW}$
$SRP_{\min,ESS_3}(d, t) = 257.6221 \text{ kW}$	$a_{ESS_3}(d, t) = -2.8391$	$ P_{ESS_3}(d, t) = 7.69 \text{ kW}$

$t = 11 \text{ am}$

$$SRP(d, t) = 309.751 \text{ kW}$$

$$SRP_{\min, ESS_1}(d, t) = 187.4155 \text{ kW}$$

$$a_{ESS_1}(d, t) = -3.6066$$

$$|P_{ESS_1}(d, t)| = 33.92 \text{ kW}$$

$$SRP_{\min, ESS_2}(d, t) = 236.9281 \text{ kW}$$

$$a_{ESS_2}(d, t) = -2.6008$$

$$|P_{ESS_2}(d, t)| = 28.00 \text{ kW}$$

$$SRP_{\min, ESS_3}(d, t) = 274.6056 \text{ kW}$$

$$a_{ESS_3}(d, t) = -2.1300$$

$$|P_{ESS_3}(d, t)| = 16.50 \text{ kW}$$

$t = 12 \text{ pm}$

$$SRP(d, t) = 314.0789 \text{ kW}$$

$$SRP_{\min, ESS_1}(d, t) = 68.3872 \text{ kW}$$

$$a_{ESS_1}(d, t) = -6.7128$$

$$|P_{ESS_1}(d, t)| = 36.60 \text{ kW}$$

$$SRP_{\min, ESS_2}(d, t) = 229.6743 \text{ kW}$$

$$a_{ESS_2}(d, t) = -2.8135$$

$$|P_{ESS_2}(d, t)| = 30.00 \text{ kW}$$

$$SRP_{\min, ESS_3}(d, t) = 290.1380 \text{ kW}$$

$$a_{ESS_3}(d, t) = -1.4815$$

$$|P_{ESS_3}(d, t)| = 16.16 \text{ kW}$$

$t = 1 \text{ pm}$

$$SRP(d, t) = 290.8751 \text{ kW}$$

$$SRP_{\min, ESS_1}(d, t) = 94.8725 \text{ kW}$$

$$a_{ESS_1}(d, t) = -6.0216$$

$$|P_{ESS_1}(d, t)| = 32.55 \text{ kW}$$

$$SRP_{\min, ESS_2}(d, t) = 213.8594 \text{ kW}$$

$$a_{ESS_2}(d, t) = -3.2772$$

$$|P_{ESS_2}(d, t)| = 23.50 \text{ kW}$$

$$SRP_{\min, ESS_3}(d, t) = 273.4484 \text{ kW}$$

$$a_{ESS_3}(d, t) = -2.1783$$

$$|P_{ESS_3}(d, t)| = 8.00 \text{ kW}$$

$t = 2 \text{ pm}$

$$SRP(d, t) = 242.7487 \text{ kW}$$

$$SRP_{\min, ESS_1}(d, t) = 101.5111 \text{ kW}$$

$$a_{ESS_1}(d, t) = -5.8484$$

$$|P_{ESS_1}(d, t)| = 24.15 \text{ kW}$$

$n_c = 0.94$

$$|E_{C, ESS_1}^{VD}(d)| = 149.65 \text{ kWh}$$

$$|E_{C, ESS_2}^{VD}(d)| = 95.61 \text{ kWh}$$

$$|E_{C, ESS_3}^{VD}(d)| = 45.45 \text{ kWh}$$

8.4 Weighted energy distribution numerical solution

The numerical solution for the distribution of energy, when the storage units were placed at terminals 31, 40, and 50, is provided in Table 13.

Table 13 Weighted energy distribution numerical solution for the lowest cost placement.

ESS1 Terminal 31		ESS2 Terminal 40		ESS3 Terminal 50	
t	$L_D(d,t) (kW)$	$w(d,t)$	$P_{ESS_1}^{PCL}(d,t) (kW)$	$P_{ESS_2}^{PCL}(d,t) (kW)$	$P_{ESS_3}^{PCL}(d,t) (kW)$
6 pm	199.4	0.158530	23.724	15.157	7.205
7 pm	216.6	0.172204	25.770	16.464	7.826
8 pm	223.9	0.178008	26.638	17.019	8.090
9 pm	207.7	0.165128	24.711	15.787	7.505
10 pm	175.5	0.139528	20.880	13.340	6.341
11 pm	135.2	0.107488	16.085	10.276	4.885
12 am	99.51	0.079114	11.839	7.564	3.595
$\int_{6pm}^{12am} L_D(d,t) dt$ (kWh)	1257.81				
$n_d = 0.9362$					
t	$P_{ESS_1}(d,t) (kW)$	$P_{ESS_2}(d,t) (kW)$	$P_{ESS_3}(d,t) (kW)$		
6 pm	22.210	14.190	6.745		
7 pm	24.126	15.413	7.327		
8 pm	24.939	15.933	7.574		
9 pm	23.134	14.780	7.026		
10 pm	19.548	12.489	5.936		
11 pm	15.059	9.621	4.573		
12 am	11.084	7.081	3.366		

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