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Operational Adequacy Studies of a PV-based & Energy Storage Stand-alone Microgrid

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Abstract— This paper presents a probabilistic approach in the modelling of stand-alone microgrids to predict their operational adequacy performance considering uncertainty of energy storage system (ESS), photovoltaic system (PVS) and conventional generator (CG). Instead of using the daily or hourly time step, operating period a minutely time step is considered to incorporate the effect of fast ramp up/down of system components on microgrid operating adequacy through expected energy not supplied (EENS) and expected energy not used (EENU), due to load and resource variations. A time varying state of charge (SOC) model is proposed to determine power output of an ESS in reliability modelling. The reliability of a PVS is modelled in detail based on the total cross-tied configuration (TCTC) of photovoltaic (PV) cells and arrays. The proposed technique and indices will be useful for system planners to select the type and size of microgrid systems that contain alternative energy sources and storage.

Index Terms—EENS, EENU, Energy storage system, operation, planning, power system reliability, photovoltaic penetration, ramp rate, spinning reserve, state enumeration, stochastic, uncertainty.

NOMENCLATURE

Indices:

i operating period (subscript)
 j operating state (subscript)

Variables:

$A_c(t_i)$ availability of component at time t_i
 CG_{ij} CG at j^{th} state and i^{th} operating period
 E_{ci}/E_{di} available ESS energy for charging and required energy for discharging at i^{th} operating period
 ENS_{ij} energy not supplied at i^{th} operating period j^{th} state
 ENU_{ij} energy not used at i^{th} operating period j^{th} state

I_d Shockley temperature-dependent diode current
 I_{oi} PV cell current at i^{th} operating period
 I_p PV cell leakage current
 I_{ri} photon current at i^{th} operating period, which depends on the light intensity and its wavelength
 I_s reverse saturated current of the diode
 LD_i load demand
 ND_i net demand
 N_{cg} total number of CG states
 N_{es} total number of ESS states
 N_{pv} total number of PVS states
 N_{si} total number of system operating intervals
 N_X total number of X system component states
 P/P_d ESS charging / discharging rate, i.e. power rating of energy storage)
 P_{ij}^{cg} state probability of CGs
 P_{ij}^{es} state probability of ESS
 P_{ij}^{pvs} state probability of PVS
 P_{ij}^X state probability of X system component
 P_{oij}^{sc} output power of a PV cell
 P_{oij}^{es} output power cell of an energy storage cell
 P_{oij}^{ess} output power cell of an ESS
 P_{oij}^{pvs} output power of the PVS
 R_p parallel resistance across the PV cell
 R_s series resistance between the photon current source and the load across the PV cell terminals
 R_i^{elnv} reliability of energy storage inverter
 R_i^{ema} reliability of energy storage modularized array
 R_i^{els} reliability of energy storage inverter system
 R_i^{es} reliability of single cell energy storage
 R_i^{ess} reliability of ESS
 R_i^{ma} reliability of PV modularized array
 R_i^{pv} reliability of PV modularized array
 R_i^{pvs} reliability of PVS
 R_i^{slnv} reliability of PV inverter
 R_i^{scell} reliability of PV cell
 R_i^{sis} reliability of PV inverter system
 SOC_i ESS state of charge
 SOC_{max}/SOC_{min} ESS maximum/minimum state of charge
 t_i duration of i^{th} operating period
 $U_c(t_i)$ unavailability of component at time t_i
 V_{oci} open-circuit voltage at i^{th} operating period
 X_{ij} X system component
 λ_c failure rate for component
 λ_{es} failure rate for single cell energy storage
 λ_{scell} failure rate for PV cell

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η_c/η_d	ESS charging / discharging efficiency
η_g^{es}	ESS g^{th} inverter efficiency
η_g^{pv}	PVS g^{th} inverter efficiency

Constants:

k	the Boltzmann constant
q	the electron charge
V_d	diode voltage (volts)
η	empirical constant
T	the absolute temperature ($^{\circ}\text{C}$)

Abbreviations:

COPT	capacity outage probability table
EENS	expected energy not supplied
EENU	expected energy not used
ESS	energy storage system
FOR	forced outage rate
PL1/2/3	priority loading order 1, 2 or 3
PVS	photovoltaic system
SR	spinning reserve
TCTC	total cross-tied configuration

I. INTRODUCTION

This paper evaluates the reliability of a stand-alone microgrid system via operational adequacy and efficiency of energy usage, with fast ramp up/down rate of demand, and high PVS penetration. Expected Energy Not Supplied (EENS) has impact on system operational adequacy, whereas Expected Energy Not Used (EENU) reflects the energy generation/demand matching efficiency and energy surplus in the system. Adequacy in the coordination of intermittent sources and random demand, and intermittent sources with ESS, with different FOR & SR are evaluated. Section I gives an introduction on literature review, research gaps and motivation of this paper. Section II narrates the system modelling approach for each system component and Section III describes the formulation of each system component. Section IV dwells in the detail system studies and finally, Section V concludes this paper.

As the penetration of renewable energy in isolated microgrids continues to increase globally, the impact of random intermittency of renewable sources on operation reliability and efficiency is becoming evident. The reliability challenges faced by system operator during system operation are power shortages and surplus due to the rapid changes in the renewable power source and load. Ramping of power production and load is a notable characteristic in a typical power system time series associated with drastic change in values in a set of consecutive time steps. AWS Truewind, January 28, 2008 reported [1] that Electric Reliability Council of Texas (ERCOT) can expect less than a 2.8GW, 30-minute drop in wind output (93MW/minute) per year with 15GW wind fleet. Two to four 1.3GW, 30-minute increase or decrease of 43MW/minute can be expected. E. Ela and B. Kirby [1] reported a rapid and large ramp-down event occurred in the ERCOT operation area on February 26, 2008, which forced ERCOT to declare system emergency. B. Kirby [2] revealed that the rapid system load fluctuations typically measured at 2-second intervals by utility control centers cannot be tracked by generator. B. Kirby indicated that generator tracks load at roughly 1 to 2-minute interval level.

Hence, if ramps in microgrid operation and dispatch are not investigated, it could lead to serious problems such as high costs and additional risks incurred.

W. Y. Li and L. Goel [3] articulated that “adequacy evaluation of generation, transmission, distribution and microgrids with random intermittent sources has been investigated for decades. However, coordination in adequacy between intermittent sources and random loads; and between intermittent sources and storages shall be investigated too”. The ramp issues have been considered in unit commitment and generation economic dispatch of large power systems [4-9]. However, the reliability problems of power systems caused by the ramp rates of conventional generators have not been investigated in detail. On the contrary, the ramp rate issues are more critical in the operation of microgrids because the system has lower ramp rates compared with the large systems. The impacts of fast minute to minute ramp on operation adequacy have hardly been investigated.

Y.A. Katsigiannis [10] argued that the reliability evaluation of small isolated power system with renewable energy sources cannot be implemented using the traditional deterministic and analytical methods. E. S. Gavanidou [11] proposed a multi-objective planning under uncertainty in the design of a stand-alone system with renewable energy sources consisting wind, solar and storage battery. P. Arun [12] considered the uncertainty of solar insolation to optimally size photovoltaic battery systems through a design space approach. R. Karki [13] used Monte Carlo simulation technique for adequacy study on variability of wind, hydro energy storage with conventional generators (CGs). Anindita Roy [14] considered the uncertainty of wind speed only to size a wind-battery system. E.S. Sreeraj [15] considered a wind-PV-battery system for isolated renewable hybrid power systems. Bagen [16] used probabilistic evaluation based on the well-being concept for small stand-alone power systems with wind, solar, diesel and energy storage. C.V. Cabral [17] applied Markov Chain as stochastic analysis to study stand-alone photovoltaic system sizing. F.M. Safie [18] used Markov Chain theory to present probabilistic approach to model stand-alone PV-battery power system for a radio repeater. The hourly constant load and renewable source models have been used in most of these papers. The ramp rates of CGs have not been considered in these papers. It is one of the motivations in this paper to deploy probabilistic 2-state enumeration approach for all system components such as CG, PVS & ESS, with minute to minute ramp up/down demand in a microgrid environment.

J. V. Milanović et al. [19] established a working group to identify the current international industry practice on load modelling for static and dynamic power system studies, and indicated that regular update of load model parameters is essential to ensure accurate simulation results. Hence, the per minute load model used in this paper will be of great research value to come. The impact of the minute to minute ramp rates can be more accurately investigated using minutely load and resource model.

To fill the research gaps of operational adequacy of microgrids, which are more versatile for load and resource variation, this paper evaluates the reliability of a stand-alone microgrid considering fast ramps of demand and high PV penetration. Expected Energy Not Supplied (EENS) and

Expected Energy Not Used (EENU) have been formulated considering the effects of ramp rates of load, renewable resources and conventional generators to represent energy generation / demand matching efficiency and energy surplus in the system operation. Adequacy coordination among intermittent sources, random demand, generalized PVS reliability model and time varying SOC of energy storage systems (ESSs) are considered in the proposed technique.

II. SYSTEM MODELLING

A microgrid consists of conventional generators (CGs), ESSs and photovoltaic systems (PVSs). Reliability models of the subsystems are presented in this section. The reliability of subsystem like PVS is determined by many system contingency states and considering component failures using probabilistic techniques [20]. All possible states of a subsystem are determined using contingency enumeration technique based on the states of components. The two-state component reliability model is used in this paper to find the system states. The availability and unavailability of component c and period i can be calculated using the following equations (1) to (3) while ignoring the repair rate.

$$U_c(t_i) = 1 - e^{-\lambda_c t_i} \quad (1)$$

$$U_c(t_i) \approx \lambda_c t_i \quad (2)$$

$$A_c(t_i) = 1 - U_c(t_i) \quad (3)$$

The reliability of a sub-system with conventional generators (CGs) has been well developed. This section focuses on PVS and ESS reliability modelling.

A. Photovoltaic System Model

A basic equivalent circuit model of a PV cell consists of a real diode in parallel with an ideal current source and resistor, and a series resistor, as shown in Fig. 1. The PV cell converts the sun's rays or photons directly to electrical energy. A parallel resistance R_p represents the internal losses, or leakage current. R_s is the equivalent source series resistance connected between the photon current source and the load across the photovoltaic cell terminals. The current-voltage (I-V) characteristic of a PV cell is described by (4)~(7).

$$I_{o_i} = I_{r_i} - I_d - I_p \quad I_d = I_s \left(e^{\frac{qV_d}{\eta kT}} - 1 \right) \quad (4)$$

$$I_{o_i} = \frac{R_p}{R_p + R_s + R_L} \left[I_{r_i} - I_s \left(e^{\frac{qV_d}{\eta kT}} - 1 \right) \right] \quad (5)$$

$$V_{oc_i} = \frac{kT}{q} \ln \left(1 + \frac{I_{r_i}}{I_s} - \frac{V_{oc_i}}{I_s R_p} \right) \quad (6)$$

$$P_{o_i}^{sc} = \frac{V_{oc_i} R_p}{R_p + R_s + R_L} [I_{r_i} - I_s (e^{\frac{qV_{oc_i}}{\eta kT} \left(\frac{1+R_s/R_L}{\eta kT} \right)} - 1)] \quad (7)$$

$$R_i^{ma} = \prod_{g=1}^{a_2} \left\{ 1 - \prod_{f=1}^{b_2} \left(1 - \prod_{e=1}^{a_1} \left(1 - \prod_{d=1}^{b_1} [1 - R_{i_{def}}^{scell}] \right) \right) \right\} \quad (8)$$

$$R_i^{sis} = R_i^{ma} R_i^{slnv} \quad (9)$$

$$R_i^{pvs} = 1 - \prod_{d=1}^{b_3} [1 - R_i^{sis}] \quad (10)$$

$$P_{o_i}^{pvs} = \sum_{g=1}^{b_3} \eta_g^{pv} \sum_{f=1}^{b_2} \sum_{e=1}^{a_2} \sum_{d=1}^{b_1} \sum_{c=1}^{a_1} P_{o_i}^{sc} \quad (11)$$

Fig. 1 The equivalent circuit for a photovoltaic cell

The reliability and output of a PVS is modelled in detail based on the total cross-tied configuration (TCTC) of PV cells, and arrays as shown in Fig. 2. The TCTC can increase the operation life of an array by 30% with higher efficiency [21]. The reliability of a cell R_i^{scell} can be calculated based on its failure rate λ_{scell} using similar equation as (3). An array is constructed with $a1$ rows and $b1$ columns of PV cells. The PV cells are connected in TCTC within an array. A modularized array (MA) consists of $a2$ rows and $b2$ columns of arrays in TCTC. The reliability R_i^{ma} of a MA is as defined in (8). A MA and the corresponding inverter are connected in series as shown in Fig. 2. The total reliability of a MA and the corresponding inverter R_i^{sis} can be calculated based on R_i^{slnv} and R_i^{ma} using (9). A PVS consists of $b3$ modularized arrays and corresponding inverters connected in parallel. The reliability R_i^{pvs} of a PVS for period i can be calculated by (10). The output power of a PVS can be calculated using (11) by considering the inverter efficiency, η_g^{pv} , and the reliability of the PV cells.

It should be noted that the power output of a PV array depends on the control of the grid tied inverter. There are many maximum power point tracking (MPPT) techniques that have been used in practical grid-tied inverters to harness maximum power in PVSs. It is assumed in this paper that the inverters can always be controlled to obtain the maximum power from a PVS. The power output from (11) is the total maximum power from a PVS.

$$SOC_{min} \leq SOC_i \leq SOC_{max} \quad (12)$$

$$SOC_i = \begin{cases} SOC_{i-1} + \eta_c \cdot E_{ci} & \text{In charging states} \\ SOC_{i-1} - \frac{1}{\eta_d} \cdot E_{di} & \text{In discharging states} \end{cases} \quad (13)$$

$$(0 \leq E_{ci} \leq P_c \cdot t_i) \quad (14)$$

$$(0 \leq E_{di} \leq P_d \cdot t_i) \quad (15)$$

$$R_i^{ema} = \prod_{g=1}^{c_2} \left\{ 1 - \prod_{f=1}^{d_2} \left(1 - \prod_{e=1}^{c_1} \left(1 - \prod_{d=1}^{d_1} [1 - R_i^{es}] \right) \right) \right\} \quad (16)$$

$$R_i^{eis} = R_i^{ema} R_i^{elnv} \quad (17)$$

$$R_i^{ess} = 1 - \prod_{d=1}^{d_3} [1 - R_i^{eis}] \quad (18)$$

$$P_{o_{ij}}^{ess} = \sum_{g=1}^{d_3} \eta_g^{es} \sum_{l=1}^{c_2} \sum_{e=1}^{d_2} \sum_{c=1}^{c_1} P_{o_{ij}}^{es} \quad (19)$$

Fig. 2 A typical PVS in TCTC with b_3 Modularize Arrays

Fig. 3 Time varying SOC of an ESS

B. Energy Storage System Model

Four important parameters usually employed to characterize a battery energy storage unit [22–25] in operational reliability evaluation are: storage capacity, charging/discharging rate (P_c/P_d), charging/discharging efficiency (η_c/η_d) and charging/discharging capacity limit (SOC_{max}/SOC_{min}). Different from conventional generators, available generation capacity and output of an ESS changes with time based on system resource and load conditions. Therefore a time varying SOC model is proposed to represent the output of an ESS, as shown in Fig. 3. The real time state of charge at the end of each operating period and corresponding limitations are determined by (12) and (13). Capacity limitations are determined by (14) and (15) to protect ESS over charged and discharged, respectively. The reliability of an ESS is determined based on battery cell reliability taking into consideration the configuration of cells. The configuration of ESS is chosen to be the same as PVS in Fig. 2, where the operation life time can increase by 30% [21]. Each single cell energy storage (ES) has reliability and failure rate of R_i^{es} and λ_{es} , respectively. An ES array is constructed with c_1 rows and d_1 columns of energy storage (ES) cells. An ES modularized array with reliability R_i^{ema} , is formed via c_2 rows and d_2 columns of ES arrays. Finally, d_3 columns of ES inverters are connected to their respective ES modularized arrays to form an ESS with reliability R_i^{ess} . Hence, (16)–(19) can be applied. The efficiency of ESS charging / discharging (η_c/η_d) cycle is

assumed at 75%.

C. Load Model

The variable load may change its level from day to day, hour to hour, minute to minute and second to second. Fig. 4 shows the modified IEEE-RTS [26] hourly load curve over a simulation period. In this paper, per minute variable load model is adopted. It is assumed that load level within each minute is ramping upward (or downward) in this load model. The IEEE-RTS hourly variable load information has been modified with per minute resolution at 1.85MW peak demand. The per minute variable load model can reflect the chronological characteristics of the system load and can be used in operational reliability evaluation.

Fig. 4 The minutely load curve with ramp up (or down)

III. FORMULATION

Considering the rapid changes in demand and resource, CGs and energy storage systems (ESSs) have to ramp up (or ramp down) to meet energy deficiency (or energy surplus). Two indices are formulated to determine the operation reliability and energy utilization efficiency of isolated microgrids under different resource and load conditions. Expected energy not supplied (EENS) can be due to the slow ramp up rate of CG, and/or slow rate of PVS solar irradiance change. Similarly, Expected energy not used (EENU) is the impact of slow ramp down rate of CG, and/or fast rate of PVS solar irradiance change. EENS and EENU also depends on priority loading order of CGs. ENS_{ij} and ENU_{ij} for operating period i under different load and resource conditions for different types of microgrids are formulated in the following three cases. It is imperative to note that in each i^{th} operating period, there are various probability states for ESS, PVS and CG. Each system component probability state is considered using their respective capacity outage probability table (COPT), in the computation of ENS_{ij} and ENU_{ij} .

A. Case 1 Microgrid with CGs

In this case, a microgrid comprises CGs only to meet load demand. CGs include Diesel Generator, Micro-turbine and Fuel Cell (FC).

Fig. 5 shows the formulation of ENU_{ij} for state j operating period i with duration t_i when load decreases from ND_{i-1} to ND_i . Type 1(a) and Type 1(b) shows two scenarios where the committed CGs have slow and fast ramp down rates, respectively. The ENU_{ij} can be computed by (20) and (21) for ramp down rate Type 1.

$$ENU_{ij} = \frac{1}{2} t_i \{ (CG_{i-1} + CG'_i) - (ND_{i-1} + ND_i) \} \quad (20)$$

$$ENU_{ij} = \frac{1}{2} t_1 \{ CG_{i-1} - ND_{i-1} \} \quad (21)$$

$$ENS_{ij} = \frac{1}{2} t_1 \{ ND_{i-1} - CG_{i-1} \} \quad (22)$$

$$ENU_{ij} = \frac{1}{2} t_2 \{ CG_i - ND_i \} \quad (23)$$

$$ENS_{ij} = \frac{1}{2} t_i \{ (ND_{i-1} + ND_i) - (CG_{i-1} + CG'_i) \} \quad (24)$$

$$ENS_{ij} = \frac{1}{2} t_1 \{ ND_{i-1} - CG_{i-1} \} \quad (25)$$

$$ENU_{ij} = \frac{1}{2} t_1 \{ CG_{i-1} - ND_{i-1} \} \quad (26)$$

$$ENS_{ij} = \frac{1}{2} t_2 \{ ND_i - CG_i \} \quad (27)$$

Fig. 6 shows a Type 2 scenario where ND is ramping down and CG ramping up, where ENS_{ij} and ENU_{ij} can be computed by (22) and (23), respectively. Fig. 7 shows that both the ND and CG are ramping up, where ENS_{ij} can be computed by (24) and (25) for Type 3(a) and Type 3(b), respectively. Fig. 8 shows a Type 4 scenario where ND_{i-1} is ramping up and CG_{i-1} ramping down. Once CG'_i meets ND'_i at the end of t_1 , depending on the ramp rate of the committed CG, the CG_i could be ramp limited and yields non-zero ENS_{ij} at end of interval t_2 . Hence, ENU_{ij} and ENS_{ij} can be computed using (26) and (27), respectively. To cater for all contingency states of CGs from 1 to N_{cg} , considering all operating periods from 1 to N_{si} , the system EENS and EENU can be calculated using (28) and (29). The contingency enumeration technique [20] has been used to determine all possible system states and the related probabilities.

It should be noted that the major difference between conventional reliability techniques and the proposed technique for EENS and EENU formulation is with and without considering the ramp rates of CGs for load and resource change. The conventional techniques usually use constant load for long period (such as an hour) without considering the ramp rates of conventional generators when the load and resource changes. Therefore the results from the conventional techniques will be smaller than those obtained from the proposed technique. As shown in Figs. 5~8, there will be no ENS_{ij} and ENU_{ij} if the CGs can follow the load change immediately.

$$EENS = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENS_{ij} (CG_{ij}, LD_i) \quad (28)$$

$$EENU = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENU_{ij} (CG_{ij}, LD_i) \quad (29)$$

Fig. 5 Type 1 ENU_{ij} formulation for both ND and CG ramp down

Fig. 6 Type 2 ENS_{ij} & ENU_{ij} formulation for ND ramp down and CG ramp up

Fig. 7 Type 3 ENS_{ij} formulation for both ND and CG ramp up

Fig. 8 Type 4 ENS_{ij} & ENU_{ij} formulation for ND ramp up and CG ramp down

B. Case 2 Microgrid with CGs & PVSs

Case 2 microgrid consists of CGs and PVSs to meet demand. PVS is treated as a negative demand as illustrated in (30). The analytic concept is the same as in Case 1, where Fig. 5 to Fig. 8 can be applied. However, the Case 2 net demand (ND_i) will have influence from intermittency of P_{oij}^{pvs} , as shown in (30). It is worthy to note from (30) that for $(LD_i - P_{oij}^{pvs}) < 0$, PVS excess energy has no storage in this case. Similarly, each contingency state j of CG and PVS is described via (31) and (32) to compute EENS and EENU,

respectively.

$$ND_i = LD_i - P_{o_{ij}}^{pvs} \quad (30)$$

$$EENS = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_{pv}} P_{ij}^{pvs} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENS_{ij} \left(P_{o_{ij}}^{pvs}, CG_{ij}, LD_i \right) \quad (31)$$

$$EENU = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_{pv}} P_{ij}^{pvs} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENU_{ij} \left(P_{o_{ij}}^{pvs}, CG_{ij}, LD_i \right) \quad (32)$$

C. Case 3 Microgrid CGs, PVSs & ESSs

Case 3 microgrid comprises CGs, PVSs and ESSs. Again, PVS is treated as a negative demand as illustrated in (30). Similarly, when $(LD_i - P_{o_{ij}}^{pvs}) < 0$, PVS excess energy will reduce ENS_{ij} and the additional energy will be stored in the ESS within charging limit. Each contingency state of CG, PVS and ESS are catered in the analysis to compute EENS and EENU as shown in (33) and (34), respectively. Each ESS contingency state j from 1 to N_{ess} is catered for in the analysis as shown in (33) and (34) for each operating period i in additional to PVS and CG contingency states.

$$EENS = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_{es}} P_{ij}^{es} \sum_{j=1}^{N_{pv}} P_{ij}^{pvs} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENS_{ij} \left(P_{o_{ij}}^{es}, P_{o_{ij}}^{pvs}, CG_{ij}, LD_i \right) \quad (33)$$

$$EENU = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_{es}} P_{ij}^{es} \sum_{j=1}^{N_{pv}} P_{ij}^{pvs} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENU_{ij} \left(P_{o_{ij}}^{es}, P_{o_{ij}}^{pvs}, CG_{ij}, LD_i \right) \quad (34)$$

There are many literature published on strategies of ESS interacting with the system. The strategy applied in this study is primarily to transfer the CG & PVS excess (or inadequate) energy, into ESS through charging (or discharging) when there is surplus (or deficiency) of energy to meet net demand (ND), as illustrated in Fig. 3.

D. Case 4 Generalized Equations

In lieu of the technique used in the EENS and EENU analysis above, (35) and (36) provide a generalized method which allows system planners to study stand-alone microgrid operational adequacy for any additional system elements to be added with uncertainty considerations.

$$EENS = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_x} P_{ij}^x \dots \sum_{j=1}^{N_{es}} P_{ij}^{es} \sum_{j=1}^{N_{pv}} P_{ij}^{pvs} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENS_{ij} \left(X_{ij}, P_{o_{ij}}^{es}, P_{o_{ij}}^{pvs}, CG_{ij}, LD_i \right) \quad (35)$$

$$EENU = \sum_{i=1}^{N_{si}} \sum_{j=1}^{N_x} P_{ij}^x \dots \sum_{j=1}^{N_{es}} P_{ij}^{es} \sum_{j=1}^{N_{pv}} P_{ij}^{pvs} \sum_{j=1}^{N_{cg}} P_{ij}^{cg} ENU_{ij} \left(X_{ij}, P_{o_{ij}}^{es}, P_{o_{ij}}^{pvs}, CG_{ij}, LD_i \right) \quad (36)$$

IV. SYSTEM STUDIES

A. Test System and Parameters

The system study is based on a stand-alone microgrid with 2.4MW CG capacity and a modified IEEE-RTS demand profile per minute variable load model with 1.85MW peak load. The CGs comprises diesel generators, micro-turbines and Fuel Cell (FC) with priority loading order as shown in Table 1. Per minute time series information from Nanyang

Technological University roof top solar irradiance measurement in year 2010 is used in the modelling of the PVS.

B. Microgrid with only CGs

In this case, the microgrid consists of only CGs. Fig. 9 shows the system EENS and EENU for different SRs under different unit commitment orders using different FOR of CGs. Fig. 9 shows the impacts of different priority orders of the unit commitment and SRs on EENS and EENU. It can be seen that priority loading order 1 (PL1) has the lowest EENS and EENU for the same SR. Using Table 1 with priority loading order 2 (PL2), changing base ramp rate to 10% of its original value (i.e. 0.1 times Base Rate) will have 57% and 244% increase in both EENS and EENU, respectively, as shown in Table 2. With reference to Table 1, there are 3 types of CG priority loading orders defined which are stipulated using various sorting criteria. It is interesting to note that PL2 criteria will experience reduced EENS and EENU with increased CG spinning reserve (SR) as shown in Fig. 9. PL1 and PL3 have insignificant increased EENS with increased SR, but EENU does not show significant reduction with varying SR. However, it is important to note that among the 3 priority loading orders, PL1 has the lowest EENS and EENU for SR variation from 0% to 25%.

TABLE 1

CG & Priority Loading Order

kW	Qty	FOR ^{#1}	kW per min ^{#2}	Type	PL1	PL2	PL3
400	1	0.060	80	Diesel	1	3	1
200	2	0.045	40	Diesel	2-3	4-5	2-3
200	2	0.045	40	Micro-turbine	4-5	6-7	4-5
50	2	0.030	10	Micro-turbine	6-7	10-11	10-11
400	2	0.090	20	FC	8-9	1-2	6-7
200	1	0.075	10	FC	10	8	8
100	1	0.060	10	FC	11	9	9

^{#1}Base FOR ^{#2}Base Ramp Rate (kW/min) for CG

Fig. 9 Impact of Spinning Reserve on EENS & EENU with PL1, PL2 and PL3

In Fig. 10, the CG Base FOR and 3 times Base FOR are considered in the study. It is evident that with PL2 sorting the size of CG, quantity and FOR order has positive impact on reduction of EENS and EENU with increase in SR. EENS with 3 times Base FOR is up to 128% more than Base FOR as shown in Fig. 10. Hence, EENS is more pessimistic with increasing FOR. Conversely, EENU with 3 times Base FOR is

up to 19% less than one with Base FOR. Therefore, increasing Base FOR gives EENU a more optimistic consideration.

Fig. 10 Impact of Spinning Reserve on EENS & EENU with Base FOR & 3 times Base FOR

TABLE 2
Impact of CG Ramp Rate on EENS & EENU

MW-Min / Month	Base Ramp Rate	0.1 times Base Ramp Rate
EENS	1,717	2,696
EENU	695	2,388

C. Microgrid with CGs & PVSs

This section attempts to address the reliability issue of microgrid with intermittent source and rapid random load for different SRs and FORs. Five PVS are added to the test system installations with 0.01 FOR each. Fig. 11 shows the system EENS and EENU under different system reliability conditions. It can be seen that for the same SR, EENS increases to 106% and EENU reduces to 16% when CGs FOR increases 3 times from the Base FOR.

Comparing Fig. 11 with Fig. 10, the EENS and EENU increase up to 10% and 73% more, respectively. The addition of rapid intermittent resource through PVS introduction will generally increase EENS and EENU, which indicates the need of energy storage.

Fig. 12 shows that EENS with 3 times Base FOR is increased up to 113% more than that with Base FOR. EENS results in more pessimistic outcome with increased FOR. Conversely, EENU with 3 times Base FOR is decreased up to 18% less than Base FOR which results in more optimistic outcome.

D. Microgrid with CGs, PVSs & ESSs

This section investigates the impacts of intermittent source with ESS; and intermittent source with rapid random load. A system level ESSs is made up of four energy storage devices with 0.02 FOR each. Fig. 13 shows EENS with 3 times Base FOR is increased up to 203% more than the EENS with Base FOR. It results in more pessimistic outcome with increased FOR. Conversely, EENU with 3 times Base FOR is decreased up to 14% less than EENU with the Base FOR, which results in more optimistic outcome.

Comparing Fig. 13 with Fig. 10, the EENS & EENU are reduced by up to 76% and 65%, respectively. This is due to positive impact of ESS. Whereas comparing Fig. 13 and Fig. 11, the EENS and EENU are reduced up to 78% and 78%, respectively. Hence, it can be observed that the addition of PVSs and ESSs into CGs results in lower EENS & EENU in general where the major contribution is from the ESS.

Fig. 11 Impact of Spinning Reserve (@ PVS=50%) on EENS & EENU with Base FOR and 3 times Base FOR

Fig. 12 Impact of PVS Capacity & CG (@ SR=15%) on EENS & EENU with Base FOR and 3 times Base FOR

Fig. 13 Impact of Spinning Reserve (@ PVS=50% & ESS=50%) on EENS & EENU with Base FOR and 3 times Base FOR

Fig. 14 Impact of ESS (with PVS 50% Capacity & CG 15% SR) on EENS & EENU with Base FOR and 3 times Base FOR

Fig. 14 shows that the EENS with 3 times Base FOR is increased up to 177% more than the EENS with Base FOR. Increased FOR shows a more pessimistic EENS results. Conversely, the EENU with 3 times Base FOR is reduced down to 16% lower than the EENU with Base FOR showing more optimistic results. It is worth noticing that EENU does not improve further once ESS capacity exceeds 50%. Comparing both Fig. 10 and Fig. 11 with Fig. 13 it is evidently shown that once ESS is implemented, both EENS and EENU reduced significantly with Base FOR and 3 times Base FOR. This explains the significance of energy storage system. It can be seen from Fig. 14 that EENU becomes almost constant

when ESS capacity increases to 50%. The further increase of ESS capacity cannot reduce EENU. However, the EENS can still reduce when EES capacity is over 50%. The final size of ESS can be simply determined by the required EENS or/and EENU levels. However, the size of an ESS should be determined using optimization technique based on balance between the benefits of reliability improvement and reduction of energy spilled taking into consideration the cost of ESS.

V. CONCLUSION

A probabilistic approach to model stand-alone microgrids and predict their operational adequacy performance considering uncertainty of energy storage system (ESS), photovoltaic system (PVS) and conventional generator (CG) has been proposed in this paper. Minutely load and resource models have been considered to incorporate the effect of fast ramp up/down of system components on microgrid operating adequacy through expected energy not supplied (EENS) and expected energy not used (EENU) due to load and resource variation. Time varying state of charge (SOC) model and TCTC-based PVS model are proposed. The proposed technique, models and indices have been applied to the modified IEEE-RTS. The results clearly show the impact of ramp rates of CGs on system reliability and energy utilization efficiency. Sensitivity studies of EENS and EENU for different FOR, SR, PVS capacity & ESS capacity clearly indicate the positive impact of ESS in improving microgrid operational reliability and energy utilization efficiency with intermittent source and rapid random demand. The generalized equations allow system planners to analyze the uncertainty, operational adequacy and energy utilization efficiency of microgrids with other different resource components.

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