<table>
<thead>
<tr>
<th>Title</th>
<th>Operational adequacy studies of a PV-based &amp; energy storage stand-alone microgrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Koh, Leong Hai; Wang, Peng; Choo, Fook Hoong; Tseng, King-Jet; Gao, Zhiyong; Püttgen, Hans B.</td>
</tr>
<tr>
<td>Date</td>
<td>2015</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10220/25846">http://hdl.handle.net/10220/25846</a></td>
</tr>
<tr>
<td>Rights</td>
<td>© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: [<a href="http://dx.doi.org/10.1109/TPWRS.2014.2334603">http://dx.doi.org/10.1109/TPWRS.2014.2334603</a>].</td>
</tr>
</tbody>
</table>
Operational Adequacy Studies of a PV-based & Energy Storage Stand-alone Microgrid

L. H. Koh1,2,∗, Wang Peng1, F. H. Choo1, K. J. Tseng1,2, Z. Y. Gao3, Hans B. Püttgen1
1Energy Research Institute @ NTU and 2School of Electrical & Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore; 3Power Grid Centre, A*STAR, 3 Pesek Road, Jurong Island, 627590 Singapore

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:

- Aij(tj): availability of component at time tj
- CGij: CG at jth state and ith operating period
- Ei/Ej: available ESS energy for charging and required energy for discharging at jth operating period
- ENSij: energy not supplied at jth operating period ith state
- ENUij: energy not used at jth operating period ith state
- NCG: total number of CG states
- NES: total number of ESS states
- NPV: total number of PVS states
- NX: total number of X system component states
- P/Pd: ESS charging / discharging rate, i.e. power rating of energy storage
- pCGij: state probability of CGs
- pesij: state probability of ESS
- ppvij: state probability of PVS
- PX: state probability of X system component
- Pij: output power of a PV cell
- pres: output power of an energy storage cell
- pest: output power of an ESS
- pds: output power of the PVS
- R: parallel resistance across the PV cell
- Rs: series resistance between the photon current source and the load across the PV cell terminals
- Rinv: reliability of energy storage inverter
- rema: reliability of energy storage modularized array
- Ress: reliability of single cell energy storage
- Res: reliability of ESS
- Rma: reliability of PV modularized array
- Rpv: reliability of PV modularized array
- Rpv: reliability of PVS
- Rinv: reliability of PV inverter
- Rscl: reliability of PV cell
- Rs: reliability of PV inverter system
- SOCi: ESS state of charge
- SOCmax/SOCmin: ESS maximum/minimum state of charge
- tij: duration of ith operating period
- Un(tij): unavailability of component at time tij
- Voc: open-circuit voltage at ith operating period
- X: system component
- λc: failure rate for component
- λs: failure rate for single cell energy storage
- λcell: failure rate for PV cell

L. H. Koh is with Energy Research Institute @ NTU and School of Electrical & Electronic Engineering, Nanyang Technology University, 50 Nanyang Avenue, 639798 Singapore (e-mail:LHKOHI1@e.ntu.edu.sg).

P. Wang is with School of Electrical & Electronic Engineering, Nanyang Technology University, 50 Nanyang Avenue, 639798 Singapore (e-mail: epwang@ntu.edu.sg).

F. H. Choo is with Energy Research Institute @ NTU, Nanyang Technology University, 50 Nanyang Avenue, 639798 Singapore (e-mail:cfchchoo@ntu.edu.sg).

K. J. Tseng is with School of Electrical & Electronic Engineering, Nanyang Technology University, 50 Nanyang Avenue, 639798 Singapore (e-mail: k.j.tseng@pmail.ntu.edu.sg).

Z. Y. Gao is with Experimental Power Grid Centre, A*STAR, 3 Pesek Road, Jurong Island, 627590 Singapore (e-mail: GAOZ0004@e.ntu.edu.sg).

Hans B. (Teddy) Püttgen is with Energy Research Institute @ NTU, Nanyang Technology University, 1 CleanTech Loop, 637141 Singapore (e-mail: teddy.puttgen@ntu.edu.sg).

∗Corresponding author. Tel.: +65-8181-8769; fax: +65-6316-3195
E-mail address: LHKOH1@e.ntu.edu.sg
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. Katsigiani [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. Sreraj [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 a 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.

\[
U_c(t_i) = 1 - e^{-\frac{t_i}{\eta_q}} \quad (1)
\]

\[
U_c(t_i) = \lambda_c t_i \quad (2)
\]

\[
A_c(t_i) = 1 - U_c(t_i) \quad (3)
\]

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 \( R_s \) represents the internal losses, or leakage current. \( R_i \) 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).

\[
I_{I} = I_{p} - I_{L} = I_{p} - I_{0}
\]

\[
I_o = \frac{R_s}{R_s + R_i + R_L} \left[ I_o e^{\frac{qV_o}{kT R_s}} - 1 \right]
\]

\[
V_{oc} = \frac{kT \ln \left( \frac{1 + I_o}{I_o} \right)}{\eta_q}
\]

\[
P_{in} = \frac{V_{oc} R_i}{R_s + R_i + R_L} \left( I_o e^{\frac{qV_o}{kT R_s}} - 1 \right)
\]

\[
R_{in} = \prod_{g=1}^{a_1} \left( 1 - \prod_{c=1}^{b_1} \frac{1}{1 - \prod_{i=1}^{d_1} \left( 1 - R_{in}^{c} \right)} \right)
\]

\[
R_{in} = R_{in}^{PV} R_{in}^{corr}
\]

The output power of a PVS can be calculated using (11) by considering the inverter efficiency, \( \eta_{P} \), 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.

\[
S_{OC_{in}} \leq S_{OC_{out}} \leq S_{OC_{max}}
\]

\[
S_{OC_{in}} = \frac{1}{\eta_q} E_{in}\; \text{In charging states}
\]

\[
S_{OC_{out}} = \frac{1}{\eta_q} E_{out}\; \text{In discharging states}
\]

\[
0 \leq E_{in} \leq P_{in}\; \text{(14)}
\]

\[
0 \leq E_{out} \leq P_{out}\; \text{(15)}
\]

\[
R_{in} = \prod_{g=1}^{a_1} \left( 1 - \prod_{c=1}^{b_1} \frac{1}{1 - \prod_{i=1}^{d_1} \left( 1 - R_{in}^{c} \right)} \right)
\]

\[
R_{in} = R_{in}^{PV} R_{in}^{corr}
\]

\[
R_{in} = 1 - \prod_{g=1}^{a_1} \left( 1 - R_{in}^{g} \right)
\]
Inverter

DC

P

\begin{equation}
\eta P = \sum_{j} \eta_{ij}^{a} \sum_{i} \sum_{d} \sum_{b} P_{ij}^{ab}
\end{equation}

Modularize Arrays

\[ [a2x b2] Array \]

\[ \text{Array with } [a2x b2] \text{ Array} \]

1

Fig. 2 A typical PVS in TCTC with b3 Modularize Arrays

\[ \text{SOC} \]

\[ \text{SOC}_{\text{max}} \]

\[ \text{SOC}_{\text{min}} \]

\[ t_r \]

\[ i-2 \]

\[ i-1 \]

\[ i \]

\[ i+1 \]

\[ i+2 \]

\[ \text{Time (minute)} \]

\[ \text{Demand (or CG)} \]

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 \((\eta_c/\eta_d)\) and charging/discharging capacity limit \((SOC_{\text{max}}/SOC_{\text{min}})\). 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 \(R_{ij}^{cs} \) and \( \lambda_{cs} \), respectively. An ES array is constructed with \( c1 \) rows and \( d1 \) columns of energy storage (ES) cells. An ES modularized array with reliability \( R_{ij}^{max} \) is formed via \( c2 \) rows and \( d2 \) columns of ES arrays. Finally, \( d3 \) columns of ES inverters are connected to their respective ES modularized arrays to form an ESS with reliability \( R_{ij}^{ESS} \). Hence, (16)-(19) can be applied. The efficiency of ESS charging / discharging \((\eta_c/\eta_d)\) 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.

\[ \text{Fig. 4 The minutely load curve with ramp up (or down)} \]

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 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 \( ND_{ij} \) 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.
\[ ENU_{ij} = \frac{1}{2} \left\{ (CG_{ij} + CG_i') - (ND_{ij} + ND_j) \right\} \]  
(20)
\[ ENU_{ij} = \frac{1}{2} t_1 \left\{ CG_{ij} - ND_{ij} \right\} \]  
(21)
\[ ENS_{ij} = \frac{1}{2} t_1 \left\{ ND_{ij} - CG_{ij} \right\} \]  
(22)
\[ ENU_{ij} = \frac{1}{2} t_2 \left\{ CG_i - ND_i \right\} \]  
(23)
\[ ENS_{ij} = \frac{1}{2} t_2 \left\{ ND_i - CG_i \right\} \]  
(24)
\[ ENU_{ij} = \frac{1}{2} t_1 \left\{ (ND_{ij} + ND_i) - (CG_{ij} + CG_i') \right\} \]  
(25)
\[ ENS_{ij} = \frac{1}{2} t_1 \left\{ (ND_{ij} - ND_i) - (CG_{ij} - CG_i') \right\} \]  
(26)
\[ ENU_{ij} = \frac{1}{2} t_2 \left\{ (ND_j - ND_i) - (CG_i - CG_i') \right\} \]  
(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 \( ND_{ij} \) is ramping up and \( CG_{ij} \) 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 \( N_C \), considering all operating periods from 1 to \( N_p \), 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.

\[ EENS = \sum_{i=1}^{N_C} \sum_{j=1}^{N_D} \sum_{p=0}^{P_0} ENS_{pq} \left( CG_{ij}, LD_j \right) \]  
(28)
\[ EENU = \sum_{i=1}^{N_C} \sum_{j=1}^{N_D} \sum_{p=0}^{P_0} ENU_{pq} \left( CG_{ij}, LD_j \right) \]  
(29)

**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 \( (ND_j) \) will have influence from intermittency of \( P_{PVS} \) as shown in (30). It is worthy to note from (30) that for \( (LD_j - P_{PVS}) < 0 \), 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.

\[
ND = LD - P_{\text{ess}}
\]

(30)

\[
EENS = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} \sum_{k=1}^{n_p} \sum_{l=1}^{n_d} ENS \left( P_{\text{ess}}, P_{\text{CG}}, LD \right)
\]

(31)

\[
EENU = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} \sum_{k=1}^{n_p} \sum_{l=1}^{n_d} ENU \left( P_{\text{ess}}, P_{\text{CG}}, LD \right)
\]

(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 \( (LD_i - P_{\text{ess}}^0) \) < 0, PVS excess energy will reduce ENS 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 \( N_{\text{ess}} \) 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.

\[
EENS = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} \sum_{k=1}^{n_p} \sum_{l=1}^{n_d} ENS \left( P_{\text{ess}}, P_{\text{CG}}, LD \right)
\]

(33)

\[
EENU = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} \sum_{k=1}^{n_p} \sum_{l=1}^{n_d} ENU \left( P_{\text{ess}}, P_{\text{CG}}, LD \right)
\]

(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.

\[
EENS = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} \sum_{k=1}^{n_p} \sum_{l=1}^{n_d} ENS \left( P_{\text{ess}}, P_{\text{CG}}, LD \right)
\]

(35)

\[
EENU = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} \sum_{k=1}^{n_p} \sum_{l=1}^{n_d} ENU \left( P_{\text{ess}}, P_{\text{CG}}, LD \right)
\]

(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>
<thead>
<tr>
<th>CG &amp; Priority Loading Order</th>
<th>kWs</th>
<th>Qty</th>
<th>FOR</th>
<th>kWs</th>
<th>Type</th>
<th>PL1</th>
<th>PL2</th>
<th>PL3</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>1</td>
<td>0.060</td>
<td>80</td>
<td>Diesel</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>2</td>
<td>0.045</td>
<td>40</td>
<td>Diesel</td>
<td>2-3</td>
<td>4-5</td>
<td>2-3</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>2</td>
<td>0.045</td>
<td>40</td>
<td>Micro-turbine</td>
<td>4-5</td>
<td>6-7</td>
<td>4-5</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>0.030</td>
<td>10</td>
<td>Micro-turbine</td>
<td>6-7</td>
<td>10-11</td>
<td>10-11</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>2</td>
<td>0.090</td>
<td>20</td>
<td>FC</td>
<td>8-9</td>
<td>1-2</td>
<td>6-7</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>0.075</td>
<td>10</td>
<td>FC</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>0.060</td>
<td>10</td>
<td>FC</td>
<td>11</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

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.

Table 2: Impact of CG Ramp Rate on EENS & EENU

<table>
<thead>
<tr>
<th>MW-Min / Month</th>
<th>Base Ramp Rate</th>
<th>0.1 times Base Ramp Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>EENS</td>
<td>1,717</td>
<td>2,696</td>
</tr>
<tr>
<td>EENU</td>
<td>695</td>
<td>2,388</td>
</tr>
</tbody>
</table>

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. 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 ESS capacity is over 50%. The final size of ESS can be simply determined by the required EENS or/and EEND 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.

VI. REFERENCE


VII. BIOGRAPHIES

L. H. KOH (S’11) received his Bachelor of Engineering-Electrical degree (First Class) from Nanyang Technological University (NTU), and currently a NTU PhD Student in School of Electrical and Electronic Engineering.

Peng Wang (SM’11) received his B.Sc. degree from Xian Jiaotong University, China, in 1978, the M. Sc. degree from Tsuuiyuan University of Technology, China, in 1987, and the M. Sc. and Ph.D. degrees from the University of Saskatchewan, Canada, in 1995 and 1998 respectively. Currently, he is an associate professor of Nanyang Technological University.

Fook Hoong Choo received his B. degree from the University of Leeds, Leeds, U.K., in 1977 and M.Sc. degree from the University of Manchester, Manchester, U.K., in 1979. He joined Nanyang Technological University (formerly Nanyang Technological Institute), Singapore, in 1984, where he is currently a Co-Director of Energy Research Institute @ NTU. His current research interests include power electronics, ac drives, magnetics, renewable energy generation and control, and energy, water, and environmental research.

King-Jet Tseng was born in Singapore. He received the B.Eng. (First Class) and M.Eng. degrees from the National University of Singapore, and the Ph.D. degree from Cambridge University, U.K. He is currently an associated professor and the Head of Power Engineering at Nanyang Technological University, Singapore.

ZhiYong Gao (S’09) received the B.E. degree from Northeastern University, Shenyang, China, in 2002, and the M.Sc. and Ph.D. degrees from Nanyang Technological University, Singapore, in 2007 and 2013 respectively. He is currently a Research Scientist in the Experimental Power Grid Centre, A*STAR, Singapore.

Hans B. Pütten is currently a visiting Professor of Energy Research Institute @ NTU and served as President of IEEE Power & Energy Society from 2004 to 2005. He held the Energy Systems Management Chair at the École Polytechnique Fédérale de Lausanne - EPFL - Swiss Federal Institute of Technology in Lausanne. Upon his arrival at EPFL, in April 2006, he also became the inaugural Director of the Energy Center at EPFL. Professor Pütten was Georgia Power Professor and Vice Chair for External Affairs in the School of Electrical and Computer Engineering at the Georgia Institute of Technology. At Georgia Tech, he launched the National Electric Energy Test, Research and Application Center, NEETRAC, and served as its Director and Management Board Chair.