A NOVEL MICROGRID SIMULATION AND DEMONSTRATION TOOL

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ABSTRACT

This paper presents a customized Microgrid simulation and demonstration tool, which allows evaluation of both economic aspects and electrical behaviour (steady state) of a Microgrid under both grid-connected and islanded modes of operation. Firstly, a brief introduction is given for the GUI and layout of functional modules of this tool. Then assumptions, algorithms, and typical simulation results are shown in further detail for three core (sub-) modules of this tool: energy balance dispatch, reliability evaluation, plus economics and demand response. In the end, possible future extensions of this tool are discussed.

INTRODUCTION TO THE MG TOOL

In this paper, a Microgrid simulation and demonstration tool (hereby referred to as 'MG tool') developed by the authors is briefly introduced. The MG tool has been implemented as a Microsoft Excel template with built-in API interface to PSS®SINCAL power system analysis software. : The main graphical user interface (dashboard) of this tool is shown in in Figure 1. The dashboard contains several blocks, which allow users to enter input data and directly view/analyze simulation results.

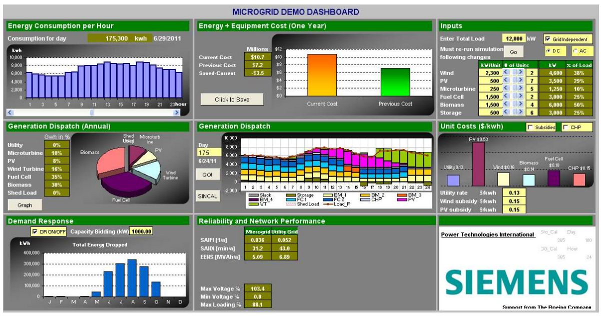

Figure 1: Dashboard User Interface of MG Tool

Figure 2 shows the PSS®SINCAL single-line diagram of a sample military Microgrid network [2] consisting of four 12.47 kV feeders forming two open-ring configurations.

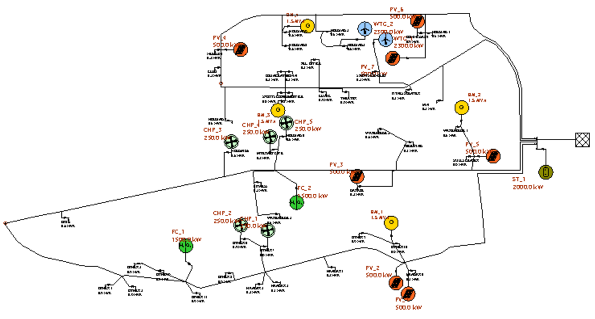

Figure 2: Sample Test Network for Microgrid Conversion

In total, seven different load types are modelled in the network: housing, office, warehouse, garage, brig, hangar, and other loads. Default maximum total peak load is about 14.5 MW (which can be modified by the user from the dashboard), and a constant universal power factor of 0.85 has been assumed for all loads within the Microgrid.

Table 1 shows number and capacity of each unit (see Figure 2) for different distributed generation (DG) and storage technologies considered in the sample network. This sample tool mainly covers wind turbines (WT), photovoltaic (PV) arrays, Micro-turbine combined heat and power (CHP) units, fuel cells (FC), biomass (BM) generators, and storage (STO) units.

	kW/Unit	# Units	kW
Wind	2,300	2	4,600
PV	500	7	3,500
Microturbine (CHP)	250	5	1,250
Fuel Cell	1,500	2	3,000
Biomass	1,500	4	6,000
Storage	500	6	3,000

Table 1: Size of Each Generation Technology

MG TOOL SYSTEM ARCHITECTURE

The MG tool essentially consists of 4 modules: economic module, dashboard module, dispatch algorithm module and SINCAL network calculation module. These modules interact with each other in the course of simulation. This system architecture can be seen from Figure 3.

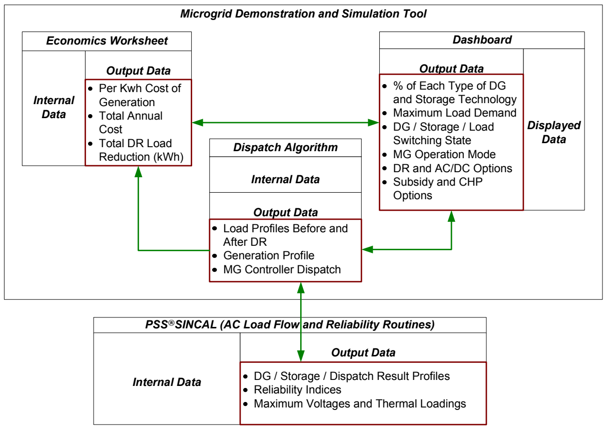

Figure 3: MG Tool System Architecture

The **dashboard module** of the MG tool allows users to choose different total load demand, various DG sizes and numbers, economic data, and Microgrid operation mode.

The **SINCAL network calculation module** takes the input data from dispatch algorithm module, performs required load flow and reliability calculations and exports the results back to the dispatch algorithm module.

The key function of **dispatch module** is to perform energy balance dispatch. also In addition, it performs reliability evaluations for typical Microgrids and their counterpart traditional passive networks.

The **economic module** calculates the total cost to operate the system. The same module also accounts for demand response (DR) impact on load profile and ensuing consequences.

In ensuing sections, energy balance dispatch, reliability evaluation, plus economic and DR functions of MG tool are further explained with an emphasis on off-grid mode.

ENERGY BALANCE DISPATCH

Energy balance calculation is the backbone of dispatch algorithm module, as it defines Microgrid operating states, which is the basis of reliability and economic evaluations.

Adopted Microgrid Dispatch Procedures

The MG tool has adopted a comparatively straightforward way for the scheduling task: namely 'priority list' method. This is a simplification of standard unit commitment and economic dispatch routine as economic signals are only reflected as dispatch priority for storage and DG units.

Energy dispatch of MG tool consists of following 5 steps:

1. **Residual Load Calculation**
2. **Storage (STO) Dispatch**
3. **Controllable Generation (CG) Dispatch**
4. **Interruptible Load (IL) Dispatch**
5. **AC Power Flow Calculation**

Ensuing sections will further clarify these 5 steps.

Residual Load Calculation

In this step, a time series profile of residual load demand (Res-Load) is obtained by subtracting the renewable and non-controllable generation (RNG) output from the load demand at each time step. It is assumed that the RNG is comprised of PV, WT and CHP. In Figure 4, a weekly example of 'Res-Load' is shown as a reference.

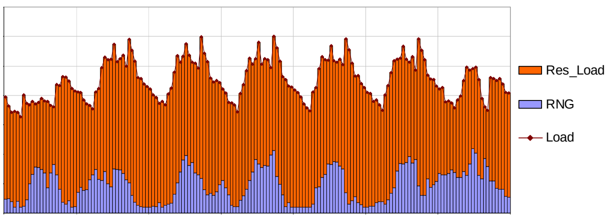

Figure 4: Sample Weekly Residual Load Profile

Dispatch of Storage Unit

The dispatch of a storage unit for energy balancing tasks targets at minimizing standard deviation of the residual load demand profile. This optimization problem is subject to the following constrains: (1) continuity of State of Charge (SoC) at begin and end of an operation cycle, (2) unit power rating, (3) max/min SoC limits, and (4) losses due to charge / discharge processes as well as self-discharges.

In principle, STO dispatch algorithm includes the following three major sub-steps:

1. *Convert time-series residual load data into cumulative positive segments and cumulative negative segments;*
2. *Perform storage dispatch for the converted segment data series to 'flatten' the demand curve;*
3. *Convert the storage utilization pattern for converted segment curve back to original time scale to minimize hourly variations of adjusted demand curve.*

A mixture of mathematical programming methods is used for this STO dispatch process. In Figure 5, a sample weekly STO dispatch result is shown (Pex_Sto stands for storage power, E_Sto stands for storage energy content).

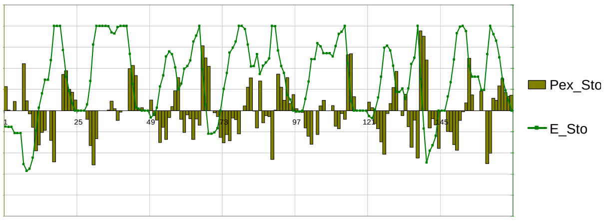

Figure 5: Sample Weekly Storage Dispatch Result

Dispatch of Controllable Generators

The remaining generation technologies including FC, BM and CHP are defined as controllable generators (CG). The priority-list method adopted for CG dispatch can be roughly described as follows:

1. *Divide modified residual load into several segments according to a number of segmentation criteria.*
2. *If load demand falls below minimum output of one BM unit, then RNG output need to be curtailed.*
3. *If load demand exceeds total capacity rating of all FC BM, and CHP units, then load shedding is needed.*
4. *For each segment, switching states of each FC and BM are determined to provide fast rotating reserve.*
5. *FC units always have priority over BM if load demand is higher than minimum output of a FC unit; and BM units always have priority over FC if load change calls for shut-down or start-up of a unit for 1-2 hours.*
6. *After switching states of BM and FC are determined, power demand is shared evenly among all units.*

A sample weekly CG dispatch result for BM is shown in Figure 6. A simplification is made here, such that a DG unit of lower index (e.g. BM1) always has higher dispatch priority over same-type unit of higher index (e.g. BM2).

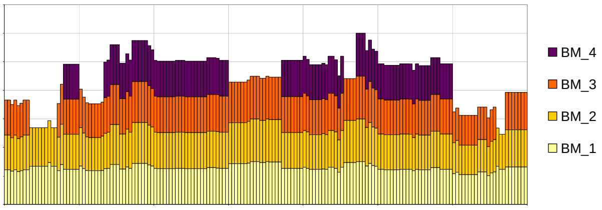

Figure 6: Sample Weekly Biomass Dispatch Result

Dispatch of Interruptible Loads

The load shedding algorithm of this MG tool is quite straightforward: each load is given a criticality index. When load shedding is necessary, loads with lowest criticality will be shed one by one until the island can sustain energy balance. One sample load shedding result can be seen in Figure 7.

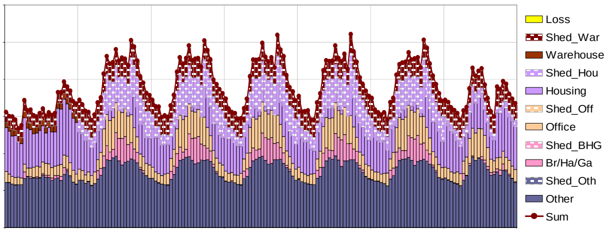

Figure 7: Sample Weekly Load Shedding Result

AC Power Flow Calculation

An iterative calculation process is performed to obtain AC power flow result, which can be described as follows:

1. *Use DC dispatch results to perform an initial annual power flow results with a virtual slack.*
2. *Distribute the slack deficit or excess of active and reactive power among STO and CG units. Recalculate power flow and redistribute the slack powers in a looped way until slack powers approximate zero.*
3. *Obtain highest and lowest nodal voltages, plus highest line / transformer thermal loading indices.*

Figure 8 shows an example of monitored network variables over a week after calculation of AC power flows.

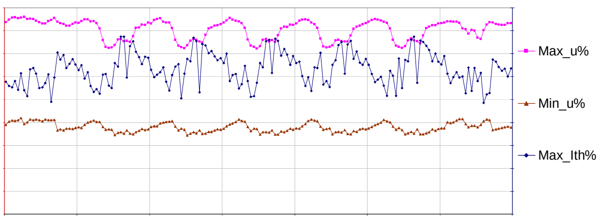

Figure 8: Sample Weekly Boundary Network Conditions

Sample Off-Grid Microgrid Dispatch Result

With the combination of all step-wise dispatch efforts, an eventual weekly energy balance diagram for an islanded Microgrid can be seen from Figure 9 as an example.

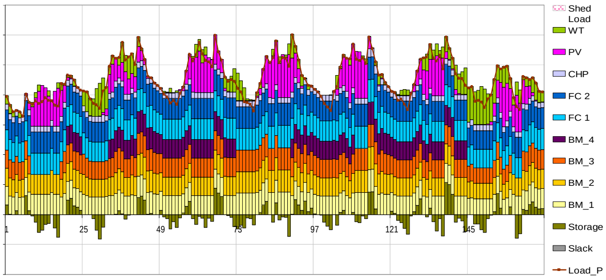

Figure 9: Dispatch Result of an Islanded Microgrid

RELIABILITY EVALUATION

In this study the reliability evaluation of demo Microgrid is carried out using a scenario-based approach. Basic workflow of this method can be described as follows:

1. *Use annual load flow result of a Microgrid to obtain continuous annual duration curves for load and DG.*
2. *Segment the continuous annual duration curves into discrete form so as to simplify evaluation.*
3. *Identify cumulative occurrence probability of all possible scenarios.*
4. *Perform stand-alone reliability evaluations with given load demand and DG switching state for all scenarios. Collect and save SAIFI, SAIDI, and EENS indices.*
5. *Calculate the weighted (using occurrence probability) average of SAIFI, SAIDI, and EENS.*

Figure 10 shows continuous and discrete annual duration curves of load, CHP, PV, WT, BM, and FC units.

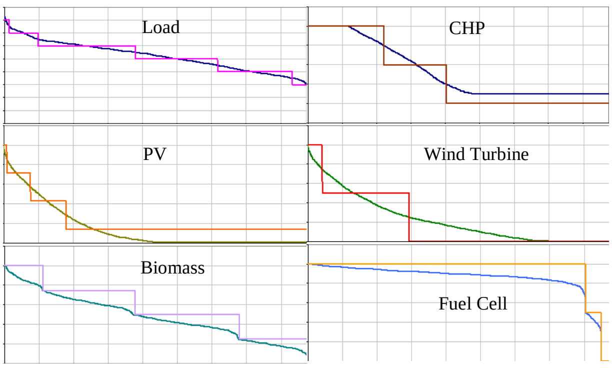

Figure 10: Segmentation of Annual Duration Curves

For benchmarking purpose, in this study two reliability evaluation modes are defined: (1) typical Microgrid with seamless transition capability, and (2) traditional passive network that shuts down all DG units under a utility fault.

In Figure 11, scenario parameters and each scenario's occurrence probability are shown for the Microgrid mode.

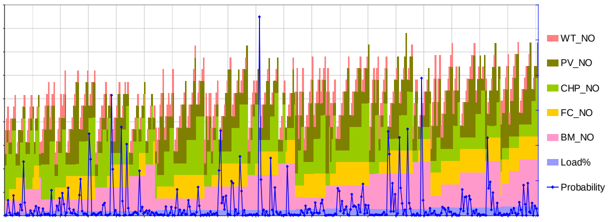

Figure 11: Scenario Definition of Demo Microgrid

In Table 2, weighted averages of all reliability indices for Microgrid and passive grid modes are summarized. Obviously, Microgrid offers better SAIFI, SAIDI, and EENS performances over passive grid due to its ability of seamless transfer to island when utility fails.

	SAIFI [1/a]	SAIDI [min/a]	EENS [MVAh/a]
Microgrid	0.0364	31.22	5.090
Passive Grid	0.0517	42.96	6.895

Table 2: Comparison of Reliability Evaluation Results

ECONOMICS AND DEMAND RESPONSE

The MG tool performs an economic calculation of total cost to operate Microgrid for the first year of deployment. It accounts for capital expenditure for DG and storage, financing, fuel, operation and maintenance, space/water heating savings from CHP units, renewable generation subsidies and participation in demand response programs.

Current cost assumptions can be seen from Table 3.

Potential Electric Source	Utility cost	Solar PV	Wind	ICE Biomass Ethanol	Fuel Cell NG	Battery Storage NaS	Micro-Turbine NG
Installation Cost ($/kW)	N/A	$5,320.00	$2,000.00	$1,075.00	$2,750.00	$960.00	$900.00
Fuel Cost ($/kWh)	N/A	N/A	N/A	0.080	0.080	0.000	0.118
O&M Cost ($/kWh)	N/A	$0.040	$0.040	$0.011	$0.008	N/A	$0.011
Subsidies ($/kWh) - User selects in dashbaord	N/A	-$0.15	-$0.15	N/A	Incentive stepped in MW sizes	N/A	N/A
CHP Heat Saving ($/kWh) - selected in dashboard	N/A	N/A	N/A	-$0.015	-$0.016	N/A	-$0.02
Equivalized Cost for Comparison ($/kWh)	$0.13	$0.57	$0.06	$0.12	$0.13	N/A	$0.14

Table 3: Assumed Costs for Different DG Technologies

Firstly, all cost entries are short-handed using Table 4.

Total Capital Cost for first year [$]	A
Size of DG [kW]	B
Installation cost [$/kW]	C
Capital recovery factor [annuity]	D
DG annual energy produced [kWh]	E
Fuel costs [$/kWh]	F
O&M [$/kWh]	G
Subsidies [$/kWh]	H
CHP saving [$/kWh]	I
Total Actual Cost for the year [$]	J
Equivalized Cost for Comparison [$/kWh]	K
Day of capacity bidding savings [$]	L
Day of capacity bidding fixed monthly payment [$/kW] = $12/kW	M
Day of capacity bidding load reduction [kW]	N
No of months participation in Day capacity bidding [months] = 12	O
Day of capacity bidding energy savings payment rate [$/kWh] = $0.13/kWh	P
Day of capacity bidding total energy saved over one year [kWh]	Q
Current load [kW]	R
Maximum possible load [kW]	S

Table 4: Cost Calculation Key Mapping

The ensuing sections will describe how the calculations are performed step by step.

Total Capital Cost for first year [$]

A= B x C x D

Total Actual Cost for the year [$]

J = A + (E x (F + G + H + I))

Equivalized Cost for Comparison [$/kWh]

K = J / E

Demand Response

Two forms of DR are modelled in the MG tool: "critical peak pricing" and "day of capacity bidding.

Day of capacity bidding

L = (M x N x O) + (P x Q)

Critical Peak Pricing

The variable utility rate under DR is modelled according to the following load steps:

- Critical peak rates at $1/kWh, when R > (S x 0.65)
- On-peak at $0.08/kWh when (S x 0.65) > R > (S x 0.55)
- Semi-peak $0.06/kWh when (S x 0.55) > R > (S x 0.43)
- Off-peak at $0.04/kWh when, (S x 0.43) > R

CONCLUSIONS

In summary, this MG tool is capable of demonstrating energy balance, reliability, economics, and demand response aspects of varying Microgrid configurations. However, the DG/STO dispatch algorithms are currently still decoupled from economic data, which is planned to be revised in future into a true unit commitment / economic dispatch sub-module for Microgrid applications.

REFERENCES

[1] Christine Schwaegerl et al, 2009, “Report on the Technical, Social, Economic, and Environmental Benefits Provided by Microgrids on Power System Operation”, “More Microgrids”, Deliverable DG3

[2] Samuel Booth, John Barnett et al, 2010, “Targeting Net Zero Energy at Marine Corps Air Station Miramar: Assessment and Recommendations”, NREL Technical Report