Open Source Market Simulation Tool for Scenario Analysis (MAST)

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Nomenclature

Variables

δ_n	Voltage angle at node n
d_g	Shutdown variable of a unit of generator g
e_p^{b}	Battery state of charge of prosumer p
e_s	Energy stored in storage plant s
p_p^{b}	Battery power flow of prosumer p
$p_p^{\mathrm{g+}}$	Grid power requirement of prosumer p
p_g	Power dispatched from supplier g
p_l	Power flow on line l
$p_p^{\mathrm{g-}}$	Feed-in power from prosumer p
p_s	Power flow of storage plant s
s_g	Number of online units of generator g
u_g	Startup variable of a unit of generator g

Initial Conditions

$\hat{d}_{g,t}$	Minimum number of units of generator $g \in \mathcal{G}^{\mathrm{syn}}$ required to remain offline for time $t < \tau_g^{\mathrm{d}}$
$\hat{e}_g$	Energy stored in TES of $g \in \mathcal{G}^{\mathrm{cst}}$ at start of horizon
$\hat{e}_p^{\mathrm{b}}$	Battery state of charge for prosumer p at start of horizon
$\hat{e}_s$	Energy stored in storage plant s at start of horizon

$\hat{p}_g$	Power dispatch of generator g at start of horizon
$\hat{s}_g$	Number of online units of generator $g \in \mathcal{G}^{\mathrm{syn}}$ at start of horizon
$\hat{u}_{g,t}$	Minimum number of units of generator $g \in \mathcal{G}^{\mathrm{syn}}$ required to remain online for time $t < \tau_g^{\mathrm{u}}$

Parameters

B_l	Susceptance of line l
c_g^{fix}	Fix cost of a unit of generator g
c_g^{sd}	Shutdown cost of a unit of generator g
c_g^{su}	Startup cost of a unit of generator g
c_g^{var}	Variable cost of a unit of generator g
η	Efficiency of component
H_g	Inertia constant of a power generating unit g
I	Synchronous inertia requirement (GW s)
p_c	Power demand of consumer c
Δp_l	Power loss on line l
p_p	Underline load demand of prosumer p
p_p^{pv}	Aggregator PV power of prosumer p
r_g^+	Ramp-up rate of a unit of generator g
r_g^-	Ramp-down rate of a unit of generator g
p^{r}	Active power reserve requirement
S_g	MVA rating of a unit of generator g
τ_g^{d}	Minimum down time of a unit of generator g
$\tilde{t}$	Time slot offset index
τ_g^{u}	Minimum up time of a unit of generator g

$\overline{U}_g$ Total number of identical units of generator g

Sets

$\mathcal{C}$ Set of consumers c

$\mathcal{G}$ Set of generators g

$\mathcal{G}^{\text{cst}}$ Set of CST generators $\mathcal{G}^{\text{cst}} \subseteq \mathcal{G}$

$\mathcal{G}_r$ Set of generators in region r

$\mathcal{N}_r$ Set of nodes in region r

$\mathcal{N}$ Set of Nodes n

$\mathcal{P}$ Set of prosumers p

$\mathcal{R}$ Set of regions r

$\mathcal{S}$ Set of storage plants s

$\mathcal{G}^{\text{syn}}$ Set of synchronous generators $\mathcal{G}^{\text{syn}} \subseteq \mathcal{G}$

$\mathcal{T}$ Set of time slots t

Other Symbols

$\overline{\bullet}$ Maximum limit of variable $\bullet$

$\underline{\bullet}$ Minimum limit of variable $\bullet$

$|\bullet|$ Cardinality of set $\bullet$

Acronyms / Abbreviations

MDT Minimum down time

MUT Minimum up time

SOC State of charge

Chapter 1

Introduction

MAST is an open source software designed to mimic electricity market behaviour for long term studies. It is useful for educators, researchers and policy makers to cater the impact of wide range of possible future evolution pathways.

1.1 Background

Power systems worldwide are moving away from domination by large-scale synchronous generation and passive consumers. Instead, in future grids[1] new actors, such as variable renewable energy sources (RES)[2], price-responsive users equipped with small-scale photovoltaic (PV)-battery systems (called prosumers), demand response (DR), and energy storage will play an increasingly important role. Given this, in order for policy makers and power system planners to evaluate the integration of high-penetrations of these new elements into future grids, new simulation tools need to be developed. Specifically, there is a pressing need to understand the effects of this technological change on future grids, in terms of energy balance, stability, security and reliability, over a wide range of highly-uncertain future scenarios. This is complicated by the inherent and unavoidable uncertainty surrounding the availability, quality and cost of new technologies (e.g. battery or PV system costs, or concentrated solar thermal (CST) generation operating characteristics) and the policy choices driving their uptake.

Thus, future powers system planning methods, requires a major departure from conventional power system planning, where only a handful of the most critical scenarios are

[1]We interpret a future grid to mean the study of national grid type structures with the transformational changes over the long-term out to 2050.

[2]For the sake of brevity, by RES we mean “unconventional” renewables like wind and solar, but excluding conventional RES, like hydro, and dispatchable unconventional renewables, like concentrated solar thermal.

analysed. To comprehend the impacts of these technological changes over a broad range of future evolution pathways, scenario analysis is more suitable.

Scenario analysis is a method of strategic planning, which is deployed to make flexible long-term plans. The method involves generation of scenarios for policy-makers by combining the known and predictive future trends and tries to identify the key deriving forces and factors. This allows policy makers to anticipate the inflexibilities and concealed disadvantages of a system and prepare for them well in advance. These scenario analysis methods involve running hundreds of different scenarios for several years to enable policy maker to judge the impact of their decisions. Note that the real strength of scenario analysis lies in establishing long-term effects of diverse policy statements.

MAST is specifically designed to bridge the gap between conventional grid planning and scenario analysis. MAST have the ability to explicitly model prosumers, utility storage and CST. It is intended to be used for long term planning and scenario analysis, as such it is not suitable for operation studies.

1.2 License and Term of Use

Chapter 2

Getting Started

2.1 Requirement

1. Matlab 2016 or higher
2. AMPL with Matlab api and a MILP solver
3. MATPOWER for power flow

For the hardware requirements, please refer to the system requirements for the version of Matlab[1]

2.2 Initialisation

1. Download all file provided on the link: Kindly use Github address.
2. Run "MAST.m" using Matlab 2016 or higher.
3. The "Market Simulation Tool" window will pop up, this represents the main interface for MAST as shown in Fig 2.1.

2.2.1 Path Definitions

Proper linkage of AMPL and data files associated with demand, PV, wind and other traces is required before executing simulations for the very first time. This is done through the "Path Setup". Perform following steps to setup path definitions:

[1] https://au.mathworks.com/support/sysreq/previous_releases.html

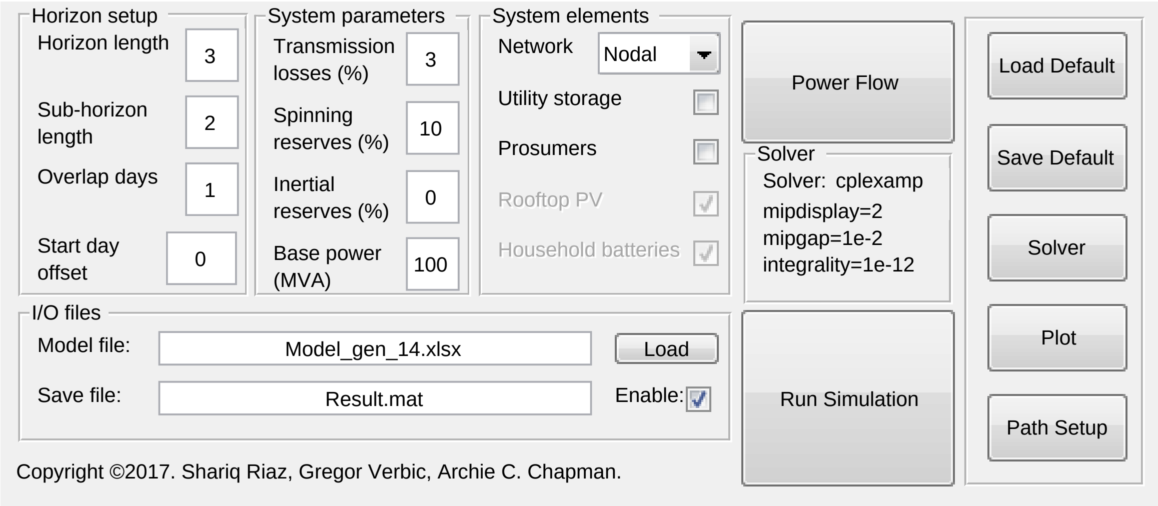

Fig. 2.1 Main interface for MAST.

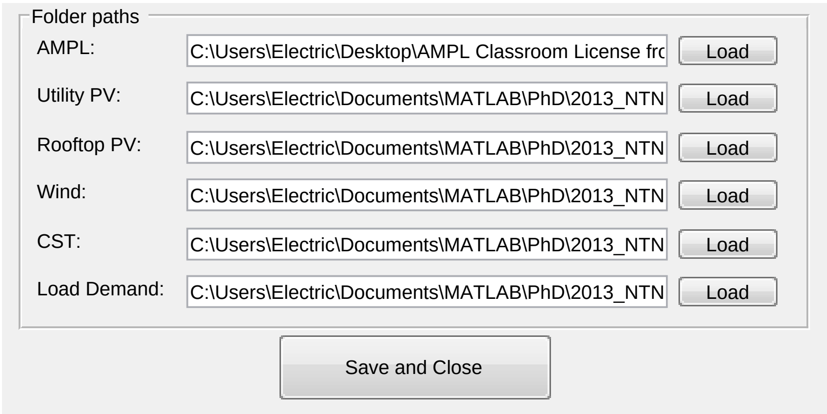

Fig. 2.2 Path Definitions Interface.

1. Click on "Path Setup" located at the bottom of right most panel, this will open "Path Setup" window as depicted in Fig. 2.2.
2. Click "Load" in front of AMPL: and select the location of main AMPL folder in your system. Make sure that it includes Matlab api files, as this setp will look for file "setupOnce.m" and set its location in the associated field. If it is unable to locate "setupOnce.m" then the associated field will be returned as blank.
3. Click on "Load" button in front of the "Utility PV", "Rooftop PV", "Wind", "CST" and "Load Demand" to set path definitions of these traces. Make sure to select the directory containing associated trace files. Note that selecting parent directory will result into errors at simulation execution stage.

4. Click "Save and Close" button at the bottom of the "Path setup" window to save these path definitions. Note that these paths definitions will only be used within the MAST and are temporarily added to the Matlab path definition.

2.3 Test Simulation

After performing the above mentioned steps; i) click "Load" in front of "Model file" and select the excel spread sheet named as "Test.xlsx". This file contains a simple 4 bus and can be used to check the functionality of MAST. ii) Adjust various options on main inter face according to your requirements. iii) Select "Run Simulation" to execute the market model for test system. Wait for the "Run Simulation" to come back to default colour. Yellow colour in MAST represent busy status and red colour indicate error. iv) Click "Plot" to open "Plot" Window and to have a quick graphical glimpse of the results.

2.4 Input Model File

Underlying power system and components details are defined in an excel spreadsheet. This file is uploaded in MAST using "Model file" option. This spread consist of five sheet named as "Generator Data", "Branch Data", "Bus Data", "Utility Storage Data" and "SVC Data". First four sheets are required for market simulations whereas SVC data is only used for power flow calculations.

All data is spread sheet is sensitive to the name of columns defined in first row. Therefore, if name of column is changed then MAST is not able to read input data correctly. However, MAST is insensitive to the location of each column, so feel free to arrange different columns in spread sheet according to your needs. Also, MAST look for "END OF DATA" as an indication that the last row of data is finished. MAST will not read any data below the "END OF LINE". Only one "END OF LINE" is required in each sheet and it can be placed in any column.

The data required by these sheet is as follows:

2.4.1 Generator Data

The parameters associated with each generator along with their brief description is provided in this section.

Generator Name

Generator name is used for the identification purposes of generators. Each and every generator is required to have a **unique** name. Note that each name should starts with an alphabet. These names are also be used in legend of plots functions.

Location Bus

Location bus describes the geographical location of generation plant in power system. Note that the defined location bus for generator must be amongst the "Bus Name" defined in "Bus Data" spreadsheet.

Number of Units

Number of units defines the number of identical unit aggregated at given generation plant.

Connected to Grid

This option is used to enable and disable a generator. Setting "connected to grid" to zero (0) mean that the generator is not to be included in the simulations, set one (1) otherwise.

Apparent Power Rating (MVA)

This defines the rated power of indvidual unit aggregated at the generation plant.

Fix Cost ($)

Defines the fix operation and maintenance cost associated with indvidual unit.

Start up Cost ($)

Defines the cost of bringing indvidual unit on-line.

Shut down Cost ($)

Defines the cost incurred by each unit to bring it off-line.

Variable Cost ($/MW)

Defines synonymous for short run marginal cost consisting of fuel cost and variable operation and maintenance cost associated with the production of each MW of power.

Maximum Real Power (MW)

This is the maximum real power that can be dispatched from each identical unit aggregated at generation plant.

Minimum Real Power (MW)

This represent the minimum stable thermal limit of each identical unit.

Ramp Up Rate (MW/h):

This option describes the maximum power increment allowed for each identical unit in one hour.

Ramp Down Rate (MW/h):

This option describes the maximum power decrement allowed each identical unit in one hour.

MUT (hour):

MUT defines the minimum up time in hours for indvidual unit. Any unit that has become on-line has to remain on-line for at least MUT (hours).

MDT (hour):

MDT defines the minimum down time in hours for indvidual unit. Any unit that has become off-line cannot be turned on for at least MDT (hours).

Generation Type

This option is used to classify generators in input resource independent (Type 1), input resource dependent (Type 2) generators and input resource dependent with storage (Type 3) generators. Type 1 generators are usually fossil fuel generators. Type 2 represents variable generation units (e.g wind and PV). Type 3 generators represents generation with storage such as CST.

Resource Collector Rating (MW)

It defines the rating of the resource collector for type 3 generation. Only require for type 3 generation. Note that size of resource collector is equal to "Maximum Real Power" for type 2 generation.

Maximum TES Capacity (MWh)

It is the maximum thermal capacity of energy storage. Only require for type 3 generation.

Minimum TES Limit (MWh)

It is the minimum stable limit of thermal energy system of type 3 generation. Only require for type 3 generation.

TES Efficiency (%)

This defines the thermal efficiency of energy storage of type 3 generation. Only require for type 3 generation.

Plot Color

Color of generator used in plots functions. For valid color names visit https://au.mathworks.com/matlabcentral/fileexchange/24497-rgb-triple-of-color-name--version-2. Plot color is only required by some plot functions.

Generation Tech:

represents technology of the generation plant such as coal, gas, PV etc. Only required by some plot functions.

2.4.2 Branch Data

Branch data spreadsheet contains information regarding transmission lines.

Line Name

Name of transmission line is used for identification purposes. Make sure that each and every transmission line has a **unique** name and each name starts with an alphabet.

End 1 Bus Name

End 1 of the transmission line. Power injected from bus 1 is considered as positive. These buses must be within the "Bus Name" defined in "Bus Data" spreadsheet.

End 2 Bus Name

End 2 of the transmission line. Power injected from bus 2 is considered as negative. These buses must be within the "Bus Name" defined in "Bus Data" spreadsheet.

Thermal Limit (MVA)

Defines the thermal limit of the transmission line. Due to DC power flow used in market simulations, the thermal limit is taken in (MW).

Nature of Line

It describes whether a line is AC or DC. (DC lines are not implemented in current version due to conflicts with MATPOWER)

In Service

This option is used to enable and disable a branch. Setting "in service" to zero (0) mean that the branch is not to be included, set one (1) otherwise.

Reactance (pu)

It is the per unit reactance of transmission line.

Susceptance (pu)

It is the per unit susceptance of transmission line. Only required for power flow calculations.

Resistance (pu)

It is the per unit resistance of transmission line. Only required for power flow calculations.

Maximum Angle Limit (degree)

This options defines the maximum allowed angle difference between two ends to a transmission line.

2.4.3 Bus Data

Bus data spreadsheet defines the properties related to system buses.

Bus Name

Name of the bus is used for identification purposes. Make sure that each and every bus has a **unique** name starting with an alphabet.

Bus Region

Determines the location of bus in a particular region. Note that each region should include at least one generator as spinning reserves and inertial reserves are maintained for each region.

Bus Type

Bus type is only used for power flow calculation and follow MATPOWER convention. That is, one(1) for PQ bus, two (2) for PV bus and three (3) for slack bus. In addition to that, all bus types can be set to zero (0) and MAST will allocate buses automatically. In automatic assignment, bus with largest in-feed generation is selected as slack bus, buses with either a generator or SVC are considered as PV bus and remaining buses are allocated as PQ buses.

Demand Trace Weightage

This options represents associated weight of demand trace for each bus. The demand trace file associated with the bus is multiplied with this factor to determine actual active power requirement of the bus. Note that demand trace is use to generate active power requirement only. Reactive power is only required for power flow calculations and is determined through power factor and active power requirement of each PQ bus.

Power Factor

Power factor of the bus is defined in this option. This is only used in power flow calculation to generate reactive power demand based on power factor and power requirement of the bus.

Prosumer Demand (%)

This option depicts the percentage of prosumers at each bus. This option is only valid if prosumers selection is enabled in main interface window. Otherwise, all users on a bus are considered as consumers.

Rooftop PV Capacity (MW)

This represents the net rooftop-PV installed by prosumers at the bus. Only used if prosumers and rooftop-PV selections are enabled in main interface window.

Feedin Price Ratio

It is the ratio of feedin power rate to price of electricity when buying from grid by prosumers. Currently prosumers are not allowed to send power back to grid due to technical challenges of reverse power flow.

Maximum Battery Capacity (MWh)

This indicates the maximum energy storage capability of prosumers at a bus. Only used if prosumers and household batteries selections are enabled in main interface window.

Minimum Battery Capacity (MWh)

It represents the minimum allowed state of charge for the house hold batteries at each bus. Only used if prosumers and household batteries selections are enabled in main interface window.

Maximum Charge Rate (MW/h)

This is the maximum charge rate of aggregated household batteries at each bus. Only used if prosumers and household batteries selections are enabled in main interface window.

Maximum Discharge Rate (MW/h)

It defines the maximum discharge rate of aggregated household batteries at each bus. Only used if prosumers and household batteries selections are enabled in main interface window.

Battery Efficiency (%)

Efficiency of household batteries stored at each bus is selected through this option. Only used if prosumers and household batteries selections are enabled in main interface window.

Minimum Voltage (pu)

This option is only required for power flow calculation and indicates the maximum allowed voltage level at each bus.

Maximum Voltage (pu)

This option is only required for power flow calculation and indicates the minimum allowed voltage level at each bus.

Base_kV

This option is only required for power flow calculation and indicates the base volatge of each bus.

Demand Trace Name

This option is used to assign demand trace file associated with each bus. This connection can either be formed through pointer to the file or name of the file. For later option, simply put the name of demand trace file of the bus in this space. If the name of the file is too long or data start date is different as compared to the other data files, a pointer is recommended to indicated the file. Then a case statement is needed in "get_Demand.m" function with same pointer name to link the pointer to corresponding data file with adjusted offset value. This also provides users flexibility to insert code to read data from different formats.

Wind Trace Name

This option is used to assign wind trace file associated with corresponding bus. This connection can either be formed through pointer to the file or name of the file. For later option, simply put the name of demand trace file of the bus in this space. If the name of the file is too long or data start date is different as compared to the other data files, a pointer is recommended to indicated the file. Then a case statement is needed in "get_WND_Trace.m" function with same pointer name to link the pointer to corresponding data file with adjusted offset value. This also provides users flexibility to insert code to read data from different formats.

PV Trace Name

This option is used to assign PV trace file associated with corresponding bus. This connection can either be formed through pointer to the file or name of the file. For later option, simply put the name of demand trace file of the bus in this space. If the name of the file is too long or data start date is different as compared to the other data files, a pointer is recommended to indicated the file. Then a case statement is needed in "get_PV_Trace.m" function with same pointer name to link the pointer to corresponding data file with adjusted offset value. This also provides users flexibility to insert code to read data from different formats.

CST Trace Name

This option is used to assign CST trace file associated with corresponding bus. This connection can either be formed through pointer to the file or name of the file. For later option, simply put the name of demand trace file of the bus in this space. If the name of the file is too long or data start date is different as compared to the other data files, a pointer is recommended to indicated the file. Then a case statement is needed in "get_CST_Trace.m" function with same pointer name to link the pointer to corresponding data file with adjusted offset value. This also provides users flexibility to insert code to read data from different formats.

Rooftop PV Trace

This option is used to assign rooftop-PV trace file associated with corresponding bus. This connection can either be formed through pointer to the file or name of the file. For later option, simply put the name of demand trace file of the bus in this space. If the name of the file is too long or data start date is different as compared to the other data files, a pointer is recommended to indicated the file. Then a case statement is needed in "get_RTPV_Trace.m" function with same pointer name to link the pointer to corresponding data file with adjusted offset value. This also provides users flexibility to insert code to read data from different formats.

2.4.4 Utility Storage Data

Parameters associated with utility storage are defined in this spreadsheet.

Utility Storage Name

Name of utility storage is used for identification purposes. Each utility storage is expected to have a **unique** name starting with an alphabet.

Location Bus

Geographical location of utility storage. These nodes must be within the "Bus Name" defined in "Bus Data" spreadsheet.

Connected to Grid

This option is used to enable and disable a storage. Setting "connected to grid" to zero (0) mean that the storage is not to be included in the simulations, set one (1) otherwise.

Maximum Storage Capacity (MWh)

It is the maximum energy capacity of utility storage.

Minimum Storage Capacity (MWh)

It represents the minimum state of charge to be maintained by utility storage.

Maximum Charge Rate (MW/h)

Maximum charge rate represents the maximum increment in state of charge of utility storage.

Maximum Discharge Rate (MW/h)

Maximum discharge rate represents the maximum decrement in state of charge of utility storage.

Storage Efficiency (%)

This represents the efficiency of utility storage to retain state of charge.

Plot Color

Color of utility storage used in plots only

2.4.5 SVC Data

Parameters related to SVC are defined in this spread sheet. Note that SVC data is only required for power flow calculations. Also, most of these options are just for following the MATPOWER notation, which treat SVC as generator. Resultantly, most of the value will be zero (0).

SVC Name

Each SVC is identified using its own **unique** name. The name must start with an alphabet.

Bus Name

This indicates the geographical location of SVC. The bus name should be amongst the "Bus Name" defined in "Bus Data" spreadsheet.

Connected to Grid

This option is used to enable and disable a storage. Setting "connected to grid" to zero (0) mean that the storage is not to be included in the simulations, set one (1) otherwise.

Maximum Real Power (MW)

SVC cannot provide real power so the value of maximum real power for SVC is always zero (0).

Minimum Real Power (MW)

SVC cannot provide real power so the value of minimum real power for SVC is always zero (0).

Maximum Reactive Power (MVar)

This is the value of maximum reactive power a SVC can provide.

Minimum Reactive Power (MVar)

This is the value of maximum reactive power a SVC can absorb.

Fix Cost ($)

SVC cannot provide real power so the value of fix cost for SVC is always zero (0).

Start up Cost ($)

SVC cannot provide real power so the value of start up cost for SVC is always zero (0).

Shut down Cost ($)

SVC cannot provide real power so the value of shut down cost for SVC is always zero (0).

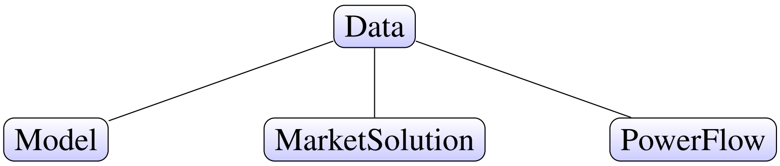

Fig. 2.3 Top layer of result structure

Variable Cost ($/MW)

SVC cannot provide real power so the value of variable cost for SVC is always zero (0).

2.5 Output data structure

Ouput results and important model parameters are sorted in a structure for organisation and ease of access. The main data structure consists of three sub structures namely "Model", "MarketSolution" and "PowerFlow", depicted in Fig.2.3. "Model" contains all the input parameters required by market and power flow, "MarketSolution" consists of the output parameters of market and "PowerFlow" contains the results of powerflow. The details of each substructure is explained in corrosponding subsections.

2.5.1 Model

Generator

Gen structure	Corresponding column name in "Generator Data" spreadsheet
N_units	Number of Units
Cost_Fix	Fix Cost ($)
Cost_Start_Up	Start up Cost ($)
Cost_Shut_Down	Shut down Cost ($)
Cost_Variable	Variable Cost ($/MW)
Power_Rating	Apparent Power Rating (MVA)
Max_Real_Power	Maximum Real Power (MW)
Min_Real_Power	Minimum Real Power (MW)
Max_Reactive_Power	Maximum Reactive Power (MVar)
Min_Reactive_Power	Minimum Reactive Power (MVar)
Ramp_Up_Rate	Ramp Up Rate (MW/h)
Ramp_Down_Rate	Ramp Down Rate (MW/h)
MUT	MUT (hour)
MDT	MDT (hour)
Bus	Location Bus
Color	Plot Color
Name	Generator Name
Tech	Generation Tech
Type	Generation Type
Trace_Factor	Resource Collector Rating (MW)
Maximum_TES	Maximum TES Capacity (MWh)
Minimum_TES	Minimum TES Limit (MWh)
TES_Efficiency	TES Efficiency (%)

Gen structure	Description
Region	Location of generator in a region
Trace.Type2	Resource trace for type 2 generators
Trace.Type3	Resource trace for type 3 generators
Seq	Sequence in which generators are defined
Seq_Type1	Sequence number of type 1 generators
Seq_Type2	Sequence number of type 2 generators
Seq_Type3	Sequence number of type 3 generators
Seq_Syn	Sequence number of synchronous generators

Bus

Bus structure	Corresponding column name in "Bus Data" spreadsheet
Demand_Weightage	Demand Trace Weightage
Power_Factor	Power Factor
Prosumer_Weightage	Prosumer Demand (%)
PV_Capacity	Rooftop PV Capacity (MW)
Feedin_price_ratio	Feedin Price Ratio
Battery.Maximum_Capacity	Maximum Battery Capacity (MWh)
Battery.Minimum_Capacity	Minimum Battery Capacity (MWh)
Battery.Maximum_ChargeRate	Maximum Charge Rate (MW/h)
Battery.Maximum_DischargeRate	Maximum Discharge Rate (MW/h)
Battery.Efficiency	Battery Efficiency (%)
Minimum_Voltage_limit_pu	Minimum Voltage (pu)
Maximum_Voltage_limit_pu	Maximum Voltage (pu)
Base_kV	Base_kV Demand
Name	Bus Name
Region	Bus Region
Type	Bus Type
Trace_Name.Demand	Demand Trace Name
Trace_Name.Wind	Wind Trace Name
Trace_Name.PV	PV Trace Name
Trace_Name.CST	CST Trace Name
Trace_Name.RTPV	Rooftop PV Trace Name

Bus structure	Description
Prosumer	Indicate buses with prosumers
Demand	Net demand trace
csmDemand	Demand trace of consumers
psmDemand	Demand trace of prosumers
PV_DR	Resource trace for rooftop-PV
Seq	Sequence in which buses are defined

Utility Storage

Uty_strg structure	Corresponding column name in "Utility Storage Data" spreadsheet
Maximum_Capacity	Maximum Storage Capacity (MWh)
Minimum_Capacity	Minimum Storage Capacity (MWh)
Maximum_ChargeRate	Maximum Charge Rate (MW/h)
Maximum_DischargeRate	Maximum Discharge Rate (MW/h)
Efficiency	Storage Efficiency (%)
Bus	Location Bus
Name	Utility Storage Name
Color	Plot Color

Name in Uty_strg structure	Description
Seq	Sequence in which utility storages are defined

Transmission line

Line structure	Corresponding column name in "Branch Data" spreadsheet
Capacity	Thermal Limit (MVA)
r	Resistance (pu)
x	Reactance (pu)
b	Susceptance (pu)
Max_Angle	Maximum Angle Limit (degree)
Name	Line Name
End_1_Bus	End 1 Bus Name
End_2_Bus	End 2 Bus Name
type	Nature of Line

Line structure	Description
Seq	Sequence in which transmission lines are defined
B	inverse of per unit reactance (1/x)

Parameter

Parameter structure	Description
G	Total number of generators in the system
R	Total number of regions in the system
B	Total number of buses in the system
S	Total number of utility storages in the system
L	Total number of lines in the system
V	Total number of SVCs in the system
T_Hrz	Hours in the simulation horizon
T	Number of hourly time slots for each sub horizon
Ntd_Lvl	Network detail level (1:Cu-plate, 2:Regional, 3:Nodal)
en_Uty_Strg	Enable/disable utility storage from simulation
en_Type2	Indicate the presence of type 2 generators in the system
en_Type3	Indicate the presence of type 3 generators in the system
en_DR	Enable/disable prosumers from simulation
Loss_factor	Percentage of demand to be considered as system losses
PReserve_factor	Percentage of demand to be considered for system reserve
Base_power	Base power (MVA) of the system
Mdl.Solver	Name of the MILP solver to be used by AMPL
Mdl.Options	Options related to MILP solver
Region.Name	Names of the regions
Region.Seq	Sequence in which regions are defined
LINKS.GXB	Relationship between generators and buses
LINKS.GXR	Relationship between generators and regions
LINKS.GT1XR	Relationship between type 1 generators and regions
LINKS.GT2XR	Relationship between type 2 generators and regions
LINKS.GT3XR	Relationship between type 3 generators and regions
LINKS.LXB_E1	Relationship between transmission line end 1 and buses
LINKS.LXB_E2	Relationship between transmission line end 2 and buses
LINKS.BXR	Relationship between buses and regions
LINKS.SXB	Relationship between utility storage and buses
U	Total number of generating units in the system

SVC

SVC structure	Corresponding column name in "SVC Data" spreadsheet
Bus	Bus Name
Name	SVC Name
Max_Real_Power	Maximum Real Power (MW)
Min_Real_Power	Minimum Real Power (MW)
Max_Reactive_Power	Maximum Reactive Power (MVar)
Min_Reactive_Power	Minimum Reactive Power (MVar)
Cost_Fix	Fix Cost ($)
Cost_Start_Up	Start up Cost ($)
Cost_Shut_Down	Shut down Cost ($)
Cost_Variable	Variable Cost ($/MW)

2.5.2 MarketSolution

Generator

Gen structure	Description
Status	Number of online units at each generation plant in each time slot; $[G \times T]$
S_Up	Number of units at each generation plants that have come online; $[G \times T]$
S_Dn	Number of units at each generation plants that are turned off; $[G \times T]$
Power	Power dispatched by each generation plant for each time slot; $[G \times T]$
Strg_engy	State of charge for type 3 generators; $[GT3 \times T]$
GenT3_Rsv	Reserve contribution from type 3 generators; $[GT3 \times T]$

Line

Line structure	Description
Power	Power transfered from end 1 to end 2 of transmission line; $[L \times T]$
Diff_Angle	Angle difference across end 1 and end 2 of transmission line in radians; $[L \times T]$

Bus

Bus structure	Description
Angle	Angle of each bus in radian for each time slot; $[B \times T]$
prosumer_gridpower	Prosumers grid power requirement; $[B \times T]$
PV.spill	PV power spilled by prosumers (currently inactive); $[B \times T]$
PV.utilisedpower	PV power utilised by prosumers; $[B \times T]$
Battery.Power	Prosumers battery power profile; $[B \times T]$
Battery.Energy	Prosumers battery state of charge; $[B \times T]$
Slack	(Inactive variable)
feedin_power	Prosumers feed-in power (currently inactive); $[B \times T]$
batteryandload_power	(Inactive variable); $[B \times T]$
csmDemand	Consumers power demand requirement; $[B \times T]$
psmDemand	Prosumers power demand requirement; $[B \times T]$

Utility Storage

Uty_Storage structure	Description
Power	Power profile of each storage for every time slot; $[S \times T]$
Energy	State of charge of each storage for each time slot; $[S \times T]$

Other

MarketSolution Sub-feid	Description
Dual	Structure to save dual variable associated with constraints.
Time	Time required by MILP solver to solve each sub-horizon

2.5.3 PowerFlow

bus

Name	Description
PD	Real power demand (MW) of each bus for each time slot; $[B \times T]$
QD	Reactive power demand (MVAr) of each bus for each time slot; $[B \times T]$
VM	Voltage magnitude (p.u.) of each bus for each time slot; $[B \times T]$
VA	Voltage angle (degrees) of each bus for each time slot; $[B \times T]$
LAM_P	Lagrange multiplier on real power mismatch (u/MW); $[B \times T]$
LAM_Q	Lagrange multiplier on reactive power mismatch (u/MVAr); $[B \times T]$
MU_VMAX	Kuhn-Tucker multiplier on upper voltage limit (u/p.u.); $[B \times T]$
MU_VMIN	Kuhn-Tucker multiplier on lower voltage limit (u/p.u.); $[B \times T]$

gen

Name	Description
PG	Real power output (MW) of each unit for each time slot; $[U \times T]$
QG	Reactive power output (MVAr) of each unit for each time slot; $[U \times T]$
VG	Voltage magnitude setpoint (p.u.) for each unit for each time slot; $[U \times T]$
STATUS	Indicate on/off state of each generator for every time slot; $[U \times T]$
PMAX	Maximum real power of each generator for every tie slot; $[U \times T]$
QMAX	Maximum reactive power of each generator for every tie slot; $[U \times T]$
QMIN	Minimum reactive power of each generator for every tie slot; $[U \times T]$

branch

Name	Description
PF	Real power injected from end 1 transmission line for each time slot; $[L \times T]$
QF	Reactive power injected from end 1 transmission line for each time slot; $[L \times T]$
PT	Real power injected from end 2 transmission line for each time slot; $[L \times T]$
QT	Reactive power injected from end 2 transmission line for each time slot; $[L \times T]$

2.6 Functionality of GUIs

Functionality of different windows in MST are explained in this section.

2.6.1 Market Simulation Tool

This is the main interface for the control of all the parameter of the market simulations as represented in Fig. 2.1. This window contains different buttons and panel which are used to adjust various options associated with the execution of the optimisation problem. Panels present in this window are as follows:

1. **Horizon setup**: To reduce computational burden MAST uses rolling horizon approach, in which the solution horizon of the problem $\mathcal{T}$ is split into several smaller intervals called sub-horizons and proper overlap between the sub-horizons ensures solution continuity. In "Horizon Setup" panel, "Horizon length", "Sub-horizon length" and "Overlapdays" represents the total length of horizon, length of each sub-horizon and overlap between sub-horizons in days. Whereas the "Start day offset" represents the start date based on load, PV and wind traces.

2. **System parameters**: Amount of system losses, spinning reserves and inertial reserves are specified using this panel. All these quantities are expressed as percentage of total demand at each hour.

3. **System elements**: This panel enable and disables different elements of the physical power system. "Network" pop-up menu set the network details as "Cu Plate", "Regional" and "Nodal". In "Cu Plate" transmission constraints are completely ignored, "Regional" option only considers transmission lines between different regions, where as "Nodal" option will consider each and every transmission line defined in the model. "Utility storage" enable/disable the utility storage constraints in the model. Similarly "Demand response", "Rooftop PV" and "Household batteries" enables and disables DR constraints, rooftop PV and batteries, respectively.

4. **Solver**: displays the current solver and corresponding directives as set using solver selection detailed in Section 2.6.2 .

5. **I/O files**: This panel specifies the names and location of input model file and output results. Upload model file containing information regarding generators, transmission lines, nodes and utility storage either via "Load" button or by provide the address of the file in field present in front of "Model file". Details of different parameter regarding system model file is presented in Section 2.4.

Functionality of buttons present on the right hand side of "Market Simulation Tool" are as follows:

1. **Load Default**: loads previously saved default MAST settings.

2. **Save Default**: stores current settings of MAST as default.

3. **Solver**: opens "Solver Selection" interface as detailed out in Section 2.6.2.

4. **Plot**: opens "Plot" interface as detailed out in Section 2.6.3.

5. **Path Setup**: opens "Path Setup" interface as detailed out in Section 2.6.4.

2.6.2 Solver Selection

AMPL high-level algebraic representation of optimisation problem provides flexibility to switch back end solvers. Click on "Solver" button present on the "Market Simulation Tool" window to open solver selection window as represented in Fig. 2.4. "Select Solver" pop-up menu allow you to set solver as "Cplex", "Gurobi" or "Other". In case of selecting "Other"

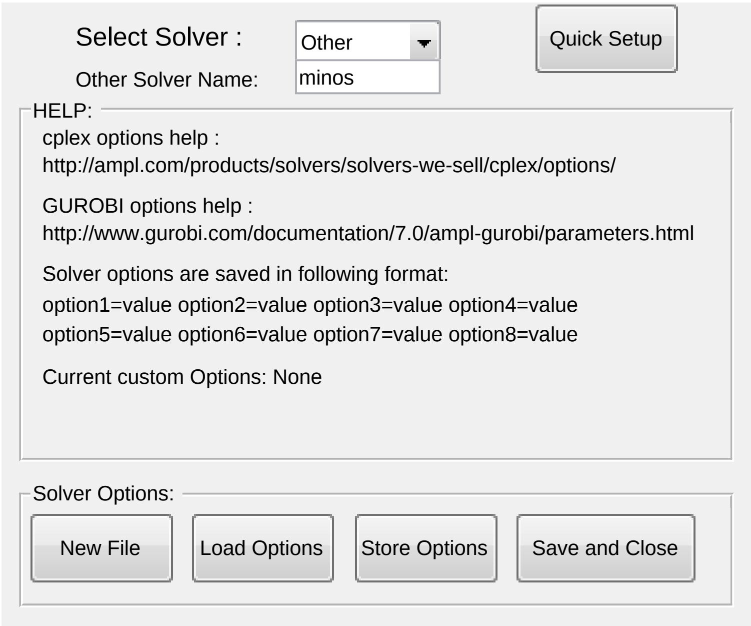

Fig. 2.4 Path Definitions Interface.

mention the name of preferred solver in field provided in front of "Other Solver Name". To set the selected solver as your default solver, click "Save and close" provided in the lower right corner of the "Solver Selection" window.

Solver Options

Different solvers allows different directives providing control over the optimisation problem. These include but not limited to selection of optimality gap, solution time, choice of algorithm, etc. Complete list of solvers that can be used with AMPL and their directives can be found on http://ampl.com/products/solvers/. "Quick Setup" button can be used to set termination time and optimality gap for Cplex and Gurobi via "Solver Quick Option" window as shown in Fig. 2.5. Click "Save and Close" button to set mentioned directives. Note that these directive will not be updated unless "Save and close" on the "Solver Selection" window is pressed.

"New File" button on "Solver Selection" window also allows you to put other directives as represented in Fig. 2.6 Click "Save and Close" button to set mentioned directives. Note that these directive will not be updated unless "Save and close" on the "Solver Selection" window is pressed.

"Store Options" button allows the options currently set using "New File" to be saved on hard drive in a .txt format. The option can later be loaded using "Load Options" button. "Load Options" also allows setup of solver options via .txt file created or modified using

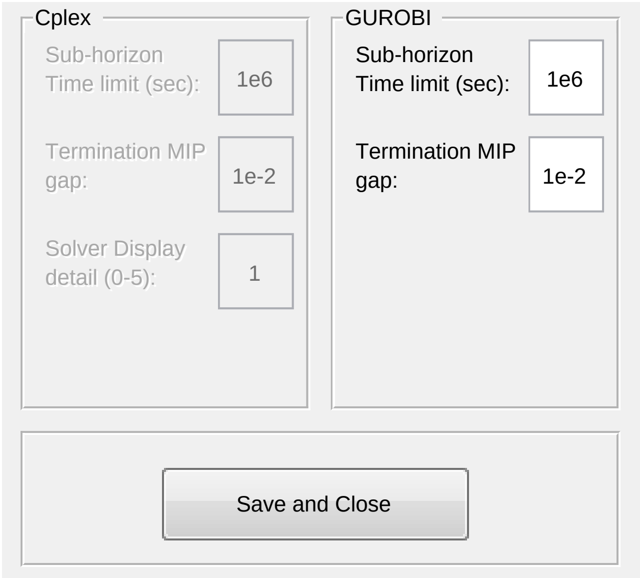

Fig. 2.5 Cplex and Gurobi quick option window.

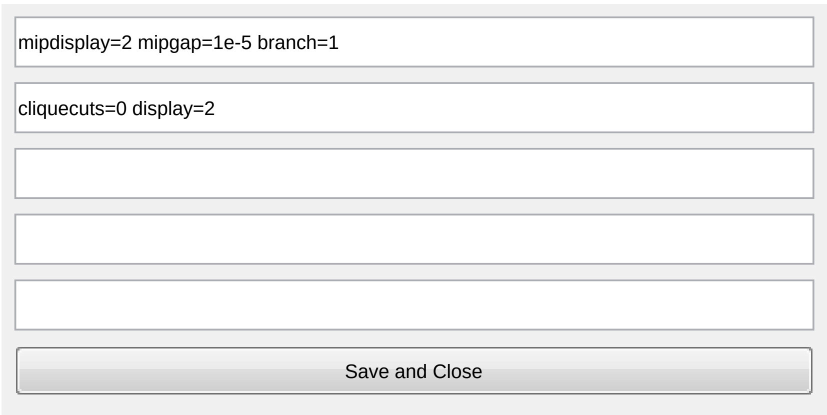

Fig. 2.6 Solver option window.

other text editors. Note that these directive will not be updated unless "Save and close" on the "Solver Selection" window is pressed.

2.6.3 Plot

Plot window provides a quick plots for a quick glance of the solution. Current and previously stored solutions can be viewed using provided functions. This window as shown in Fig. 2.7, also provides different functionality of plotting different plots like: "New Figure" plots a new plot in a new window, "Reuse Figure" close the last window and reuse it to plot the next data,

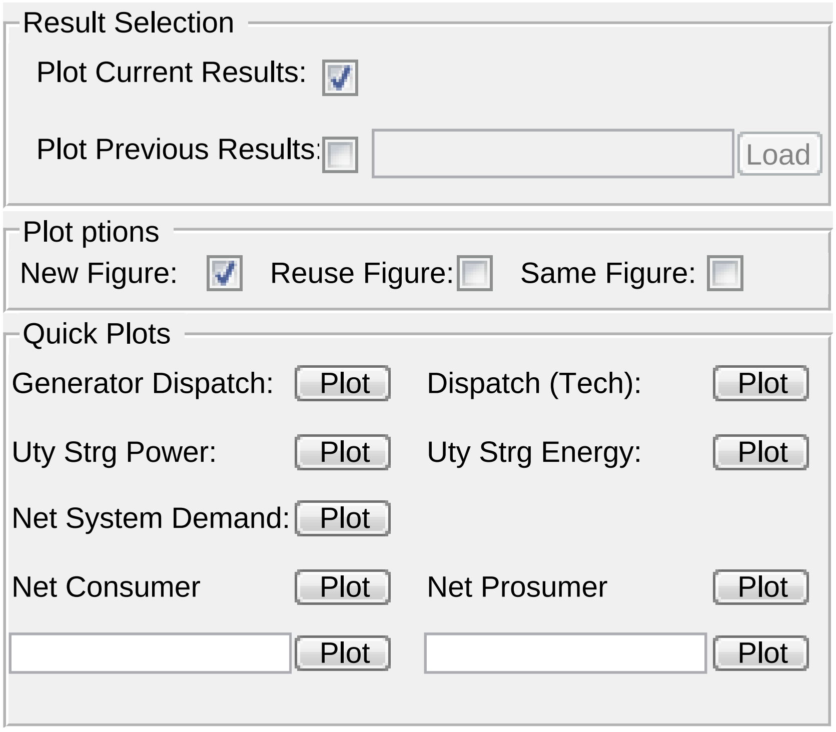

Fig. 2.7 Plot window.

"Same Figure" plots the new data in the last figure while preserving the previously shown data.

"Quick Plots" panel allows user to plot generation dispatch, utility storage power and stored energy, consumers, prosumers and system power requirement. It also allows user to plot user defined functions. Click load button in front of empty edit tabs and simply select the function to plot.

2.6.4 Path Setup

This window allows user to define paths for AMPL and different input traces required for market model. Simply press the load button in front of each entity to set path of relevant folder.

AMPL

This points to the "setupOnce.m" function provided in AMPL api. User can select any parent folder of this file and MAST will look for this file and set the correct path automatically.

Utility PV/Rooftop PV/Wind/CST

These tabs points to the actual folder containing normalised traces of utility scale and rooftop PV, wind and CST traces. Function "get_PV_Trace.m","get_RTPV_Trace.m","get_WND_Trace.m" and "get_CST_Trace.m" will go to corresponding folder and find the associated file based on the location of each entity. Note that these files should contain only the normalised trace as these will be multiplied by the rated value of the plant as defined in model file.

Load Demand

This points to the folder containing the folder containing true load demand for each node defined in the system.

Chapter 3

Mathematical Model

3.1 MAST UC Formulation

3.1.1 Objective function

The objective of the MAST is to minimise total generation cost for all sub-horizons t:

$$\underset{\Omega}{\text{minimise}} \sum_{t\in\mathcal{T}} \sum_{g\in\mathcal{G}} \left(c_g^{\text{fix}} s_{g,t} + c_g^{\text{su}} u_{g,t} + c_g^{\text{sd}} d_{g,t} + c_g^{\text{var}} p_{g,t} \right), \tag{3.1}$$

where $\Omega = \{s_{g,t}, u_{g,t}, d_{g,t}, p_{g,t}, p_{s,t}, p_{l,t}\}$ are the decision variables of the problem, and c_g^{fix}, c_g^{su}, c_g^{sd}, and c_g^{var} are fixed, startup, shutdown and variable cost, respectively. As typically done in planning studies the costs are assumed constant to reduce the computation complexity.

3.1.2 System constraints

System constraints[1] include power balance constraints, power reserve and minimum synchronous inertia requirements.

Power balance: Power generated at node n must be equal to the node power demand plus the net power flow on transmission lines connected to the node:

$$\sum_{g\in\mathcal{G}_n} p_{g,t} = \sum_{c\in\mathcal{C}_n} p_{c,t} + \sum_{p\in\mathcal{P}_n} p_{p,t}^{\text{g}+} - \sum_{p\in\mathcal{P}_n} p_{p,t}^{\text{g}-} + \sum_{s\in\mathcal{S}_n} p_{s,t} + \sum_{l\in\mathcal{L}_n} (p_{l,t} + \Delta p_{l,t}), \tag{3.2}$$

[1] All the constraints must be satisfied in all time slots t, however, for sake of notational brevity, this is not explicitly mentioned.

where $\mathcal{G}_n, \mathcal{C}_n, \mathcal{P}_n, \mathcal{S}_n, \mathcal{L}_n$ represent respectively the set of generators, consumers, prosumers[2], utility storage plants and lines connected to node n.

Power reserves: To cater for uncertainties, active power reserves provided by synchronous generation $g \in \mathcal{G}^{\text{syn}}$ are maintained in each region r:

$$\sum_{g \in \{(\mathcal{G}^{\text{syn}} - \mathcal{G}^{\text{cst}}) \cap \mathcal{G}_r\}} (\overline{p}_g s_{g,t} - p_{g,t}) + \sum_{g \in \{\mathcal{G}^{\text{cst}} \cap \mathcal{G}_r\}} \min(\overline{p}_g s_{g,t} - p_{g,t}, e_{g,t} - p_{g,t}) \geq \sum_{n \in \mathcal{N}_r} p^{\text{r}}_{n,t}. \quad (3.3)$$

For synchronous generators other than concentrated solar thermal, reserves are defined as the difference between the online capacity and the current operating point. For CST, reserves can either be limited by their online capacity or energy level of their thermal energy system. Variable $s_{g,t}$ in (3.3) represents the total number of online units at each generation plant, and $\mathcal{G}_r$ and $\mathcal{N}_r$ represent the sets of generators and nodes in region r, respectively.

Minimum synchronous inertia requirement: To ensure frequency stability, a minimum level of inertia provided by synchronous generation must be maintained at all times.

$$\sum_{g \in \{\mathcal{G}^{\text{syn}} \cap \mathcal{G}_r\}} s_{g,t} H_g S_g \geq \sum_{n \in \mathcal{N}_r} I_{n,t}, \quad (3.4)$$

where $I_{n,t}$ is the minimum synchronous inertia requirement of node n.

Network constraints

Network constraints include DC power flow constraints and thermal line limits for AC lines, and active power limits for HVDC lines.

Line power constraints: A DC load flow model is used for computation simplicity for AC transmission lines[3]:

$$p^{x,y}_{l,t} = B_l(\delta_{x,t} - \delta_{y,t}), \quad l \in \mathcal{L}^{\text{AC}}, \quad (3.5)$$

where the variables $\delta_{x,t}$ and $\delta_{y,t}$ represent voltage angles at nodes $x \in \mathcal{N}$ and $y \in \mathcal{N}$, respectively.

Thermal line limits: Power flows on all transmission lines are limited by the respective thermal limits of line l:

$$|\, p_{l,t} \,| \leq \overline{p}_l, \quad (3.6)$$

where $\overline{p}_l$ represents the thermal limit of line l.

[2]Price-responsive users equipped with small-scale PV-battery systems.

[3]A sufficiently small ($\sim 30°$) voltage angle difference over a transmission line is used to reduce the number of nonconvergent AC power flow cases.

Generation constraints

Generation constraints include physical limits of individual generation units. For the binary unit commitment (BUC), we adopted a UC formulation requiring three binary variables per time slot (on/off status, startup, shutdown) to model an individual unit. In the MST, identical units of a plant are clustered into one individual unit. This requires three *integer* variables (on/of status, startup, and shutdown) *per generation plant* per time slot as opposed to three *binary* variables *per generation unit* per time slot in the BUC.

Generation limits: Dispatch levels of a synchronous generator g are limited by the respective stable operating limits:

$$s_{g,t}\underline{p}_g \le p_{g,t} \le s_{g,t}\overline{p}_g, \quad g \in \mathcal{G}^{\text{syn}}. \tag{3.7}$$

The power of RES[4] generation is limited by the availability of the corresponding renewable resource (wind or sun):

$$s_{g,t}\underline{p}_g \le p_{g,t} \le s_{g,t}\overline{p}^{\text{res}}, \quad g \in \{\mathcal{G}^{\text{res}} \cap \mathcal{G}^{\text{cst}}\}. \tag{3.8}$$

Unit on/off constraints: A unit can only be turned on if and only if it is in off state and vice versa:

$$u_{g,t} - d_{g,t} = s_{g,t} - s_{g,t-1}, \quad t \ne 1,\ g \in \mathcal{G}^{\text{syn}}. \tag{3.9}$$

In a rolling horizon approach, consistency between adjacent time slots is ensured by:

$$u_{g,t} - d_{g,t} = s_{g,t} - \hat{s}_g, \quad t = 1,\ g \in \mathcal{G}^{\text{syn}}, \tag{3.10}$$

where $\hat{s}_g$ is the initial number of online units of generator g. Equations (3.9) and (3.10) also implicitly determine the upper bound of $u_{g,t}$ and $d_{g,t}$ in terms of changes in $s_{g,t}$.

Number of online units: Unlike the BUC, the MST requires an explicit upper bound on status variables:

$$s_{g,t} \le \overline{U}_g, \tag{3.11}$$

where $\overline{U}_g$ is total number of identical units of generator g.

[4] For the sake of brevity, by RES we mean “unconventional” renewables like wind and solar, but excluding conventional RES, like hydro, and dispatchable unconventional renewables, like concentrated solar thermal.

Ramp-up and ramp-down limits: Ramp rates of synchronous generation should be kept within the respective ramp-up (3.12), (3.13) and ramp-down limits (3.14), (3.15):

$$p_{g,t} - p_{g,t-1} \leq s_{g,t} r_g^+, \qquad t \neq 1, g \in \{\mathcal{G}^{\text{syn}} | r_g^+ < \overline{p}_g\}, \tag{3.12}$$

$$p_{g,t} - \hat{p}_g \leq s_{g,t} r_g^+, \qquad t = 1, g \in \{\mathcal{G}^{\text{syn}} | r_g^+ < \overline{p}_g\}, \tag{3.13}$$

$$\hat{p}_g - p_{g,t} \leq s_{g,t-1} r_g^-, \qquad t \neq 1, g \in \{\mathcal{G}^{\text{syn}} | r_g^- < \overline{p}_g\}, \tag{3.14}$$

$$\hat{p}_g - p_{g,t} \leq \hat{s}_g r_g^-, \qquad t = 1, g \in \{\mathcal{G}^{\text{syn}} | r_g^- < \overline{p}_g\}. \tag{3.15}$$

In the MST, a ramp limit of a power plant is defined as a product of the ramp limit of an individual unit and the number of online units in a power plant $s_{g,t}$. If $s_{g,t}$ is binary, these ramp constraints are mathematically identical to ramp constraints of the BUC. If a ramp rate multiplied by the length of the time resolution Δt is less than the rated power, the rate limit has no effect on the dispatch, so the corresponding constraint can be eliminated. Constraints explicitly defined for $t = 1$ are used to join two adjacent sub-horizons in the rolling-horizon approach.

Minimum up and down times: Steam generators must remain on for a period of time τ_g^{u} once turned on (minimum up time):

$$s_{g,t} \geq \sum_{\tilde{t}=\tau_g^{\text{u}}-1}^{0} u_{g,t-\tilde{t}}, \qquad t \geq \tau_g^{\text{u}},\ g \in \{\mathcal{G}^{\text{syn}} | \tau_g^{\text{u}} > \Delta t\}, \tag{3.16}$$

$$s_{g,t} \geq \sum_{\tilde{t}=t-1}^{0} u_{g,t-\tilde{t}} + \hat{u}_{g,t}, \qquad t < \tau_g^{\text{u}},\ g \in \{\mathcal{G}^{\text{syn}} | \tau_g^{\text{u}} > \Delta t\}. \tag{3.17}$$

Similarly, they must not be turned on for a period of time τ_g^{d} once turned off (minimum down time):

$$s_{g,t} \leq \overline{U}_g - \sum_{\tilde{t}=\tau_g^{\text{d}}-1}^{0} d_{g,t-\tilde{t}}, \qquad t \geq \tau_g^{\text{d}},\ g \in \{\mathcal{G}^{\text{syn}} | \tau_g^{\text{d}} > \Delta t\}, \tag{3.18}$$

$$s_{g,t} \leq \overline{U}_g - \sum_{\tilde{t}=t-1}^{0} d_{g,t-\tilde{t}} - \hat{d}_{g,t}, \qquad t < \tau_g^{\text{d}},\ g \in \{\mathcal{G}^{\text{syn}} | \tau_g^{\text{d}} > \Delta t\}. \tag{3.19}$$

Similar to the rate limits, if the minimum up and down times are smaller than the time resolution Δt, the corresponding constraints can be eliminated. Due to integer nature of discrete variables in the MAST, the definition of the MUDT constraints in the RH approach requires the number of online units for the last $\tau^{\text{u/d}}$ time interval to establish the relationship between the adjacent sub-horizons. If the $\tau_g^{\mathrm{u/d}}$ is smaller than time resolution Δt, then these constraints can be eliminated.

CST constraints

CST constraints include thermal energy storage energy balance and storage limits.

TES state of charge determines the thermal energy storage energy balance subject to the accumulated energy in the previous time slot, thermal losses, thermal power provided by the solar farm and electrical power dispatched from the CST plant:

$$e_{g,t} = \eta_g e_{g,t-1} + p_{g,t} - p_{g,t}, \qquad t \neq 1,\ g \in \mathcal{G}^{\mathrm{cst}}, \tag{3.20}$$

$$e_{g,t} = \eta_g \hat{e}_g + p_{g,t} - p_{g,t}, \qquad t = 1,\ g \in \mathcal{G}^{\mathrm{cst}}, \tag{3.21}$$

where, $p_{g,t}$ is the thermal power collected by the solar field of generator $g \in \mathcal{G}^{\mathrm{cst}}$.

TES limits: Energy stored is limited by the capacity of a storage tank:

$$\underline{e}_g \leq e_{g,t} \leq \overline{e}_g, \quad g \in \mathcal{G}^{\mathrm{cst}}. \tag{3.22}$$

Utility storage constraints

Utility-scale storage constraints include energy balance, storage capacity limits and power flow constraints. The formulation is generic and can capture a wide range of storage technologies.

Utility storage SOC limits determine the energy balance of storage plant s:

$$e_{s,t} = \eta_s e_{s,t-1} + p_{s,t}, \qquad t \neq 1, \tag{3.23}$$

$$e_{s,t} = \eta_s \hat{e}_s + p_{s,t}, \qquad t = 1. \tag{3.24}$$

Utility storage capacity limits: Energy stored is limited by the capacity of storage plant s:

$$\underline{e}_s \leq e_{s,t} \leq \overline{e}_s. \tag{3.25}$$

Charge/discharge rates limit the charge and discharge powers of storage plant s:

$$\overline{p}_s^- \leq p_{s,t} \leq \overline{p}_s^+, \tag{3.26}$$

where $\overline{p}_s^-$ and $\overline{p}_s^+$ represent the maximum power discharge and charge rates of a storage plant, respectively.

Prosumer sub-problem

The prosumer sub-problem captures the aggregated effect of prosumers. It is modeled using a bi-level framework in which the upper-level unit commitment problem described above minimises the total generation cost, and the lower-level problem maximises prosumers' self-consumption. The coupling is through the prosumers' demand, not through the electricity price, which renders the proposed model market structure agnostic. As such, it implicitly assumes a mechanism for demand response aggregation. The Karush-Kuhn-Tucker optimality conditions of the lower-level problem are added as the constraints to the upper-level problem, which reduces the problem to a single mixed integer linear program.

The model makes the following assumptions: (i) the loads are modeled as price anticipators; (ii) the demand model representing an aggregator consists of a large population of prosumers connected to an unconstrained distribution network who collectively maximise self-consumption; (iii) aggregators do not alter the underlying power consumption of the prosumers; and (iv) prosumers have smart meters equipped with home energy management systems for scheduling of the PV-battery systems, and, a communication infrastructure is assumed that allows a two-way communication between the grid, the aggregator and the prosumers.

Prosumer objective function: Prosumers aim to minimise electricity expenditure:

$$\underset{p_p^{g+/-},p_p^b}{\text{minimise}} \sum_{t\in\mathcal{T}} p_{p,t}^{\text{g}+} - \lambda p_{p,t}^{\text{g}-}, \tag{3.27}$$

where λ is the applicable feed-in price ratio. In current version of MAST, we assumed $\lambda = 0$, which corresponds to maximization of self-consumption.

The prosumer sub-problem is subject to the following constraints:

Prosumer power balance: Electrical consumption of prosumer p, consisting of grid feed-in power, $p_{p,t}^{\text{g}-}$, underlying consumption, $p_{p,t}$, and battery charging power, $p_{p,t}^{\text{b}}$, is equal to the power taken from the grid, $p_{p,t}^{\text{g}+}$, plus the power generated by the PV system, $p_{p,t}^{\text{pv}}$:

$$p_{p,t}^{\text{g}+} + p_{p,t}^{\text{pv}} = p_{p,t}^{\text{g}-} + p_{p,t} + p_{p,t}^{\text{b}}. \tag{3.28}$$

Battery SOC limits: Battery state of charge is the sum of the power inflow and the state of charge in the previous period:

$$e_{p,t}^{\text{b}} = \eta_p^{\text{b}} e_{p,t}^{\text{b}} + p_{p,t}^{\text{b}}, \qquad t \neq 1, \tag{3.29}$$

$$e_{p,t}^{\text{b}} = \eta_p^{\text{b}} \hat{e}_p^{\text{b}} + p_{p,t}^{\text{b}}, \qquad t = 1, \tag{3.30}$$

where $\hat{e}^{\mathrm{b}}_{p}$ represents the initial state of charge and is used to establish the connection between adjacent sub-horizons.

Battery charge/discharge limits: Battery power should not exceed the charge/discharge limits:

$$\overline{p}^{\mathrm{b}-}_{p} \leq p^{\mathrm{b}}_{p,t} \leq \overline{p}^{\mathrm{b}+}_{p}, \tag{3.31}$$

where $\overline{p}^{-}_{b}$ and $\overline{p}^{+}_{b}$ represent the maximum power discharge and charge rates of the prosumer's battery, respectively.

Battery storage capacity limits: Energy stored in a battery of prosumer p should always be less than its capacity:

$$\underline{e}^{\mathrm{b}}_{p} \leq e^{\mathrm{b}}_{p,t} \leq \overline{e}^{\mathrm{b}}_{p}. \tag{3.32}$$