Online Resource 1

A diagnostic of voltage infeasibility at low net load and the role of inverter-based grid support

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These tables give the counts behind the figures and tables of the paper. A state is voltage-operable when one setting of machine and plant set points, transformer taps and shunts keeps every network bus within 0.95 to 1.05 pu before any outage and 0.95 to 1.0875 pu after each outage, and the plant side of every step-up transformer within 0.90 to 1.10 pu. Unless stated otherwise, the battery co-located with a plant stops charging when the plant trips, the floor is 0.95 pu, the droop slope 3.33% and the plant capability 30% of the converter rating. The code and the result files are in the Zenodo package cited in the data availability statement of the paper.

Column headings:

- Table S1: the last two columns are voltage control with the battery that keeps charging and plants at constant reactive power.
- Table S2: *No setting*, the pre-event state alone admits no setting within the limits; *With outages*, it admits one, but not together with the outages. Both are split by the side, floor or upper limits, of the largest remaining violation of the best setting. *No solution*: no load flow converges even with that setting.
- Table S3: classes as in Table 1 of the paper, from the problems with the floor relaxed to 0.70 pu or the upper limits relaxed to 1.30 pu. *Before any outage*: the violation lies in the pre-event state. *Lack*, *Excess* and *Inconclusive*: result of the probe with 1 Mvar at every network bus. *Not probed*: part of the class without equilibrium in the normal range, as explained in Section 3.5 of the paper.
- Table S6: *Plant with battery*, states whose worst outage for the floor is a plant with a charging battery at its bus; *No setting*, states with no optimal setting, hence no worst outage recorded.
- Table S7: for each state that loses operability with every battery charging, the optimal setting is computed with a single battery charging. *Buses that suffice*: buses whose battery alone removes operability. *Restored*: whether stopping only the battery at the bus of the outage with the largest violation restores operability. *Tests*: batteries tested alone.
- Table S8: *Constant Q*, plants at constant reactive power within a capability of 30%; *VC not Q*, operable in voltage control but not at constant reactive power, and *Q not VC*, the opposite. The last six columns are voltage control with capabilities of 15, 30 and 45% of the converter rating, with the common set point (com.) and the optimal setting (opt.).

Table S1: Voltage-operable states of the RTS-GMLC by decommitment sequence, with the optimal setting

Scenario	Sequence	States	Units online	Fixed power factor	Unity power factor	Voltage control	Voltage control, battery keeps charging	Constant reactive power
E1	max resource	34	16–49	0	10	10	10	10
E1	min load	34	16–49	10	10	34	34	34
E2	max resource	49	1–49	0	10	44	9	18
E2	min load	46	4–49	0	0	46	46	46
E3	max resource	34	16–49	0	0	0	0	0
E3	min load	33	17–49	0	0	33	33	33
E4	max resource	49	1–49	0	0	26	0	0
E4	min load	46	4–49	0	0	45	45	42

Table S2: Limit that prevents operability, by set of states and plant mode, with the optimal setting

Set of states	Plant mode	States	Operable	No setting, floor	No setting, upper limits	With outages, floor	With outages, upper limits	No solution
9-bus, sequences	Fixed power factor	20	16	1	1	0	1	1
9-bus, sequences	Unity power factor	20	18	0	1	1	0	0
9-bus, sequences	Voltage control	20	20	0	0	0	0	0
39-bus, sequences	Fixed power factor	59	9	11	2	8	7	22
39-bus, sequences	Unity power factor	59	21	4	6	14	9	5
39-bus, sequences	Voltage control	59	59	0	0	0	0	0
RTS-GMLC, sequences	Fixed power factor	325	10	159	29	18	2	107
RTS-GMLC, sequences	Unity power factor	325	30	185	23	59	23	5
RTS-GMLC, sequences	Voltage control	325	238	0	0	61	2	24
RTS-GMLC, scheduled hours	Fixed power factor	86	3	5	56	3	13	6
RTS-GMLC, scheduled hours	Unity power factor	86	20	12	20	4	20	10
RTS-GMLC, scheduled hours	Voltage control	86	62	17	0	7	0	0

Table S3: Diagnostic of the combinations that are not operable but have a load-flow solution, by set of states and plant mode

Set of states	Plant mode	States	Floor	Upper limits	Conflict	No equilibrium	Unclassified	Before any outage	Lack	Excess	Inconclusive	Not probed
9-bus, sequences	Fixed power factor	3	0	1	2	0	0	2	3	0	0	0
9-bus, sequences	Unity power factor	2	0	0	2	0	0	1	2	0	0	0
39-bus, sequences	Fixed power factor	28	3	3	19	3	0	13	28	0	0	0
39-bus, sequences	Unity power factor	33	0	3	29	1	0	10	33	0	0	0
RTS-GMLC, sequences	Fixed power factor	208	69	0	108	31	0	188	177	0	0	31
RTS-GMLC, sequences	Unity power factor	290	0	14	263	13	0	208	277	0	0	13
RTS-GMLC, sequences	Voltage control	63	56	0	7	0	0	0	63	0	0	0
RTS-GMLC, scheduled hours	Fixed power factor	77	0	15	21	41	0	61	74	0	2	1
RTS-GMLC, scheduled hours	Unity power factor	56	0	24	22	10	0	32	54	2	0	0
RTS-GMLC, scheduled hours	Voltage control	24	1	0	23	0	0	17	24	0	0	0

Table S4: Voltage-operable states with the optimal setting and floors of 0.95 and 0.90 pu

Set of states	States	Fixed power factor, 0.95 pu	Fixed power factor, 0.90 pu	Unity power factor, 0.95 pu	Unity power factor, 0.90 pu	Voltage control, 0.95 pu	Voltage control, 0.90 pu
9-bus, sequences	20	16	16	18	19	20	20
39-bus, sequences	59	9	14	21	34	59	59
RTS-GMLC, sequences	325	10	54	30	102	238	256
RTS-GMLC, scheduled hours	86	3	6	20	25	62	78

Table S5: Voltage-operable states with the common set point and plants in voltage control, by droop slope

Set of states	States	Slope 2%	Slope 3.33%	Slope 7%
9-bus, sequences	20	20	20	20
39-bus, sequences	59	31	22	10
RTS-GMLC, sequences	325	231	226	201
RTS-GMLC, scheduled hours	86	23	22	18

Table S6: States that lose operability when the battery keeps charging after the outage of the plant at its bus

Set of states	States lost	Plant with battery	Buses	No setting
9-bus, sequences	6	6	5	0
39-bus, sequences	2	2	20	0
RTS-GMLC, sequences	71	55	119, 208, 308	16
RTS-GMLC, scheduled hours	15	15	308	0

Table S7: Attribution of the loss of operability to each co-located battery

Set of states	State	Plant mode	Tests	Buses that suffice	Restored
39-bus, sequences	E1, max resource, 7	Unity power factor	1	20	yes
39-bus, sequences	E2, max resource, 7	Unity power factor	1	20	yes
9-bus, sequences	E2, max resource, 1	Unity power factor	1	5	yes
9-bus, sequences	E2, max resource, 2	Fixed power factor	1	5	yes
9-bus, sequences	E2, max resource, 2	Unity power factor	1	5	yes
9-bus, sequences	E4, max resource, 1	Voltage control	1	5	yes
9-bus, sequences	E4, max resource, 2	Voltage control	1	5	yes
9-bus, sequences	E4, max resource, 2	Unity power factor	1	5	yes
RTS-GMLC, scheduled hours	E1, high net ramp C0 h14, 14	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E1, high net ramp C1-8 h12, 15	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E1, high net ramp C4 h12, 14	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E1, high resource C0 h12, 11	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E1, high resource C1-8 h12, 15	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E1, high resource C4 h12, 11	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, high net ramp C0 h12, 9	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, high net ramp C4 h14, 9	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, high resource C0 h11, 9	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, high resource C1-8 h13, 15	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, high resource C4 h09, 9	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, median C0 h10, 11	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E2, median C1-8 h10, 15	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E3, high resource C0 h08, 12	Voltage control	1	308	yes
RTS-GMLC, scheduled hours	E3, high resource C4 h08, 12	Voltage control	1	308	yes
RTS-GMLC, sequences	E2, max resource, 1	Voltage control	1	119	yes
RTS-GMLC, sequences	E2, max resource, 11	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 12	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 13	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 14	Voltage control	1	208	no

Table S7, continued

Set of states	State	Plant mode	Tests	Buses that suffice	Restored
RTS-GMLC, sequences	E2, max resource, 15	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 16	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 17	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 18	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 19	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 20	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 21	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 22	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 23	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 24	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 25	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 26	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 27	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 28	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 29	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 30	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 31	Voltage control	1	208	yes
RTS-GMLC, sequences	E2, max resource, 32	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 33	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 34	Voltage control	1	208	no
RTS-GMLC, sequences	E2, max resource, 40	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 40	Unity power factor	1	308	no
RTS-GMLC, sequences	E2, max resource, 41	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 41	Unity power factor	1	308	no
RTS-GMLC, sequences	E2, max resource, 42	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 42	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 43	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 43	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 44	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 44	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 45	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 45	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 46	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 46	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 47	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 47	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 48	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 48	Unity power factor	1	208	no
RTS-GMLC, sequences	E2, max resource, 49	Voltage control	1	308	no
RTS-GMLC, sequences	E2, max resource, 49	Unity power factor	1	208	no

Table S7, continued

Set of states	State	Plant mode	Tests	Buses that suffice	Restored
RTS-GMLC, sequences	E4, max resource, 10	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 11	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 12	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 13	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 14	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 15	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 16	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 17	Voltage control	15	108 208 308	–
RTS-GMLC, sequences	E4, max resource, 18	Voltage control	15	108 208 308	–
RTS-GMLC, sequences	E4, max resource, 19	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 4	Voltage control	1	119	no
RTS-GMLC, sequences	E4, max resource, 40	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 41	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 42	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 43	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 44	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 45	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 46	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 47	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 48	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 49	Voltage control	15	208 308	–
RTS-GMLC, sequences	E4, max resource, 5	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 6	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 7	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 8	Voltage control	1	208	no
RTS-GMLC, sequences	E4, max resource, 9	Voltage control	1	208	no

Table S8: Plants in voltage control compared with constant reactive power and with other reactive capabilities

Set of states	Unity power factor	Constant Q	VC not Q	Q not VC	15% com.	15% opt.	30% com.	30% opt.	45% com.	45% opt.
9-bus, sequences	18	20	0	0	20	20	20	20	20	20
39-bus, sequences	21	54	5	0	11	59	22	59	31	59
RTS-GMLC, sequences	30	183	55	0	179	211	226	238	242	250
RTS-GMLC, scheduled hours	20	54	8	0	17	58	22	62	23	63

Table S9: Voltage-operable scheduled hours by commitment rule and plant mode, with the optimal setting

Commitment rule	Hours	Fixed power factor	Unity power factor	Voltage control
No rule beyond frequency	30	1	6	23
At least eight units	26	1	8	17
Evaluated frequency constraint	30	1	6	22