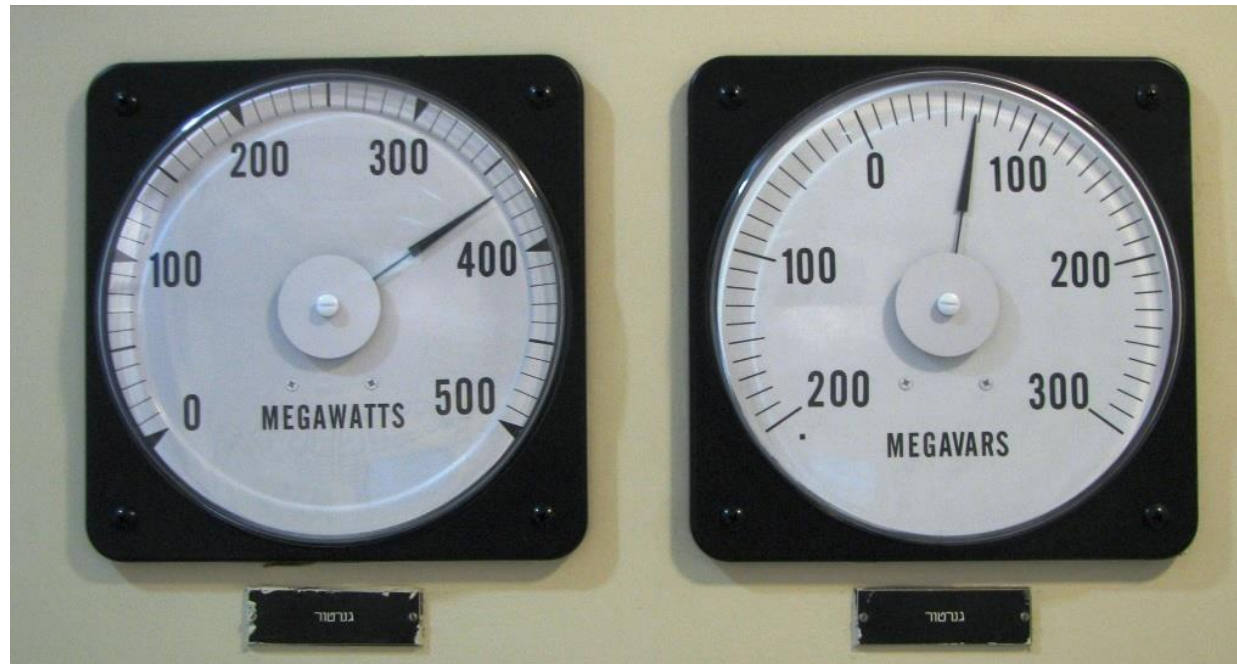


Optimizing the Generator-Transformer Operation

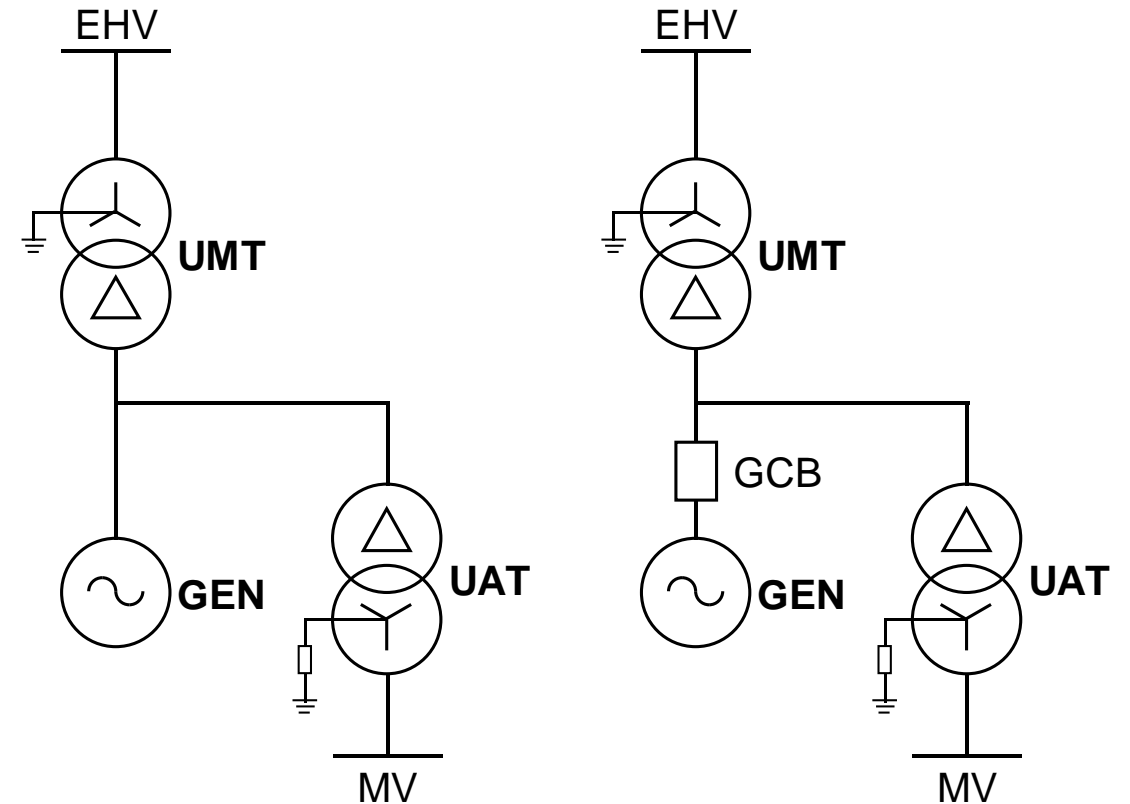
Relu ILIE

Iris Rotating Machine Conference, June 18, 2024



Introduction

- Typical generating unit configurations: block scheme or with generator circuit breaker
- Generator reactive capability in the system relies on unit transformer tap-changer position
- The goal: select the most suitable tap, providing maximum usefulness of generator reactive power
- This is an important *generator related task*, the transformer being a link in generator - network
- Typically, UMT and UAT have de-energized tap-changers, e.g. $\pm 2 \times 2.5\%$ at low current side
- Occasionally, UAT (less common UMT) have on-load tap-changers, for instance $\pm 10 \times 1.25\%$




Tap selection methods

- The literature recommends methods to choose the most suitable transformer tap by *interpreting graphically* the unit behavior during various operating regimes
- Ideally, it is desirable for generator to be able to produce MVAR to its overexcited limit when the system voltage is at its lowest expected level, and to absorb MVAR to its underexcited limit when the system voltage is at its highest expected level
- In most cases, it is not possible that a fixed tap will completely fulfill both above requirements, and thus a *compromise* have to be made. Appropriate tap-changer position should be able to meet most likely operating conditions, and preferably uncommon situations too
- Assumption: UMT and UAT parameters have been already set and cannot be changed (MVA, primary and secondary voltages, tap-changer range, impedance)
- Two tap selection methods will be presented, based on generator and transformer equivalent diagrams and equations

Exemplified unit

- Both methods exemplified for a 647 MVA, 22 kV generator; 651 MVA, 22/420 kV transformer
- In this particular case, UMT is actually a bank of 3 single-phase 217 MVA transformers
- The power system network has a nominal extra-high-voltage of 400 kV
- The unit has 3 UATs, the auxiliary bus system medium nominal voltage is 6.9 kV



Generator Unit

ATB	2 POLES	50 HERTZ	NO. 280T189	HYDROGEN & WATER COOLED
Y CONNECTED FOR 22,000 VOLTS			GAS PURITY 98%	RATING
EXCITATION 425 VOLTS			GAS PRESSURE (PSIG)	45
TEMPERATURE RISE AT RATED LOAD			KVA:	647,000
GUARANTEED NOT TO EXCEED			STATOR AMPERES:	16,979
54°C ON STATOR WINDING BY DETECTOR			FIELD AMPERES:	4,483
64°C ON FIELD BY RESISTANCE			POWER FACTOR:	0.85


CAUTION! BEFORE INSTALLING, OPERATING OR DISMANTLING READ INSTRUCTIONS GEK-84387

MANUFACTURED UNDER ONE OR MORE OF THE FOLLOWING U.S. PATENTS

3,422,478	3,488,940	3,566,010	3,614,437	3,713,272	3,766,732	3,804,923	4,078,021	4,154,900	4,216,051	4,378,179	4,412,700
3,429,557	3,493,501	3,572,928	3,652,801	3,714,477	3,778,190	3,878,988	4,032,874	4,114,884	4,206,422	4,330,828	4,420,161
3,432,759	3,531,907	3,572,968	3,659,956	3,719,422	3,778,838	3,887,189	4,040,890	4,157,040	4,200,090	4,343,434	4,408,053
3,437,859	3,561,888	3,607,817	3,693,036	3,748,588	3,808,429	3,919,854	4,048,902	4,177,387	4,202,000	4,340,708	4,404,588
3,461,330	3,564,201	3,604,296	3,702,864	3,748,491	3,840,950	3,942,804	4,074,137	4,198,829	4,217,211	4,362,778	4,421,700
3,476,964	3,565,548	3,614,112	3,748,540	3,801,818	3,871,654	4,078,471	4,211,521	4,318,981	4,402,014	4,477,707	

GE Power Systems
General Electric Company

Schenectady, New York
Made in U.S.A.



GENERAL ELECTRIC

TRANSFORMER

CLASS FOR SINGLE-PHASE
60 HERTZ
SYN-COMP & SLAMMING SYSTEM

CAUTION! BEFORE INSTALLING OR OPERATING READ INSTRUCTIONS GEK-86599

VOLTAGE RATING 42000000Y/24248Y-22000
 KVA RATING 27000 CONTINUOUS 65°C RISE FORCED-OIL AND FORCED-AIR-COOLED

A WINDING CONNECTIONS

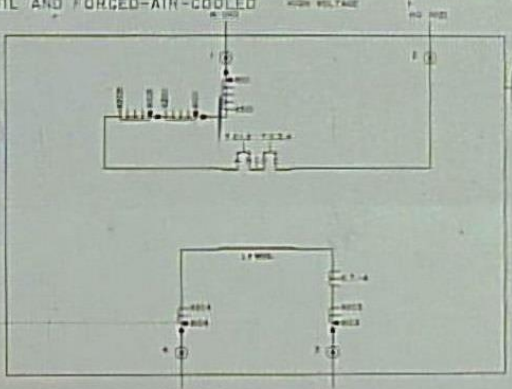
LINE TO LINE (V)	LINE TO GND (V)	PHASE-TO-PHASE (V)	PHASE-TO-GND (V)	LINE TO LINE (A)	LINE TO GND (A)	PHASE-TO-PHASE (A)	PHASE-TO-GND (A)
42000	24248	42000	24248	16979	9800	16979	9800

B WINDING CONNECTIONS

LINE TO LINE (V)	LINE TO GND (V)	PHASE-TO-PHASE (V)	PHASE-TO-GND (V)	LINE TO LINE (A)	LINE TO GND (A)	PHASE-TO-PHASE (A)	PHASE-TO-GND (A)
42000	24248	42000	24248	16979	9800	16979	9800

WINDING INSULATION LEVELS

ITEM	INSUL. LEVEL	TEMP. CLASS	TEMP. CLASS
WINDING	Class B	130°C	266°F
INSULATOR	Class B	130°C	266°F



INDUCTIVE PHENOMENA:
 WINDING CONDUCTION MATERIAL IS COPPER
 SUITABLE FOR OPERATION WITH THE NEUTRAL EITHER SOLIDLY GROUNDED OR IMPEDANCE GROUNDING WHICH WILL LIMIT THE LINE TO GROUND FAULT CURRENT TO THAT PERMITTED BY THE SYSTEM DESIGNER.
 WITH THE NEUTRAL POINT OF THE WINDING IS NOT SOLIDLY GROUNDED, THE TRANSFORMER SHOULD BE OPERATED WITH THE NEUTRAL POINT OF THE WINDING IS NOT SOLIDLY GROUNDED.
 TRANSFORMER OPERATING PRESSURE RATING IS 2.0 PSI POSITIVE TO 0 PSI.
 TRANSFORMER TANK SUITABLE TO WITHSTAND 5 PSI PRESSURE AND FULL VACUUM.
 C.T. TO 3 AND 4 ARE 0800/5 AMP.
 C.T. TO 5 AND 6 ARE 0800/5 AMP.
 C.T. TO 7 IS 0800/5 AMP.
 REFER TO C.T. TERMINAL PLATE APPROX FOR CONNECTIONS AND RATINGS.
 C.T. IS FOR USE WITH INDICATING THERMAL RELAY AND REMOTE WINDING TEMPERATURE INDICATOR.

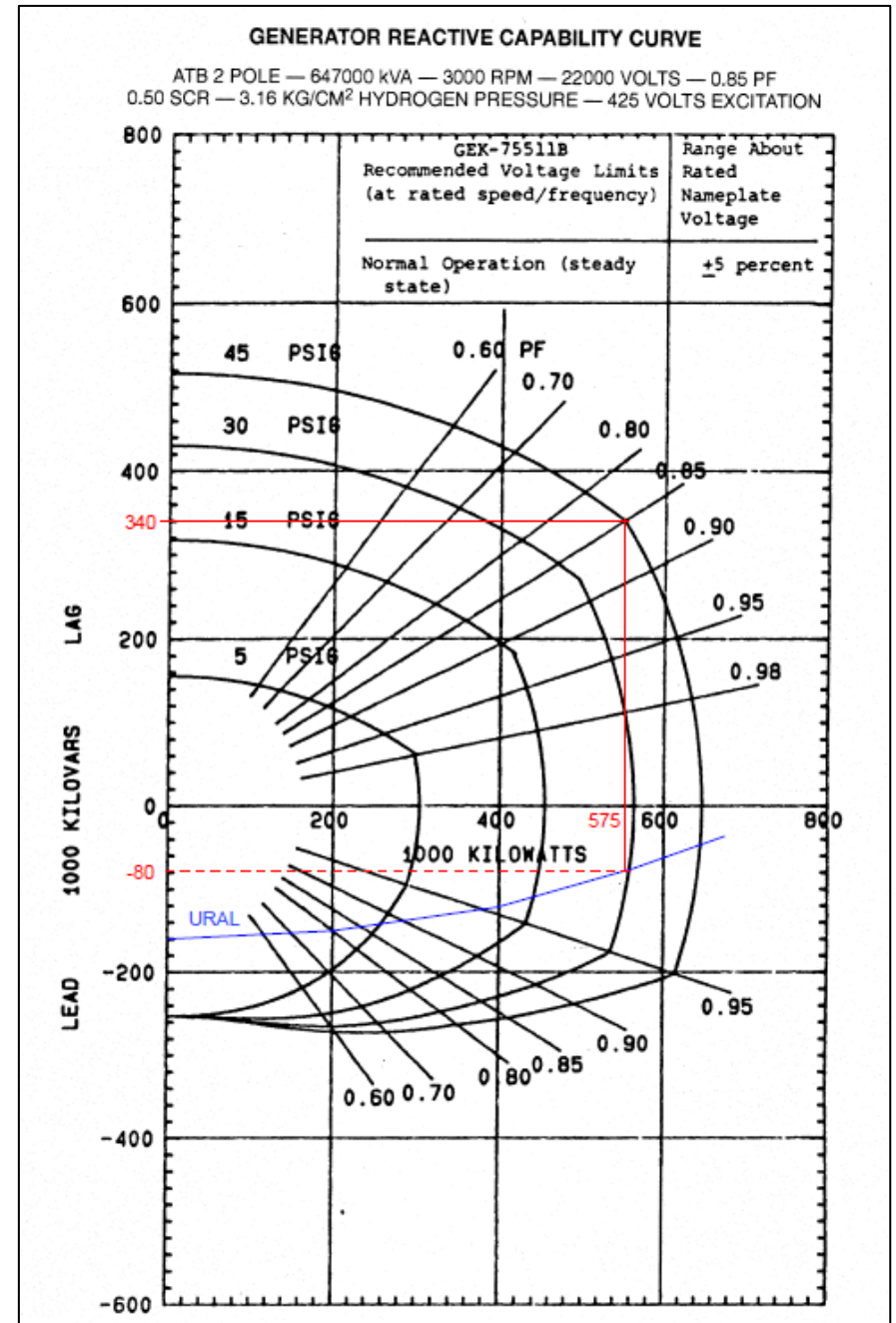
YEAR OF MANUFACTURE

SUITABLE FOR CONTINUOUS OPERATION WITH 5% VARIATION OF THE APPLIED VOLTAGE.

APPROX WEIGHT IN POUNDS
 TOTAL 22760 KG 49900 LB
 WITH UNLOADING 14225 KG 31300 LB
 TANK AND FITTINGS 3300 KG 7280 LB
 DE APPROVED TYPE 1 OIL 55040 L 14540 GAL 4900 KG 10800 LB
 ATMOSPHERIC OIL PRECIPITATION SYSTEM

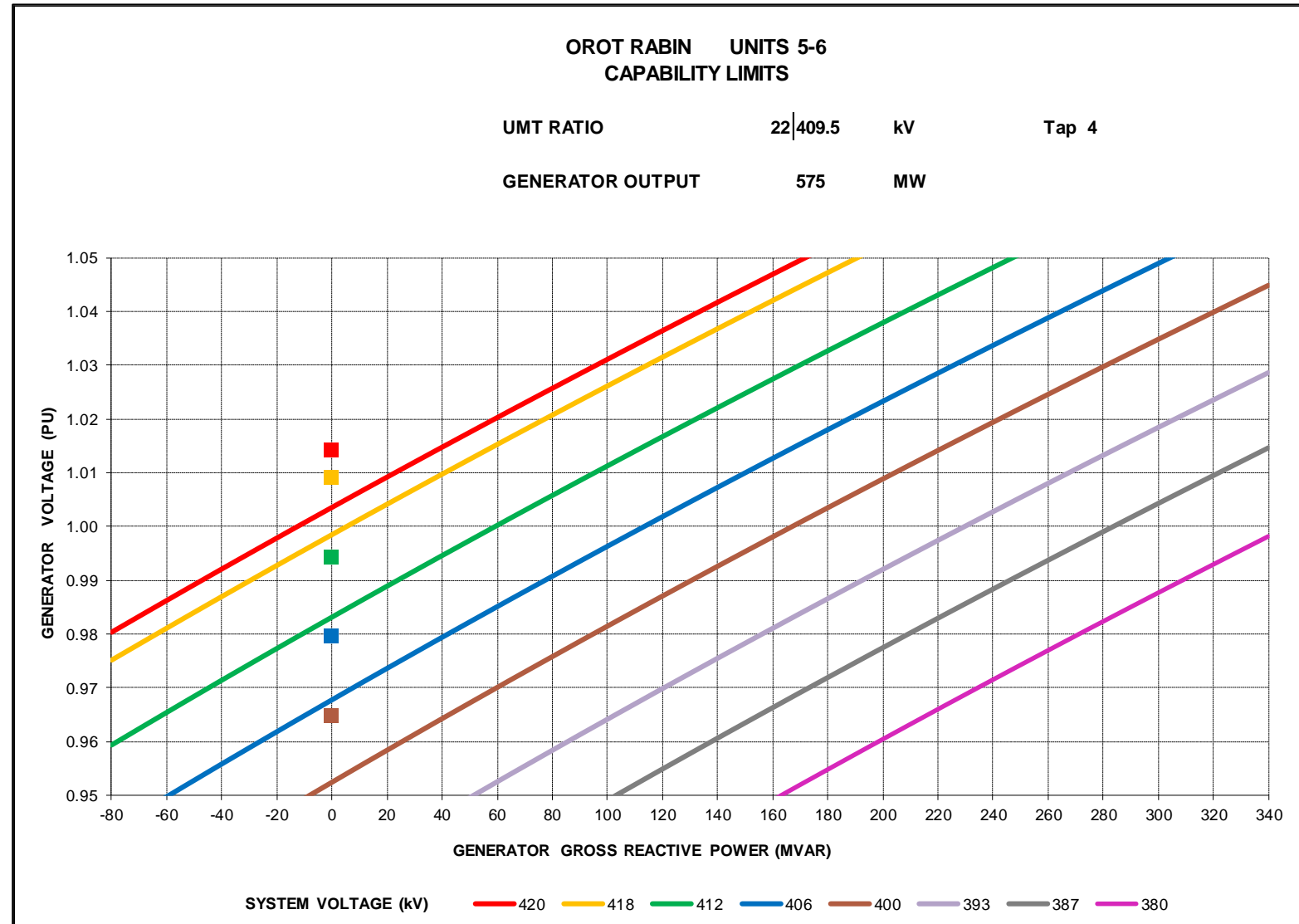
Basic data

- Generator gross active load: rated (matches turbine capability); also checked at operational minimum
- Generator gross reactive power boundaries: from capability curve and underexcited limiter (UEL or MEL or URAL) at a certain gross active load
- Generator voltage limits for continuous operation: 0.95-1.05 pu by IEEE C50.13 and IEC 60034-3
- System voltage at unit connection point according to Grid Code: normal conditions 400-418 kV, abnormal situations 380-420 kV



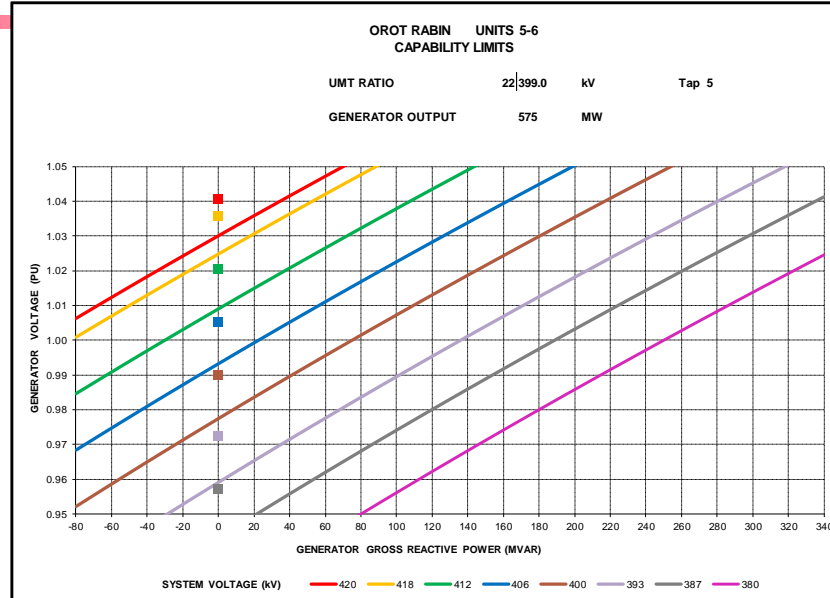
First method chart

- Shows generator gross reactive capabilities within generator voltage limits at various system voltages, certain gross active load and given UMT tap
- Based on guide IEEE C57.116
- Horizontal axis: generator gross reactive power (MVAR). Vertical axis: generator voltage in pu
- Small squares: synchronization capabilities (at zero active and reactive load)

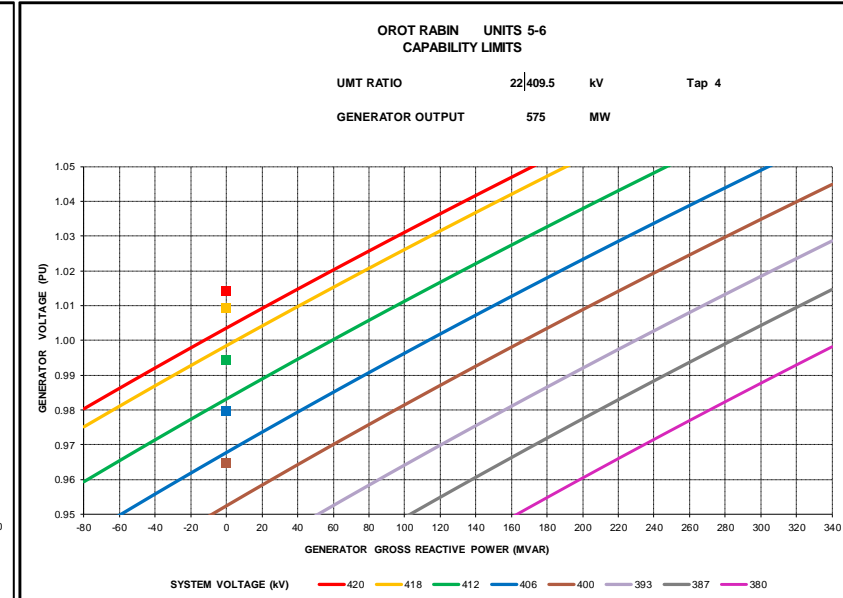


First method analysis

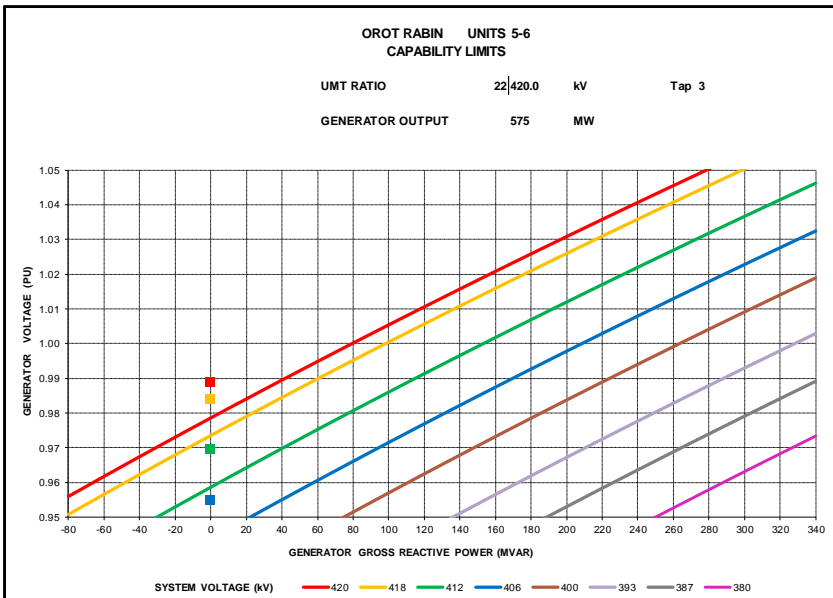
- UMT tap 5: limits delivered reactive power above 400 kV
- UMT tap 4: *best compromise* for usual range 400-418 kV
- UMT tap 3: limits received reactive power below 418 kV
- UMT tap 2 or 1: no received reactive power at any voltage



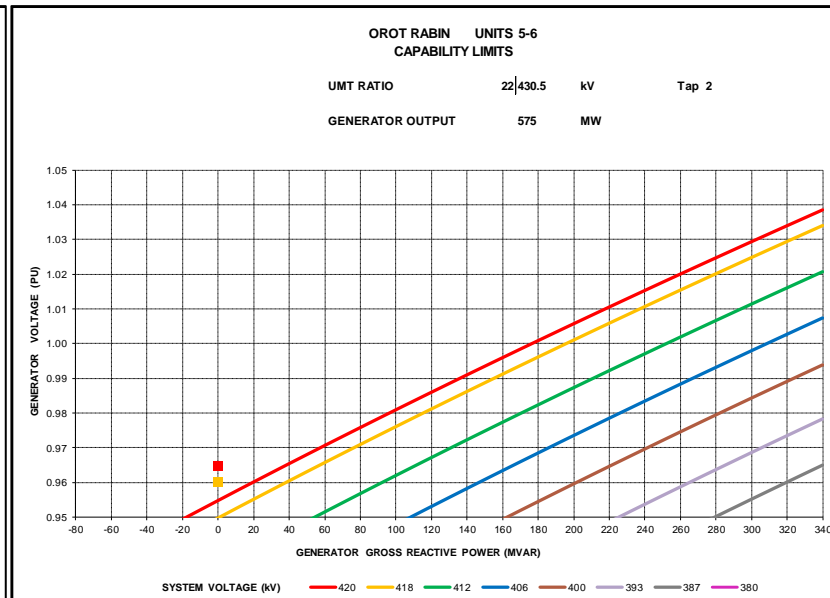
UMT at tap 5 (95.0%)



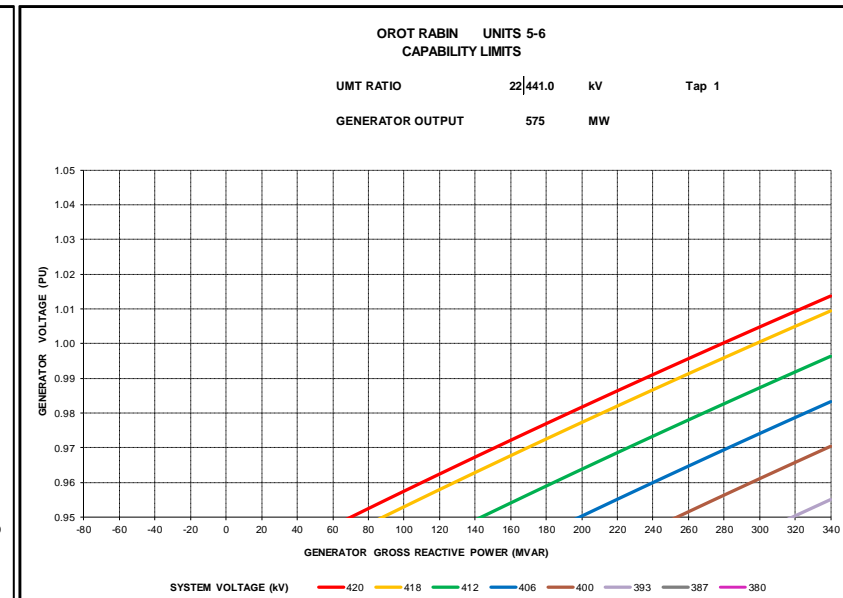
UMT at tap 4 (97.5%)



UMT at tap 3 (100.0%)



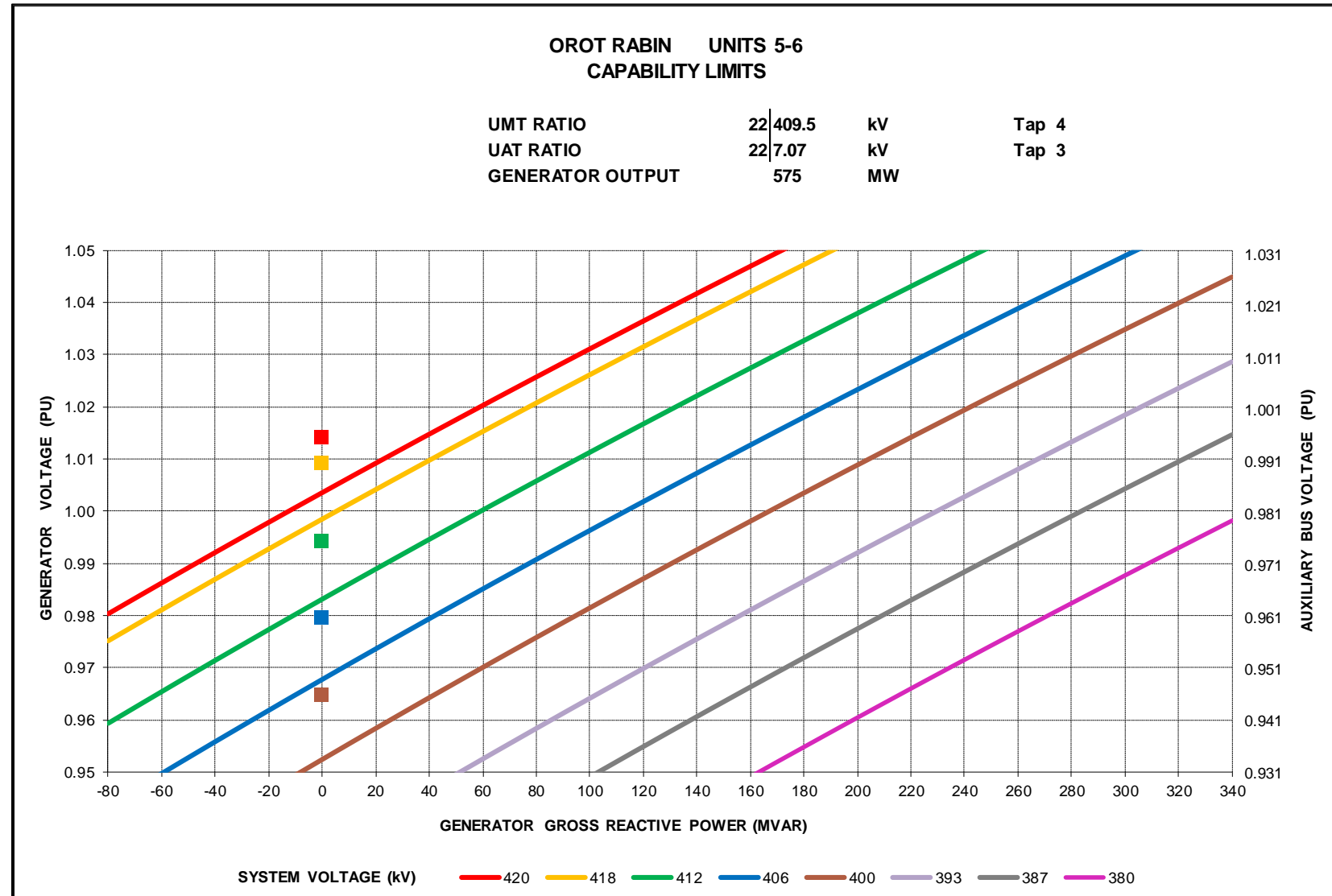
UMT at tap 2 (102.5%)



UMT at tap 1 (105.0%)

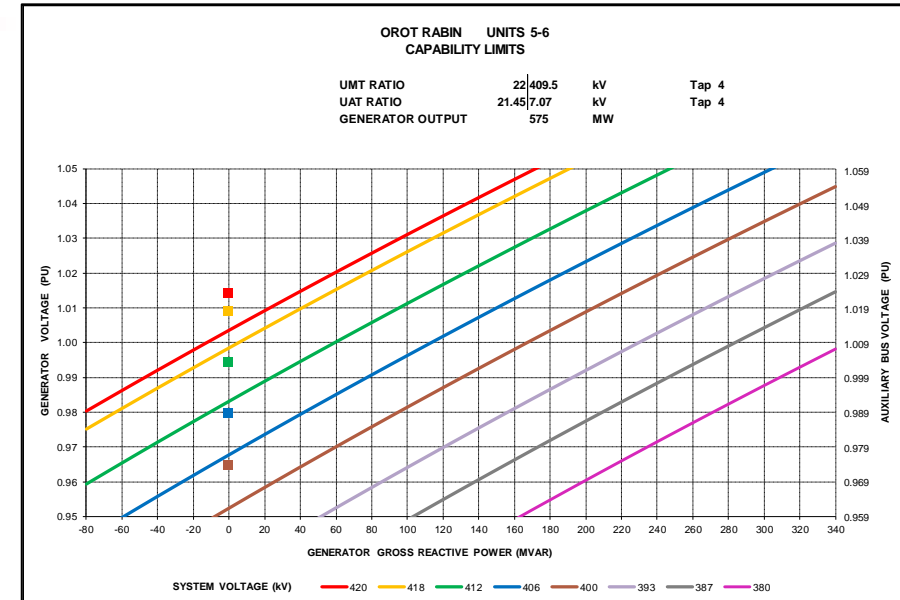
First method chart...

- For UMT at chosen tap 4 and the same gross active load, UAT tap can be further selected
- Secondary vertical axis: auxiliary bus voltage pu
- The sum of all UAT loads to be taken into account

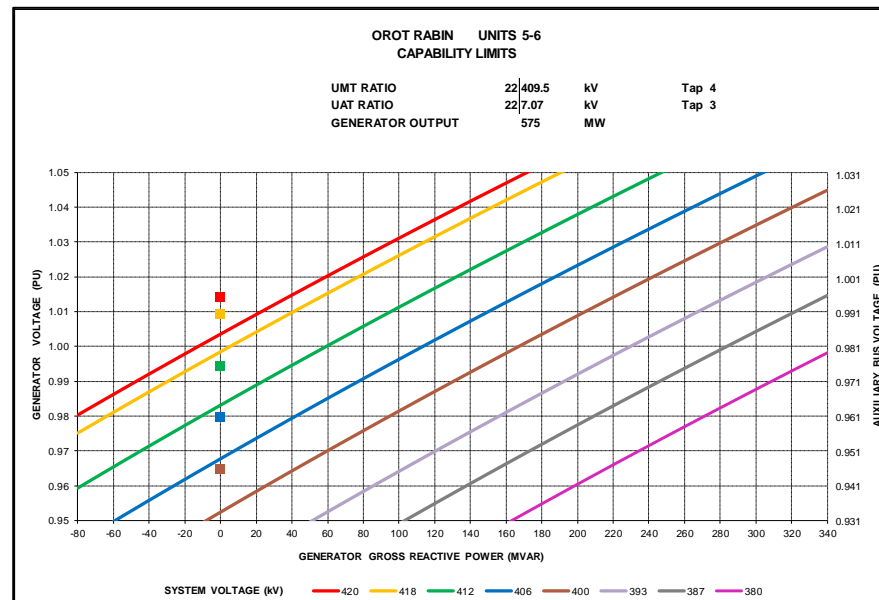


First method analysis...

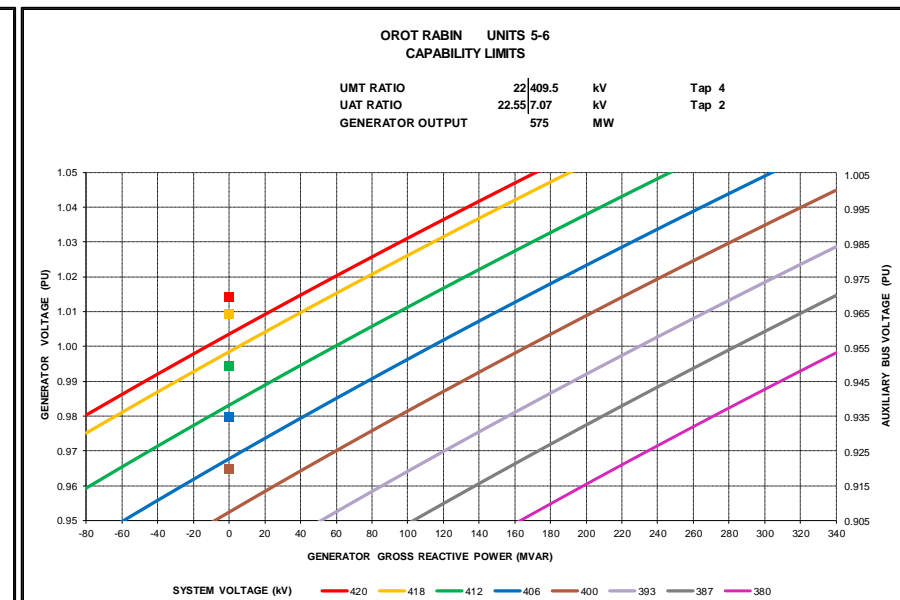
- UAT tap 4: auxiliary bus voltage too high in certain conditions
- UAT tap 3: *preferred* because suitable voltages of 0.93-1.03 pu
- UAT tap 2: bus voltages can drop until about 0.90 pu



UAT at tap 4 (97.5%)



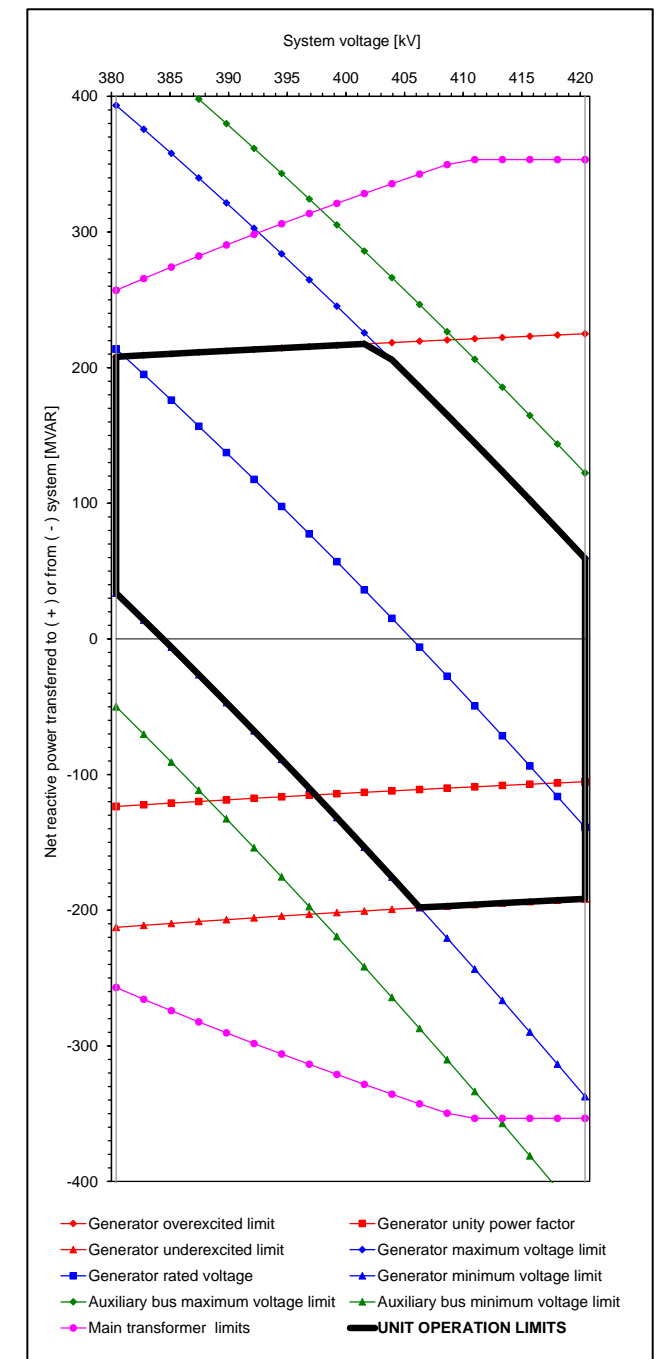
UAT at tap 3 (100.0%)



UMT at tap 2 (102.5%)

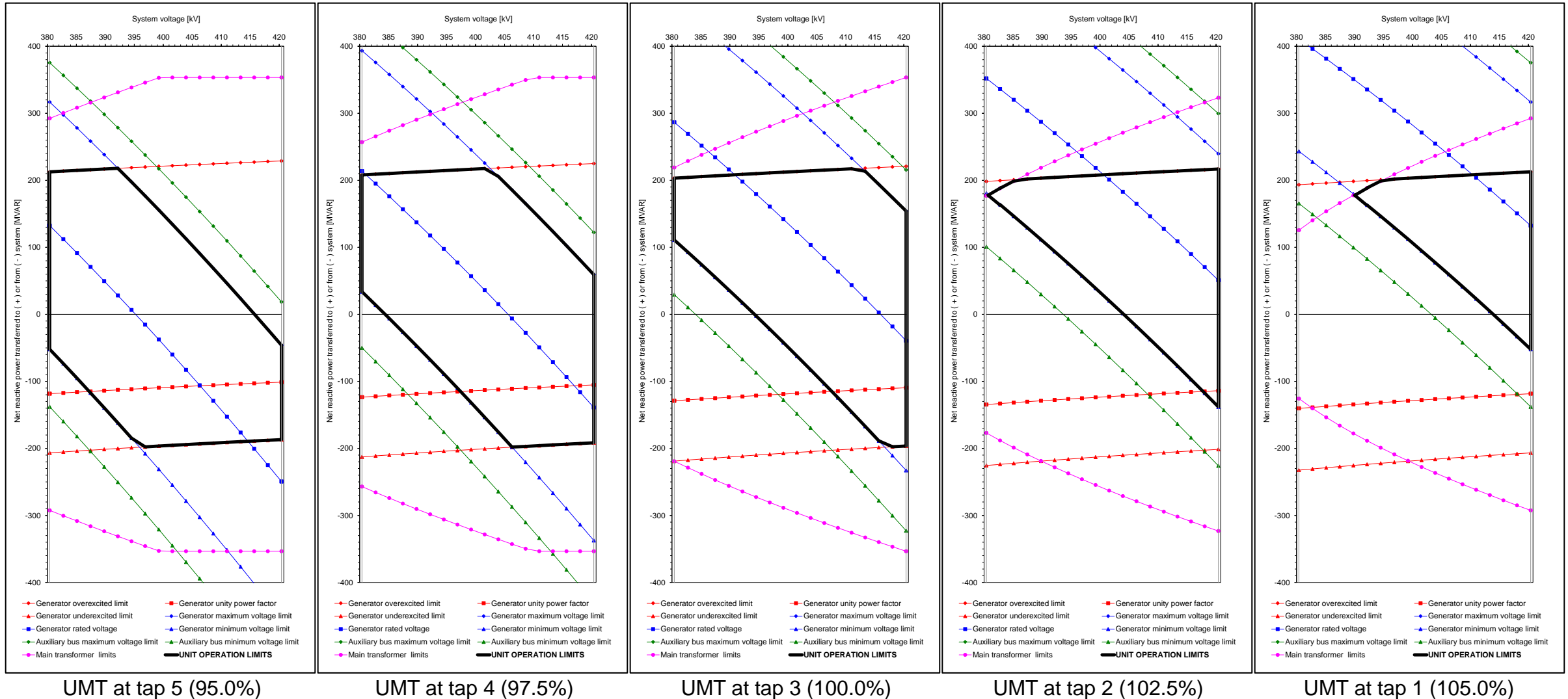
Second method chart

- Shows unit net reactive capabilities (at unit connection point) within system voltage limits, for assumed generator voltage range, certain unit net active load and given UMT tap
- Based on IEEE paper from 1981 and EPRI booklet dated 1987
- Considers more limits: generator voltage, auxiliary bus voltage, generator overexcited / underexcited, main transformer power tapping, transformer over-flux, synchronization capability
- Unit operation range: the most restrictive limitations from all above considerations (thick contour)
- Horizontal axis: system voltage at unit connection point in kV; boundaries: according to Grid Code. Vertical axis: unit net reactive power in MVAR at a certain net active load
- All charts shown for the same case analyzed by the first method



Second method analysis

- The conclusion is the same as by first method: tap 4 offers the *broadest operation possibilities*



UMT at tap 5 (95.0%)

UMT at tap 4 (97.5%)

UMT at tap 3 (100.0%)

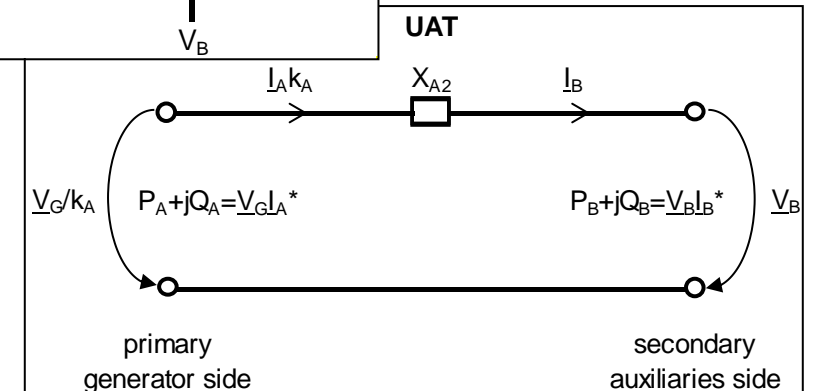
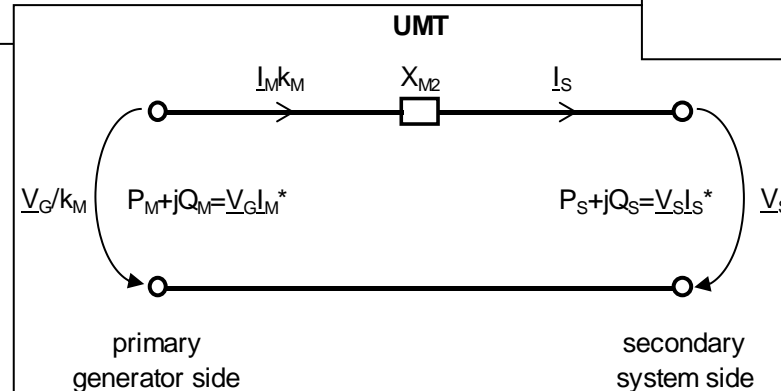
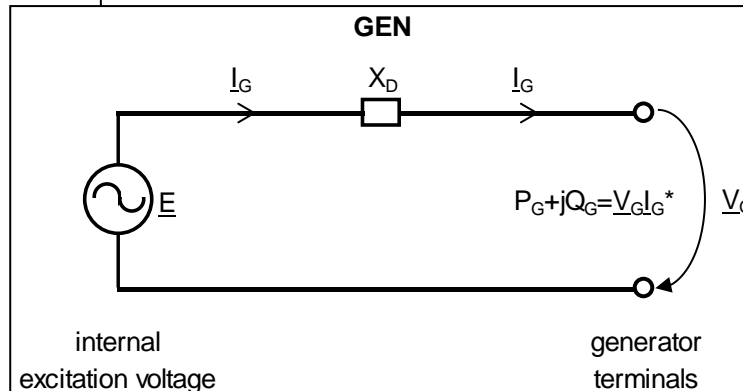
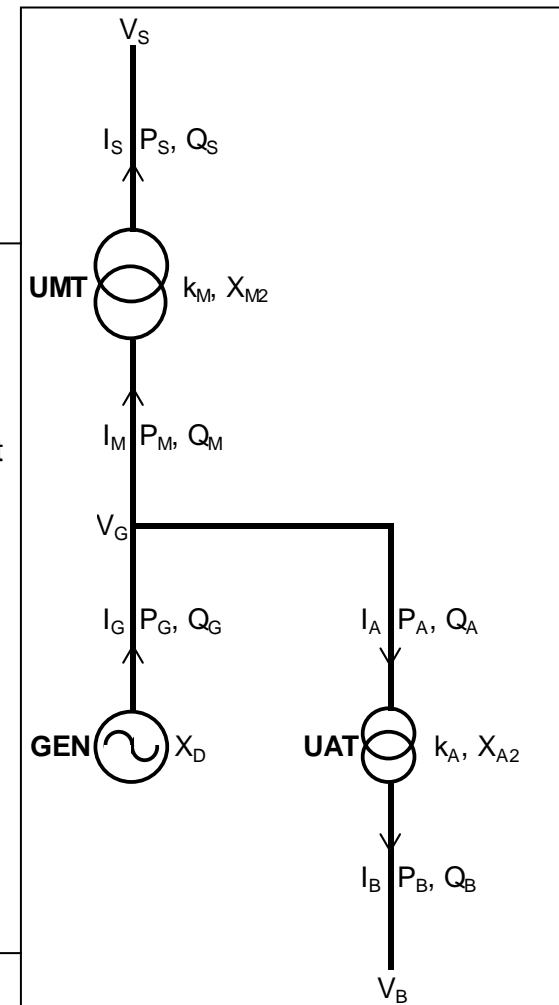
UMT at tap 2 (102.5%)

UMT at tap 1 (105.0%)

Theoretical calculation

List of Symbols

- I_G – generator current
- I_M, I_S – UMT primary, respectively secondary current
- I_A, I_B – UAT primary, respectively secondary current
- V_G, V_S – generator, respectively system (high/extra high) voltage at unit connection point
- V_B – auxiliary bus (medium) voltage
- P_G, Q_G – active and reactive gross power at generator terminals
- P_M, Q_M – UMT primary active and reactive power
- P_S, Q_S – active and reactive net power transferred to / from system
- P_A, Q_A – UAT primary active and reactive power
- P_B, Q_B – UAT secondary active and reactive power
- k_M, k_A – UMT, respectively UAT ratio (at a specific tap)
- $X_{M\%}, X_{A\%}$ – UMT, respectively UAT reactance [percent]
- X_{M2}, X_{A2} – UMT, respectively UAT equivalent reactance viewed from secondary [Ohm]
- X_D – GEN synchronous reactance [pu]
- E - internal generator voltage induced by the field winding flux (excitation voltage)
- (underline text) – used for complex numbers
- * (asterisk symbol) – used for complex conjugate



Excel calculation

Input Data

Fixed rated data (blue):

- S_{MN} , S_{AN} – UMT, respectively UAT rated power [MVA]
- V_{M1N} , V_{M2N} – UMT rated primary voltage, respectively rated secondary voltage [kV]
- V_{A1N} , V_{A2N} – UAT rated primary voltage, respectively rated secondary voltage [kV]
- $X_{M\%}$, $X_{A\%}$ – UMT respectively UAT reactance [percent]
- V_{GN} – GEN rated voltage [kV]
- V_{BN} – rated auxiliary bus voltage [kV]
- S_{GN} – GEN rated apparent power
- Nr_of_UAT connected in parallel (assumed identical)

Range of variable values (green):

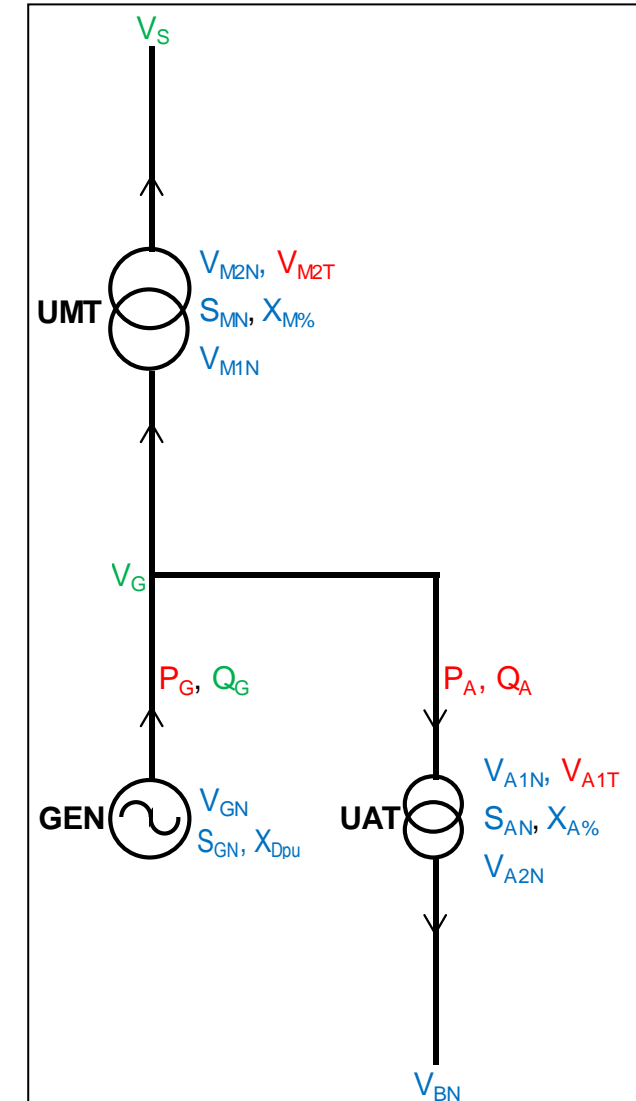
- Q_G – generator gross reactive power range [MVAR]
- V_G – generator terminal voltage range for continuous operation: 0.95 to 1.05 pu
- V_S – system voltage range at unit connection point [kV]

Changeable values (red):

- V_{M2T} – UMT tap secondary voltage [kV] – a particular value for the tap to be analyzed
- V_{A1T} – UAT tap primary voltage [kV] – a particular value for the tap to be analyzed
- P_G – generator gross active power [MW] – a particular value to be analyzed
- P_A , Q_A – UAT primary side active [MW] / reactive [MVAR] loads (total for all UATs)

Output Chart

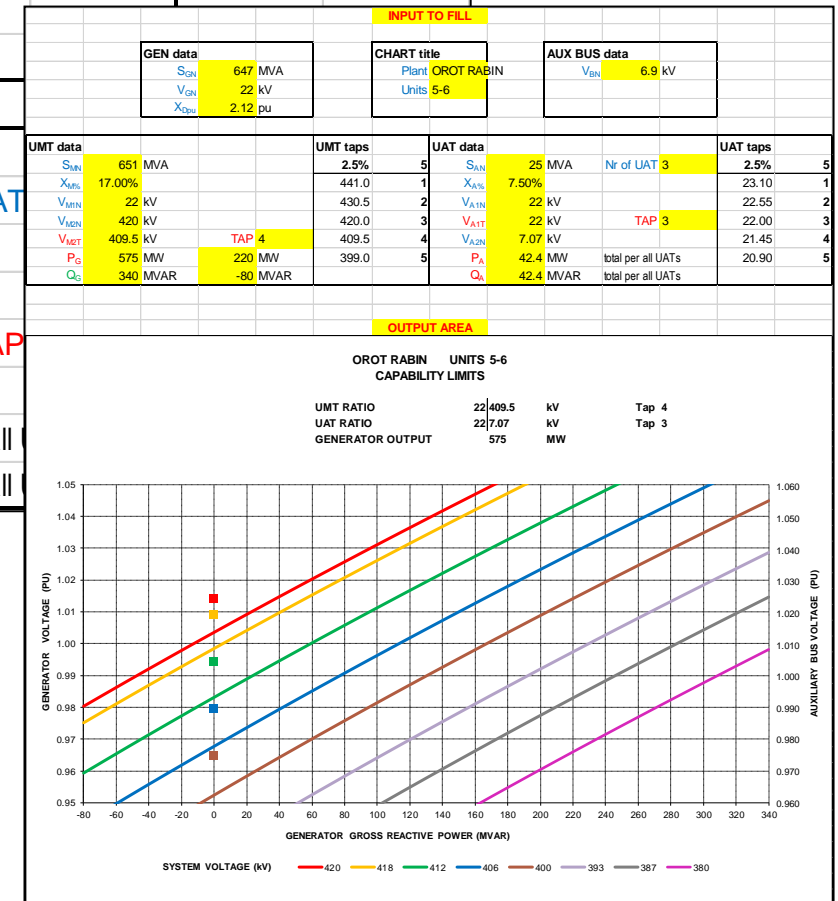
One obtained for each set of changeable (red) input data



Excel screenshot

INPUT TO FILL											
GEN data				CHART title				AUX BUS data			
S_{GN}	647	MVA		Plant	OROT RABIN	V_{BN}	6.9	kV			
V_{GN}	22	kV		Units	5-6						
X_{Dpu}	2.12	pu									
UMT data				UMT taps		UAT data		UAT taps			
S_{MN}	651	MVA		2.5%	5	S_{AN}	25	MVA	Nr of UAT		
$X_{M\%}$	17.00%			441.0	1	$X_{A\%}$	7.50%				
V_{M1N}	22	kV		430.5	2	V_{A1N}	22	kV			
V_{M2N}	420	kV		420.0	3	V_{A1T}	22	kV	TAP		
V_{M2T}	409.5	kV	TAP 4	409.5	4	V_{A2N}	7.07	kV			
P_G	575	MW	220	MW	5	P_A	42.4	MW	total per all		
Q_G	340	MVAR	-80	MVAR		Q_A	42.4	MVAR	total per all		

- For a particular unit, several charts should be obtained and analyzed, one for each set of changeable (red) input values, i.e. for each transformer tap-changer position



Conclusions

- A proper main transformer tap-changer position is critical for optimizing the utilization of the desired range of generator reactive capability.
- The selection of most suitable tap should be performed before operating a new generating unit or when the system operation conditions change.
- The presentation describes two tap selection methods and applies them to the same practical case, confirming the same conclusions are obtained.
- The operation experience achieved during about 30 years demonstrates the accuracy of these tap selecting methods in various power plants.
- The calculations have been performed in Excel, a simple readily accessible tool for field engineers; no doubt that more sophisticated tools are available.
- The first method is usually simpler to implement and analyze. The second method is comprehensive, however it requires a larger amount of work.

Thank you!

Please email me if you are interested in my detailed paper on this subject

reluilie@gmail.com