GENQEC FIELD REVIEW

PRESENTER: JONATHAN M DENMAN

- Spice model development power mosfets, IGBTs JFET etc. Internship APT now Microsemi
- Hydro Generator Overhaul Electrical Engineer, in-house WECC model validation PacifiCorp
- Field Services Representative NERC Testing, Siemens PTI
- Field Services Representative Reivax, NA
- Field Services Representative Basler Electric and formerly E2PSI (Basler Services) -current
- O&M Engineering, Energy Northwest -current

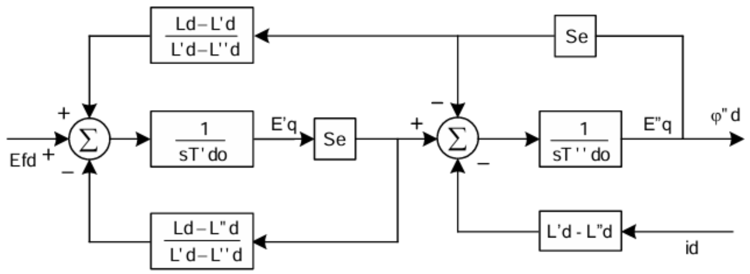
<Public>

Introduced to Quincy during BC Hydro, WAC Bennett excitation system commissioning, June 2025

Basler DECS2100 retrofit of Cutler Hammer ECS2100

Data presented is from a hydroelectric generator tested in 2015, with GENTPJ modeled published, The generator was tested in 2024 with GENQEC model. GENQEC model applied to 2015 data to show vee-curve difference

GENTPJ



$$Se = 1. + fsat(\varphi ag + Kis * It)$$

Q – Axis similar except:

$$Se = 1. + \frac{Lq}{Ld} * fsat(\varphi ag + Kis * It)$$

- JOHN UNDRILL DEVELOPED
- ARMATURE REACTION SATURATES FLUX WITHIN STATOR CORE FINGERS.
- USES A CURRENT SATURATION MULTIPLIER KIS TO REPRESENT THIS PHENOMENA
- A DEPARTURE FROM POTIER REACTANCE
- IMAGE ON THE LEFT ARE DIAMOND COIL WINDINGS BEING INSTALLED

GENTPJ RESULTS

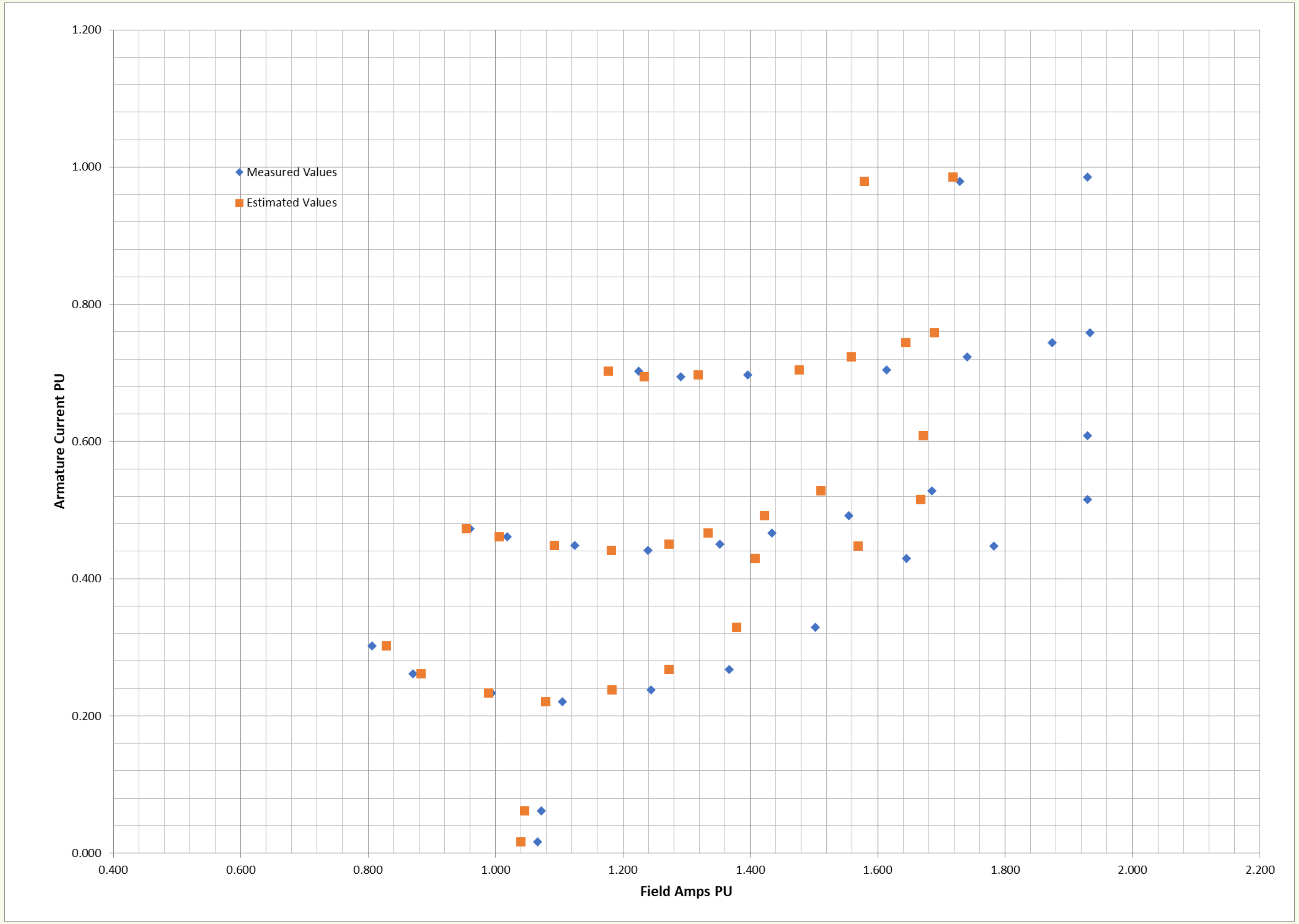
Steady State Parameters				
Xq	0.81	Kis	0	
Xd	1.29	Se1	0.0878	
Xl	0.19	Se12	0.168	
Ra	0.005			
Measured IFD base	285	amps		
MVA base	38	MVA		
Vt	11	KV		
Ibase	1994.48	Amps		

pu	pu	pu	pu	pu	pu													
Vab	Ifd	Ia	KW	Kvar	MVA	Pf radian	Delta radians	Id	Iq	Vd	Vq	El	Sat funct	Sd	Sq	Xds	Xqs	Calc Ifd
0.99	1.066	0.016	0.016	0.004	0.0163	0.245	0.0129849	0.0042	0.0159	0.0129	0.9899165	0.9908	0.15	0.1486	0.0933	1.1477	0.7571	1.0388
0.9899	1.072	0.061	0.061	0.005	0.0608	0.0867	0.0497311	0.0083	0.0608	0.0492	0.9886852	0.9913	0.15	0.1487	0.0933	1.1476	0.7571	1.0427
0.9906	1.105	0.221	0.219	0.003	0.219	0.0145	0.1781178	0.0423	0.217	0.1755	0.9749634	0.9932	0.15	0.149	0.0936	1.1474	0.757	1.0703
0.9941	1.244	0.238	0.221	0.085	0.2367	0.3661	0.1672654	0.1211	0.2051	0.1655	0.9802171	1.0123	0.1503	0.1521	0.0955	1.1447	0.7559	1.1729
0.9962	1.367	0.268	0.216	0.157	0.2671	0.6287	0.1542176	0.1892	0.1901	0.153	0.9843591	1.028	0.1505	0.1547	0.0971	1.1426	0.7551	1.2612
0.9988	1.502	0.329	0.226	0.238	0.3287	0.8114	0.1516295	0.2702	0.1879	0.1509	0.987358	1.0461	0.1507	0.1576	0.099	1.1402	0.7542	1.3643
0.911	1.645	0.429	0.232	0.315	0.391	0.9369	0.1695934	0.3837	0.1922	0.1538	0.8979303	0.9791	0.1437	0.1407	0.0883	1.1543	0.7597	1.3915
1.005	1.782	0.448	0.229	0.387	0.4498	1.0354	0.1379906	0.4127	0.1732	0.1382	0.9954469	1.0801	0.1512	0.1633	0.1025	1.1356	0.7523	1.5492
1.0091	1.930	0.515	0.238	0.462	0.52	1.0945	0.1360574	0.4858	0.172	0.1369	0.9997654	1.0981	0.1515	0.1664	0.1045	1.1331	0.7514	1.6446
0.9874	0.994	0.234	0.220	-0.069	0.2307	-0.302	0.1918374	-0.026	0.2323	0.1883	0.969251	0.9762	0.1498	0.1462	0.0918	1.1497	0.7579	0.9803
0.9844	0.870	0.261	0.208	-0.151	0.2569	-0.63	0.1967707	-0.11	0.2369	0.1924	0.9653684	0.9571	0.1495	0.1431	0.0898	1.1523	0.7589	0.8733
0.9823	0.806	0.303	0.220	-0.199	0.2972	-0.736	0.2194481	-0.149	0.2631	0.2138	0.9587156	0.9458	0.1493	0.1412	0.0887	1.1539	0.7595	0.8172
0.99	1.239	0.441	0.437	0.009	0.4369	0.0211	0.3433069	0.1573	0.4124	0.3332	0.9322302	0.9975	0.15	0.1496	0.0939	1.1469	0.7568	1.1649
0.9869	1.125	0.448	0.437	-0.068	0.4424	-0.155	0.3674209	0.0944	0.4382	0.3545	0.9210397	0.9796	0.1497	0.1467	0.0921	1.1493	0.7577	1.0755
0.9842	1.018	0.462	0.432	-0.142	0.4543	-0.318	0.3884744	0.0327	0.4604	0.3728	0.9108485	0.9627	0.1495	0.1439	0.0904	1.1516	0.7586	0.9888
0.9826	0.960	0.473	0.426	-0.185	0.4647	-0.409	0.4004738	-0.004	0.4729	0.3831	0.9048866	0.9527	0.1494	0.1423	0.0894	1.153	0.7591	0.9371
0.9931	1.353	0.451	0.439	0.084	0.4475	0.1893	0.3245929	0.2215	0.3924	0.3167	0.9412324	1.0149	0.1502	0.1525	0.0957	1.1445	0.7558	1.2538
0.9993	1.434	0.466	0.447	0.130	0.4659	0.2833	0.3160057	0.263	0.385	0.3105	0.949793	1.0297	0.1507	0.1552	0.0975	1.1422	0.7549	1.315
1.0022	1.554	0.492	0.450	0.203	0.4934	0.4238	0.3008193	0.3263	0.3686	0.2969	0.9571779	1.0463	0.151	0.1579	0.0992	1.14	0.7541	1.4011
1.0045	1.685	0.528	0.453	0.277	0.5307	0.5482	0.287661	0.392	0.3542	0.285	0.9631816	1.0624	0.1511	0.1606	0.1008	1.1378	0.7532	1.4886
1.009	1.930	0.609	0.461	0.406	0.6141	0.7229	0.2682852	0.5093	0.3333	0.2675	0.9729049	1.0911	0.1515	0.1653	0.1038	1.134	0.7517	1.6442
0.9935	1.396	0.697	0.692	-0.028	0.6927	-0.041	0.5251821	0.3246	0.617	0.4981	0.859648	1.0004	0.1503	0.1503	0.0944	1.1463	0.7565	1.2913
0.999	1.614	0.704	0.692	0.124	0.7032	0.1779	0.470043	0.4249	0.5612	0.4525	0.8906573	1.0345	0.1507	0.1559	0.0979	1.1416	0.7547	1.4486

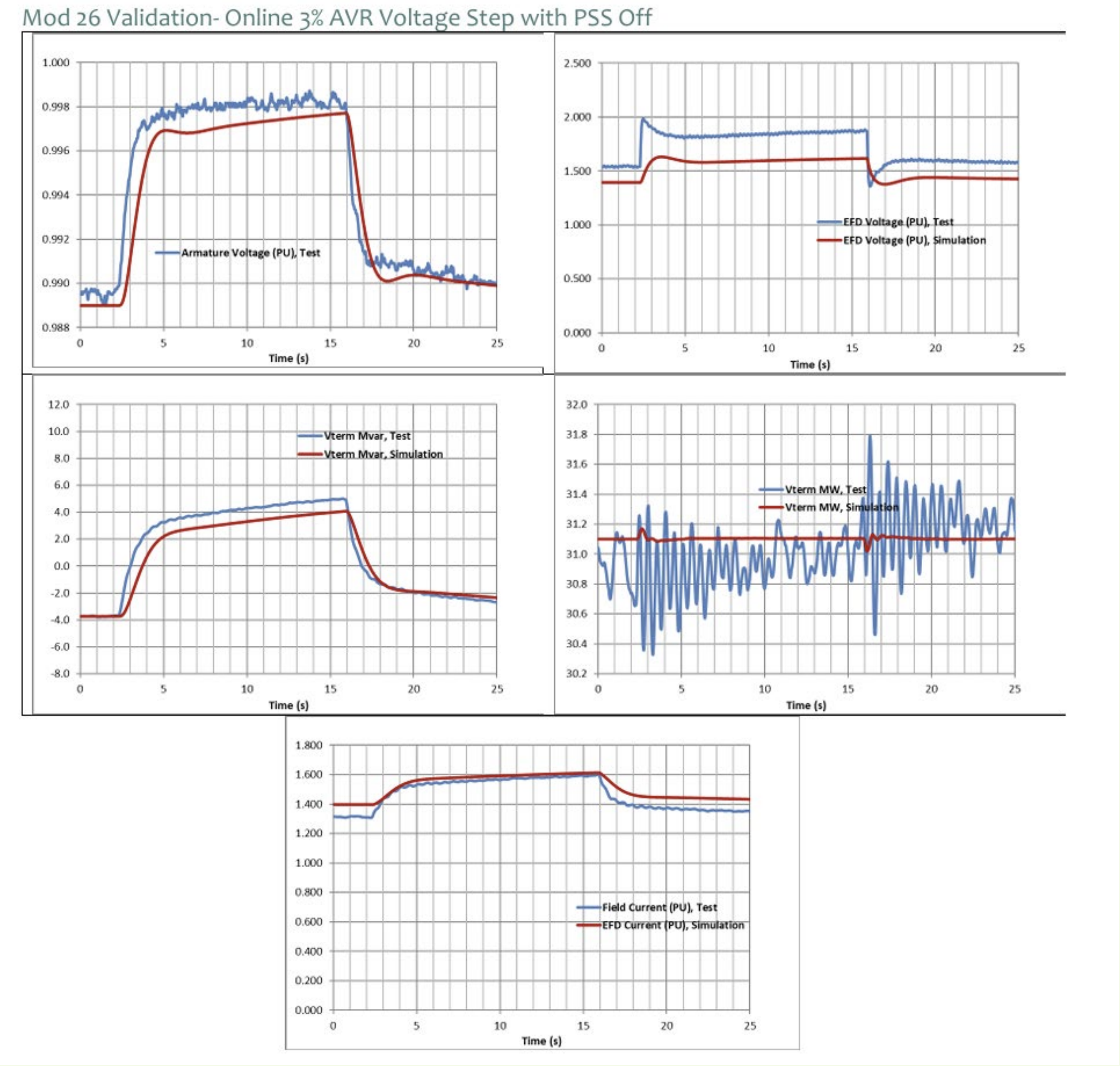
K_{is} ($0 \le K_{is} < 1$), current multiplier for saturation calculation

- PURPOSE -ARMATURE REACTION AFFECTS FLUX WITHIN STATOR CORE FINGERS
- USES A CURRENT SATURATION MULTIPLIER KIS TO REPRESENT THIS PHENOMENA
- A DEPARTURE FROM POTIER REACTANCE, OPEN CIRCUIT AND SHORT CIRCUIT TESTING PERFORMED DURING GENERATOR COMMISSIONING. WHAT'S THE ALTERNATIVE MANUFACTURER TEST?
- INACCURATE AT THE PERIPHERY OF VEE-CURVE ESTIMATES. MAKE UP THE DIFFERENCE BY MANIPULATING SATURATION VALUES, “ADJUSTING THE SIMULATION KNOBS”
- TYPICALLY SEE THE SATURATION MULTIPLIER INTENTIONALLY SET TO ZERO IN STUDIES PUBLISHED BY OTHER GROUPS. KIS SKEWS THE SIMULATED VEE-CURVE TO THE LEFT, INCREASING MEASURED VS. SIMULATED ERROR
- VEE-CURVE SHOWN USING GENTPJ.

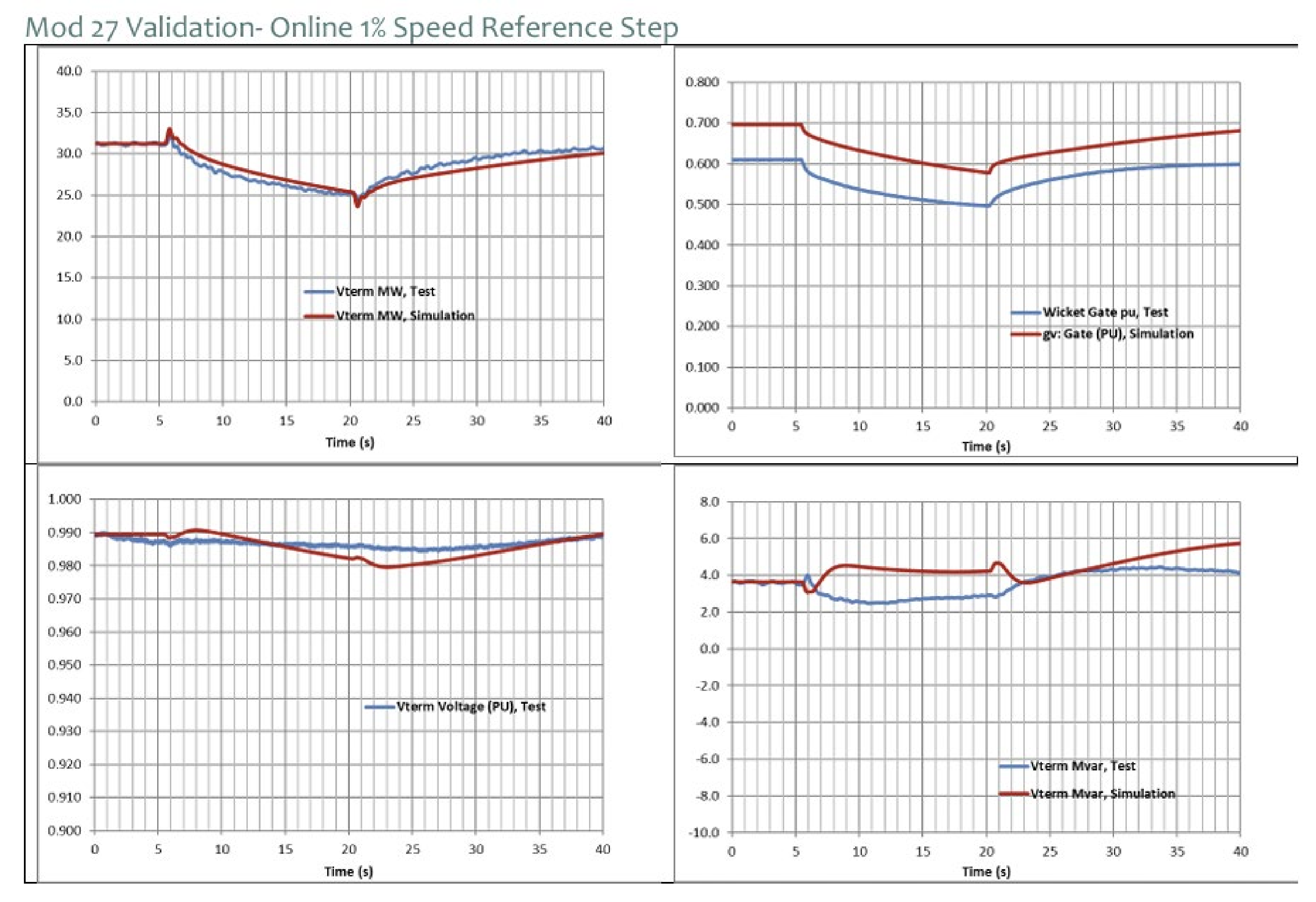
VEE-CURVE 2015 DATA GENTPJ



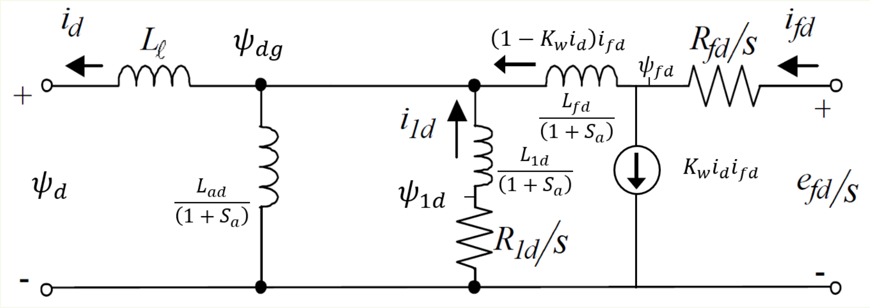
2015 GENTPJ, 3% AVR STEP



2015 GENTPJ, 1% GOV STEP



GENQEC



Reactances (per unit)		Saturated	Unsaturated
Synchronous direct axis	x_d	1.655	1.833
Transient direct axis	x'_d	0.310	0.352
Sub-transient direct axis	x''_d	0.230	0.267
Synchronous quadrature axis	x_q	1.629	1.804
Transient quadrature axis	x'_q	0.488	0.555
Sub-transient quadrature axis	x''_q	0.228	0.265
Armature leakage, steady-state	x_l	0.207	0.218
Zero sequence	x_0	0.108	0.113
Negative sequence	x_2	0.229	0.266
Potier Reactance	x_p	----	0.351

Resistance and Capacitance.

Armature:		
Zero Sequence Resistance (p.u.)	r_0	0.00241
Positive Sequence Res. (p.u.)	r_1	0.00322
Negative Sequence Res. (p.u.)	r_2	0.03187
DC Resistance @ 75°C (Ω/phase)	r_a	0.00242
Capacitance to ground (µF/phase)		0.1810
Field:		
DC Resistance @ 75°C (Ω)	r_f	0.10170

Excitation/Field Data

Minimum Exciter Rating voltage (V)	350
Minimum Exciter Rating power (kW)	1130
Generator field voltage at rated output (V)	317
Generator field current at rated output (A)	3018
Field current required to put magnetic flux across air gap (A)	1109
Field current at no load & rated voltage (A)	1228
Saturation factor at rated voltage (p.u.)	0.107
Saturation factor at 1.2 times rated voltage (p.u.)	0.421

Inertia Constants

Generator and Exciter: rotor kinetic energy at rated speed per kVA of rated output, *H* Constant (kW•sec/kVA)	0.821

Time Constants (sec)		
Transient, open circuit direct axis	T'_{do}	5.208
Sub-transient, open circuit direct axis	T''_{do}	0.047
Transient, L-N short-circuit direct axis	T'_{d1}	1.553
Sub-transient, L-N s.c. direct axis	T''_{d1}	0.041
Transient, L-L short-circuit direct axis	T'_{d2}	1.362
Sub transient, L-L s.c. direct axis	T''_{d2}	0.040
Transient, 3-phase s.c. direct axis	T'_{d3}	0.881
Sub transient, 3-phase s.c. direct axis	T''_{d3}	0.035
Transient, open-circuit quadrature axis	T'_{qo}	0.579
Sub-transient, open-circuit quad. axis	T''_{qo}	0.075
Transient, L-N, s.c. quadrature axis	T'_{q1}	0.223
Sub-transient, L-N, s.c. quadrature axis	T''_{q1}	0.051
Transient, L-L, s.c. quadrature axis	T'_{q2}	0.204
Sub-transient, L-L s.c. quadrature axis	T''_{q2}	0.048
Transient, 3-phase s.c. quadrature axis	T'_{q3}	0.157
Sub-transient, 3 ph. s.c. quadrature axis	T''_{q3}	0.035
DC component of short-circuit current	T_{A3}	0.381
DC component of L-N fault	T_{A1}	0.314
DC component of L-L fault	T_{A2}	0.381

Short-circuit Torque Data.
Line-to-Line s.c. at 105% rated voltage

T_1 = 5.445 (p.u.)	α = 4.243 (1/sec)
T_2 = 2.722 (p.u.)	β = 3.235 (1/sec)
T_3 = 0.653 (p.u.)	γ = 3.838 (1/sec)

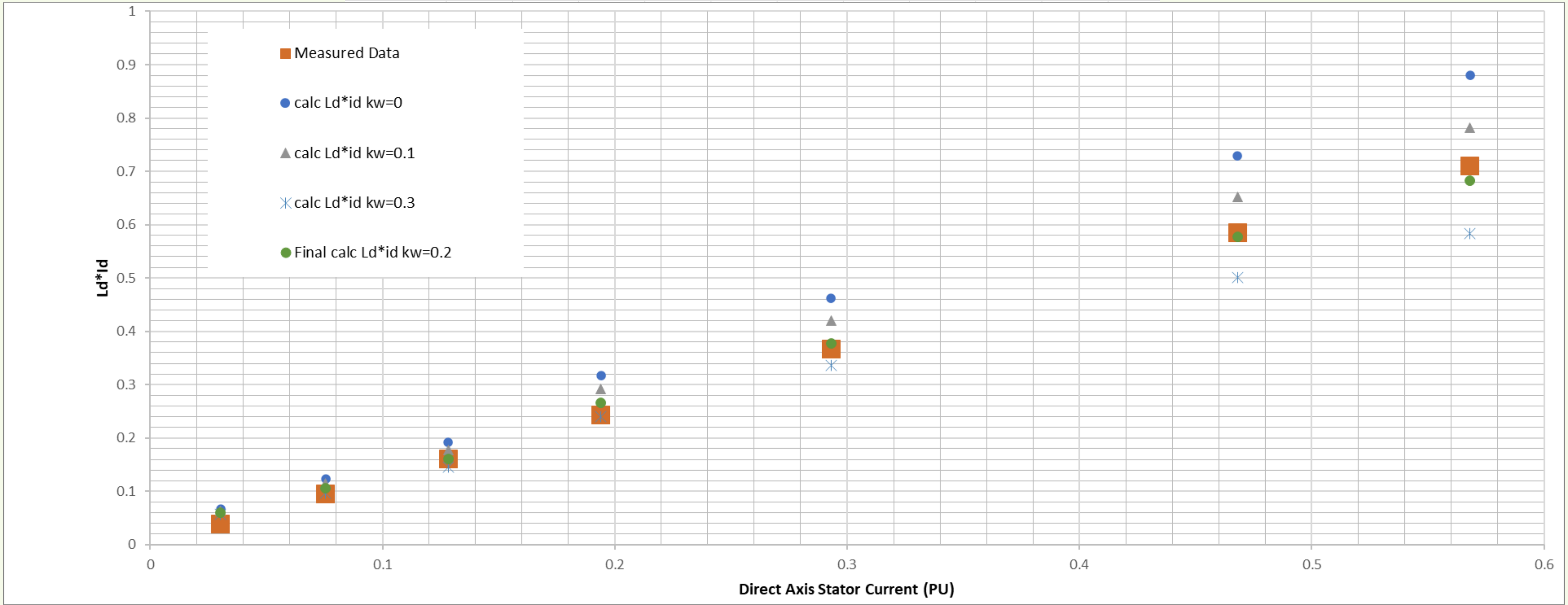
S_{MVA} – generator rated apparent output (MVA)
T_{sc} – electromagnetic torque applied to shaft during Line-to-Line s.c. transient (Mega-N•m)
Ω_{shaft} – shaft speed (Rad./sec.)
t – time (sec.)
T_0 – constant magnetic torque component (Per unit torque). This coefficient is numerically equal to the generator rated Power Factor
ω – voltage angular frequency $\omega = 2\pi \cdot f$, *where f is rated voltage frequency in Hz.*

$$T_{SC} = \frac{S_{MVA}}{\Omega_{shaft}} \cdot [-T_0 + T_1 \cdot e^{-\alpha t} \cdot sin(\omega t) -$$

- **WANG, QUINCY PARTICIPATED IN ITS DEVELOPMENT**
- **RE-INTRODUCES POTIER REACTANCE PRINCIPLE. POTIER REACTANCE CAN BE TYPICALLY MEMORIALIZED WITHIN COMMISSION REPORTS OR GENERATOR SPECIFICATIONS**
- **COMPATIBLE WITH OLDER GENERATION MODELS.**
- **GENQEC IS NOT A MODEL BASED UPON A POSTULATE REGARDING FLUX VARIANCE AT THE GENERATOR IRON CORE FINGERS. GENQEC IS AN IMPROVEMENT OF OLDER MODELS.**
- **APPRECIATIVE OF THE WECC 2021, WHITE PAPER ON GENQEC**

2024 GENQEC TEST

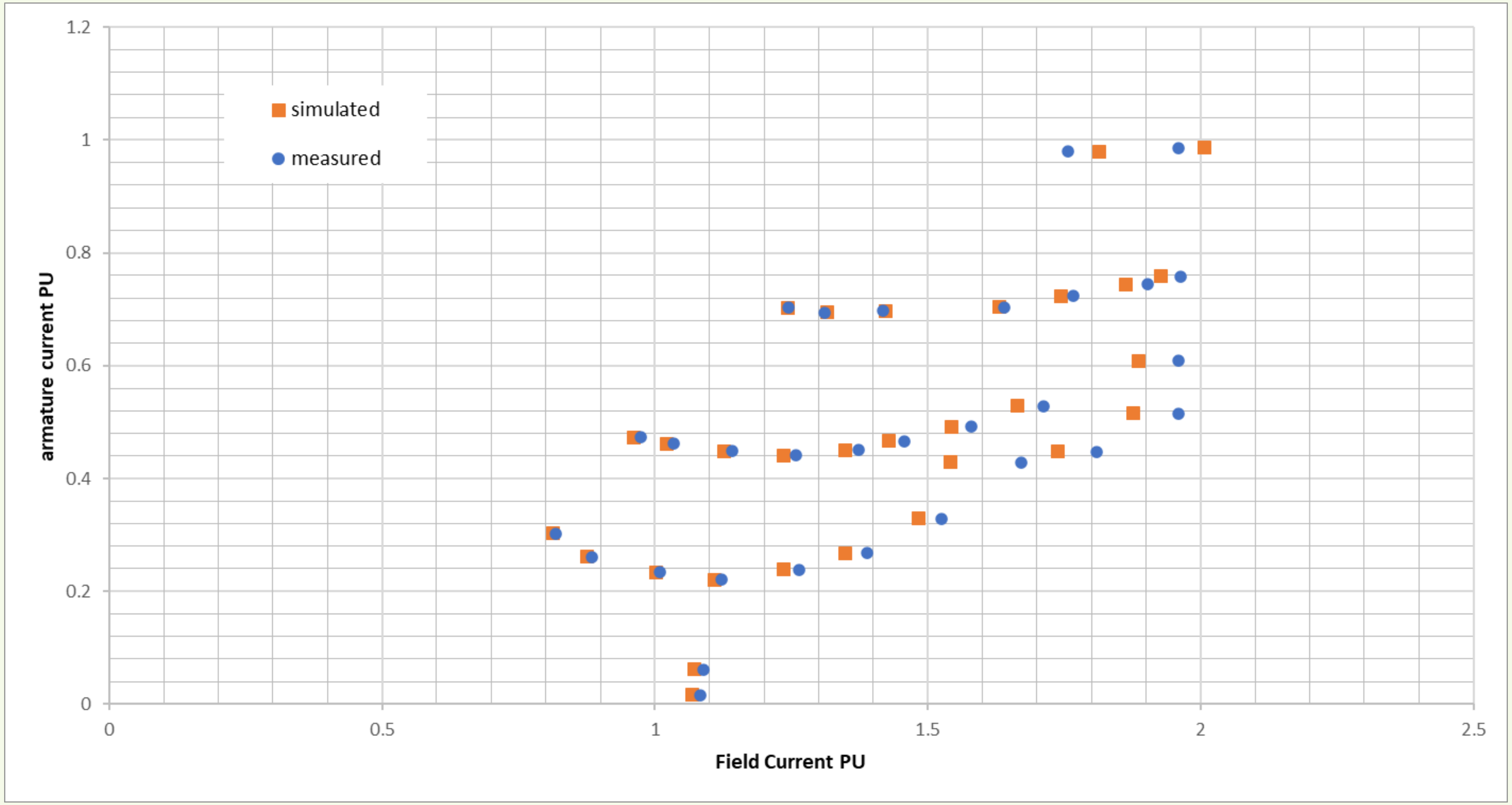
			Steady State Parameters				Saturation Eq	
			Xq	0.79			B	4.589502
			Xd	1.25	Se1	0.0869	A	0.000883
			Xl	0.15	Se12	0.2176		
			Ra	0.003				
		Measured IFD base		280.6	amps		KW	
38	MVA						0.2	
11	KV							
1994.482748	Amps							



VEE-CURVE 2015 DATA GENQEC MODEL

(IDENTICAL DATA, DIFFERENT MODEL) USING KW = 0.2 FOUND DURING 2024 TEST

			Steady State Parameters				Saturation Eq	
			Xq	0.81	Kis	0.3	B	0.5408
			Xd	1.29	Se1	0.0878	A	0.0878
			Xl	0.19	Se12	0.168		
			Ra	0.005				
			Measured IFD base	285	amps			
MVA								
base	38	MVA						
Vt	11	KV						
Ibase	1994.48	Amps						



2024 GENQEC 2% AVR STEP

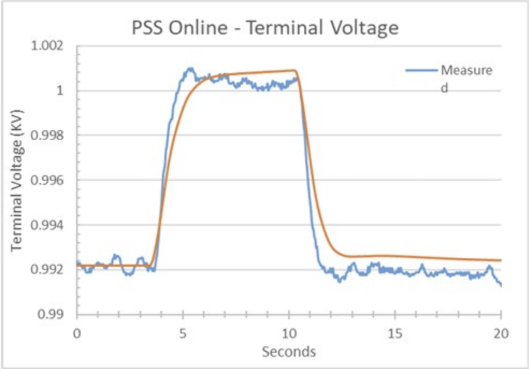


Figure 5-5. Test 3 - Voltage

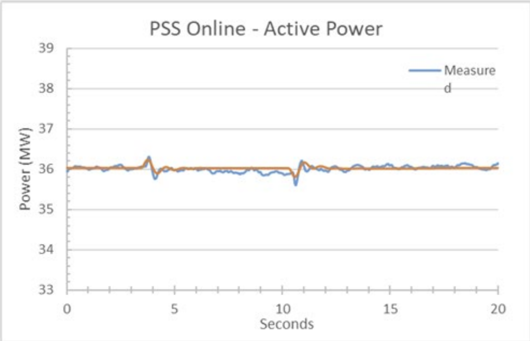
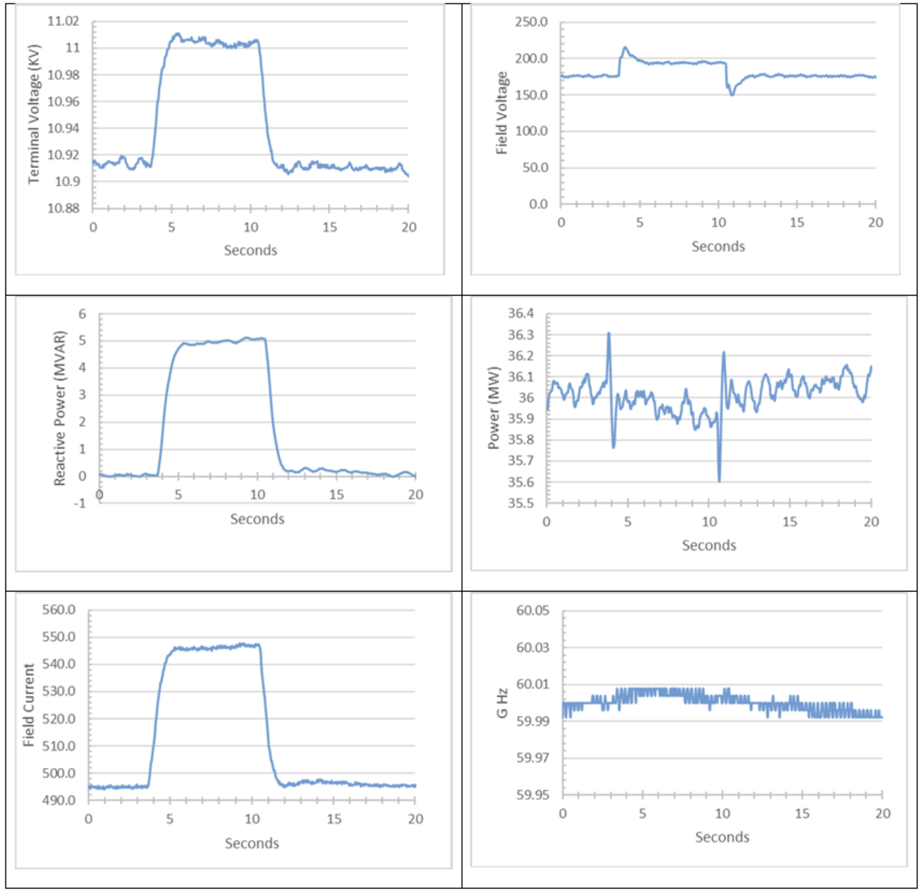


Figure 5-6. Test 3 – Real Power (MW)



2024 GENQEC, 0.5% GOV STEP

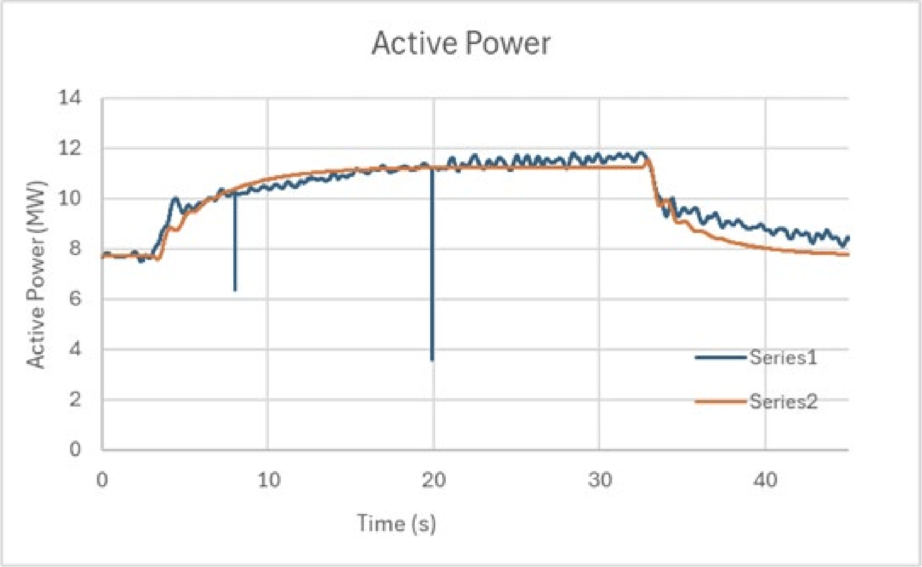


Figure 6-1. Speed Reference Step Response – Real Power Output (MW)

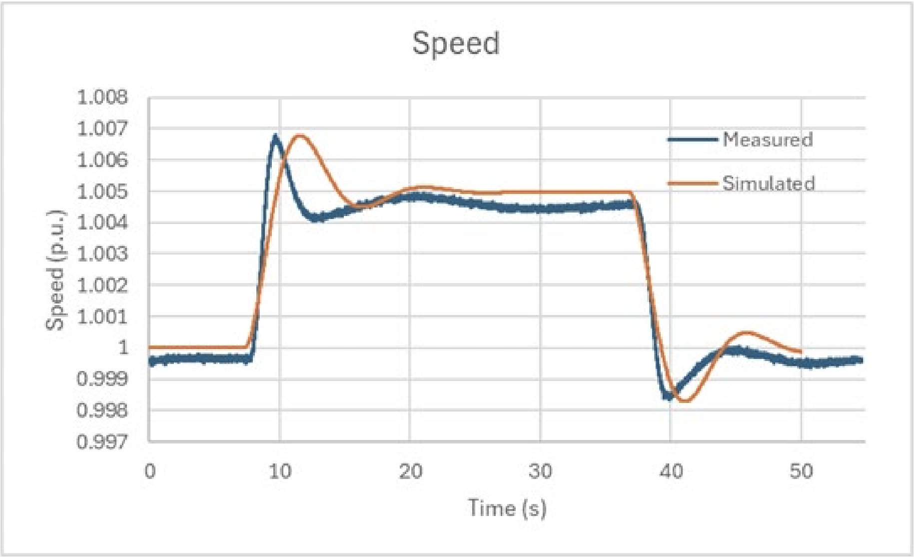
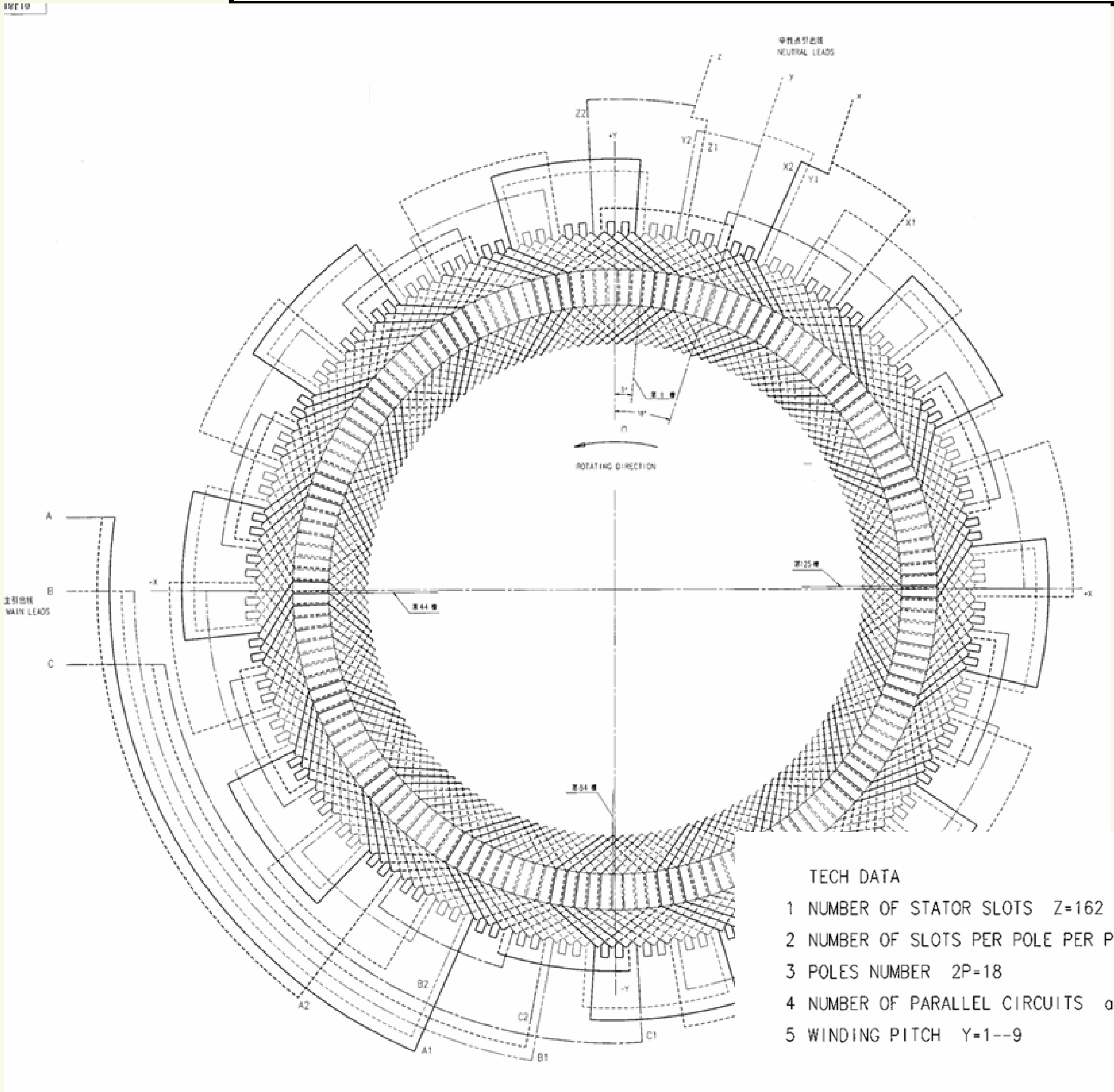


Figure 6-2. Speed Reference Step Response – Real Power Output (MW)

INSPECTING THE KIS, FLUX PINCHING IDEA



TECH DATA

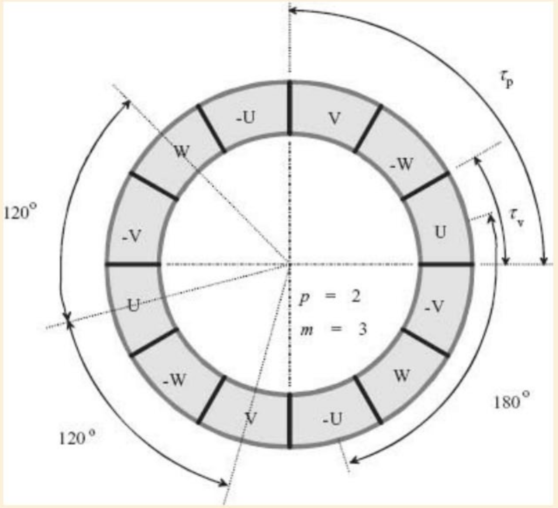
1 NUMBER OF STATOR SLOTS Z=162
2 NUMBER OF SLOTS PER POLE PER PHASE Q=3
3 POLES NUMBER 2P=18
4 NUMBER OF PARALLEL CIRCUITS a=2
5 WINDING PITCH Y=1--9

The winding arrangement of salient pole generators –double layer Diamond coils typical design for hydro machines

18 poles (7200/18) = 400 RPM

162 slots/(3ph*18) = 3 slots/Zone

Figure 2.5 Division of the periphery of a three-phase, four-pole machine into phase zones of positive and negative values. The pole pitch is τ_p and phase zone distribution τ_v. When the windings are located in the zones, the instantaneous currents in the positive and negative zones are flowing in opposite directions.

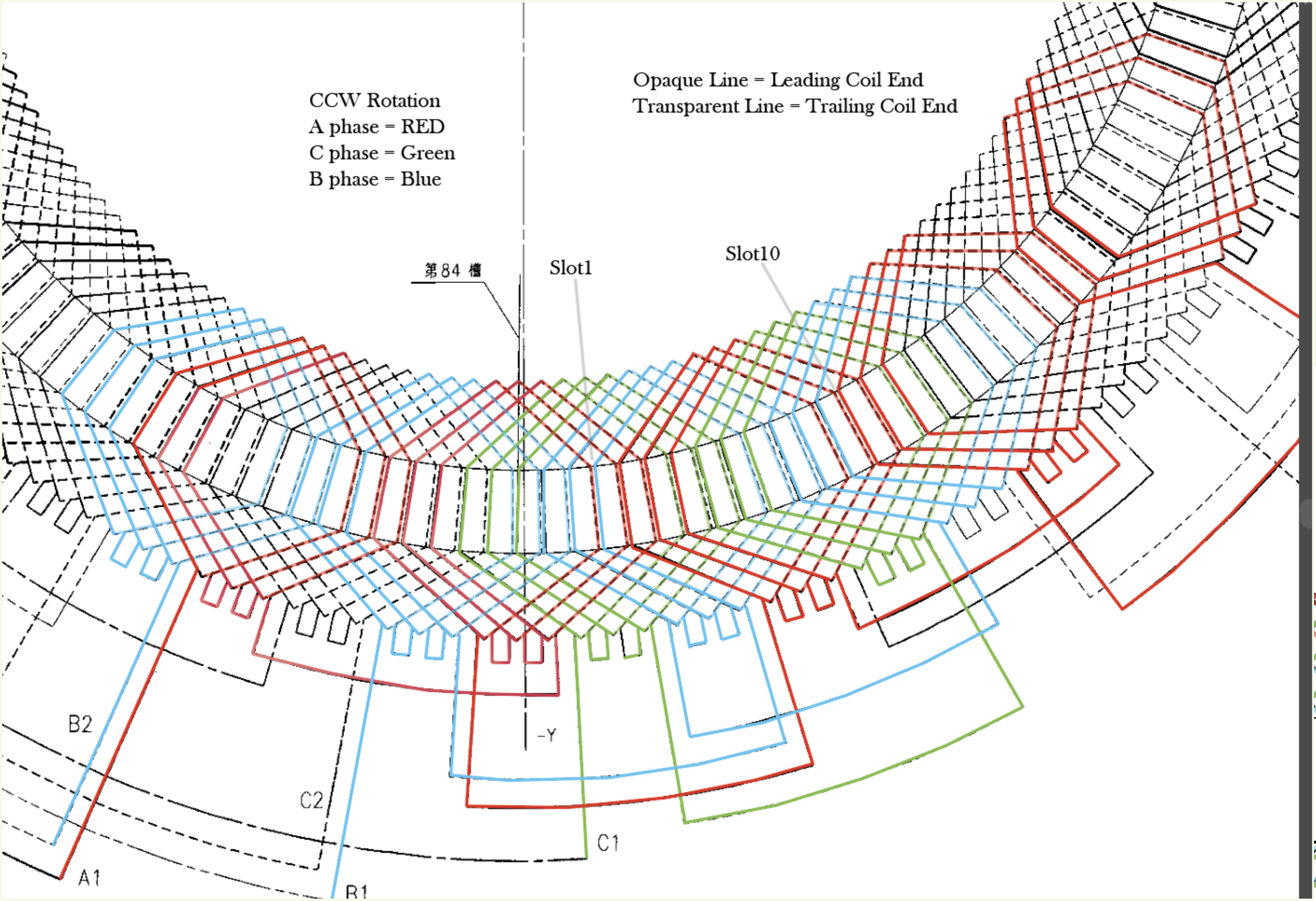


The phase zone distribution is written as

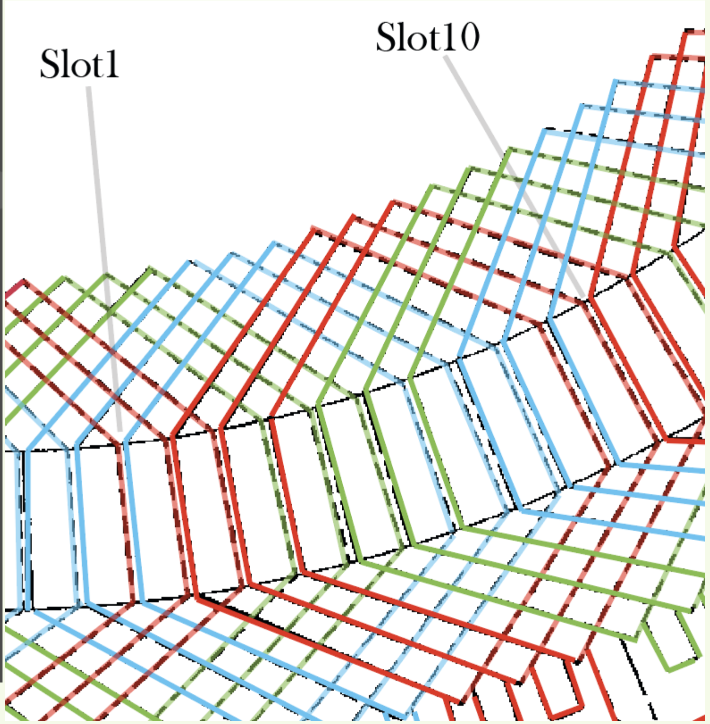
$$\tau_v = \frac{\tau_p}{m}. \qquad (2.4)$$

The number of zones will thus be $2pm$. The number of slots for each such zone is ex-

INFORMATION FROM THE STATOR WINDING DIAGRAM



- A single Zone **appears** to be about 4 slots, 2 Slots contain an exclusive phase. The rotor pole span should be relatively similar 4 poles
- Stator coil span is 9 Slots
- Red, Green, Blue in CCW rotation. Generator is ACB wound



INFORMATION FROM THE STATOR WINDING DIAGRAM

- 3 slot winding group with top and bottom coil group offset. Each A-phase zone appears to reside in 4 slots rather than 3.
- Rotor shoe appears to be about 4 Slots in Span. Be mindful of the physical width due to the rotor copper coil.

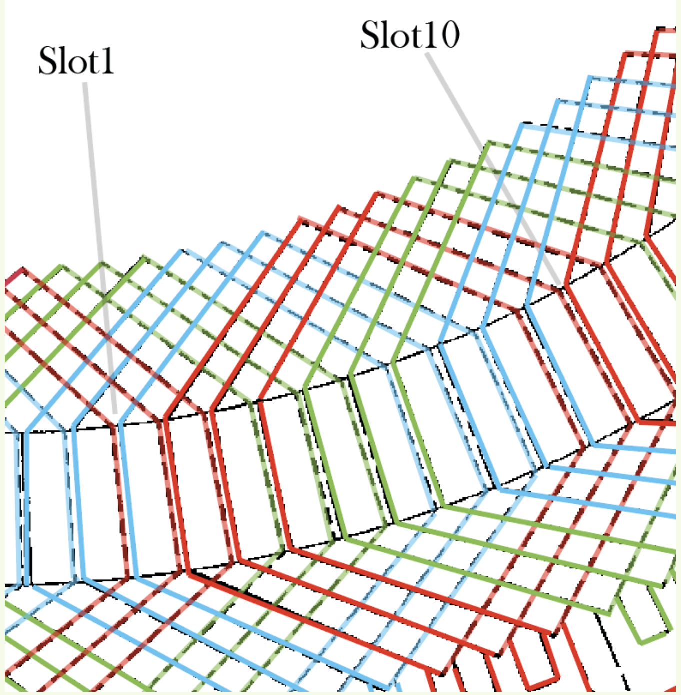
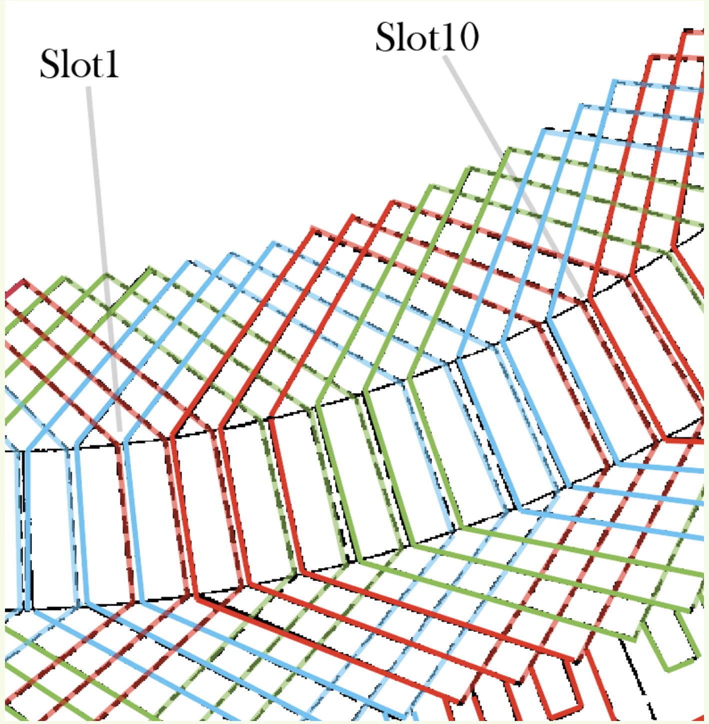


CHART REPRESENTATION SLOTS 1 TO 10



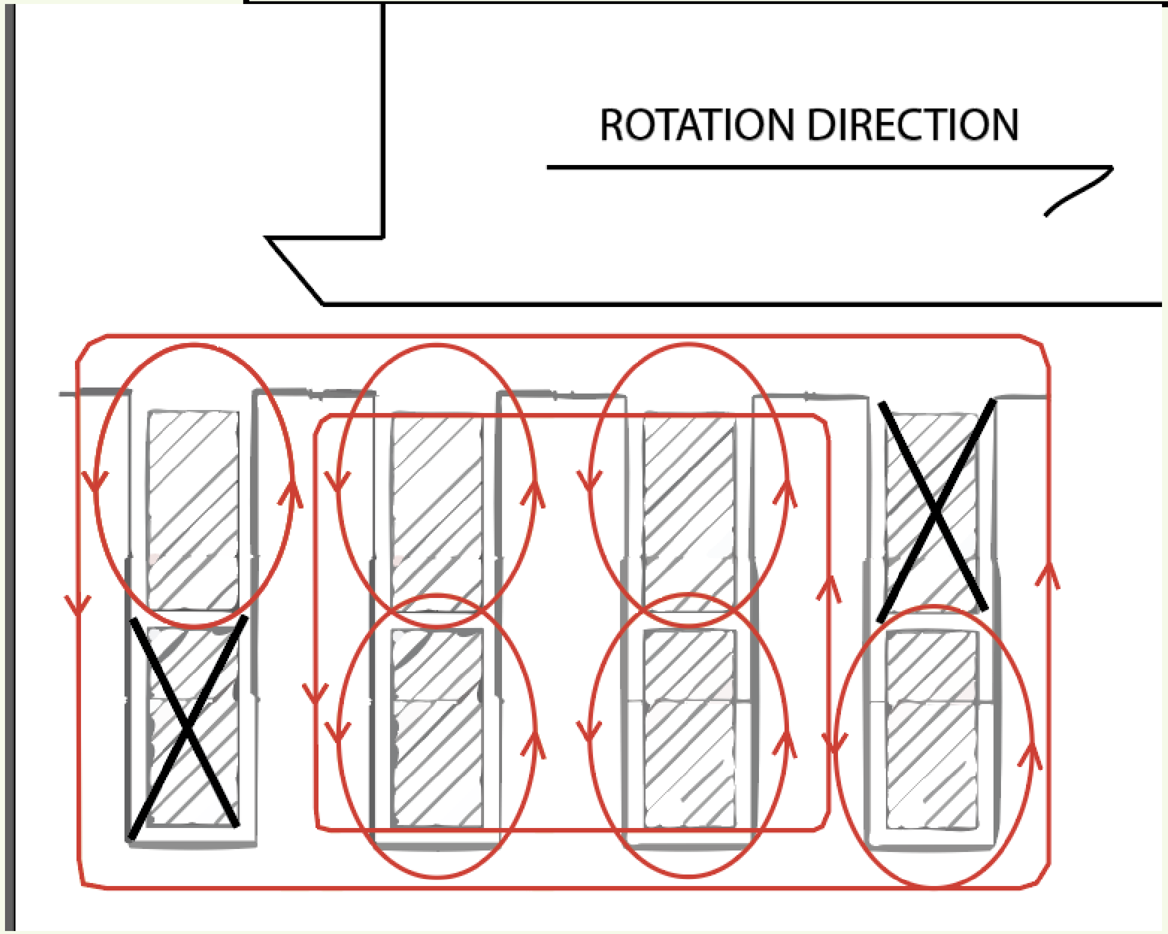
Looking at the Spreadsheet representation of the coils in each slot shows the rotor center axis aligned with the A-phase MMF center axis. Coils in Slot 2 and 3 Have a Leading and trailing coil side.

This generator has only 2 parallel strings of coils. The leading and trailing edge coil sides are part of a series of A phase coils. Currents flow in slots 2 and 3 in the same direction.
Phase A (Red) shares a coil slot with another phase.

For a phase the flux direction of phase coil ends in slots 1 through 4 have the same polarity

Slot#	1	2	3	4	5	6	7	8	9	10
Top Coil End	B	A	A	A	C	C	C	B	B	A
Bottom Coil End	a	a	a	c	c	c	b	b	b	b
		rotor								

CHART REPRESENTATION SLOTS 1 TO 10



Short pitching and special distribution leakage flux a better explanation for Saturation dependency to generator loading?

- Rotor is egregiously offset to show power angle.

The idea of flux gradient across stator tooth at the periphery may be an explanation to variance of saturation due to loading. My experience with generators of different vintages, older generators seem to work better than newer generators. Xq is generally smaller on older generators. Small Xq means small power angle changes induce larger armature reaction current.

Something else to consider, older generators have thicker insulation, new insulating materials are thinner allowing for uprates.

- Per “Design of Rotating Electrical Machines” Textbook, discuss the types of leakage flux listed

Leakage flux not crossing the airgap

- Slot leakage flux – shown in the image
- Tooth tip leakage flux
- End winding leakage flux
- Pole leakage flux

Leakage flux crossing the airgap

- Short pitching
- spacial distribution

SHORT PITCH AND SPACIAL DISTRIBUTION

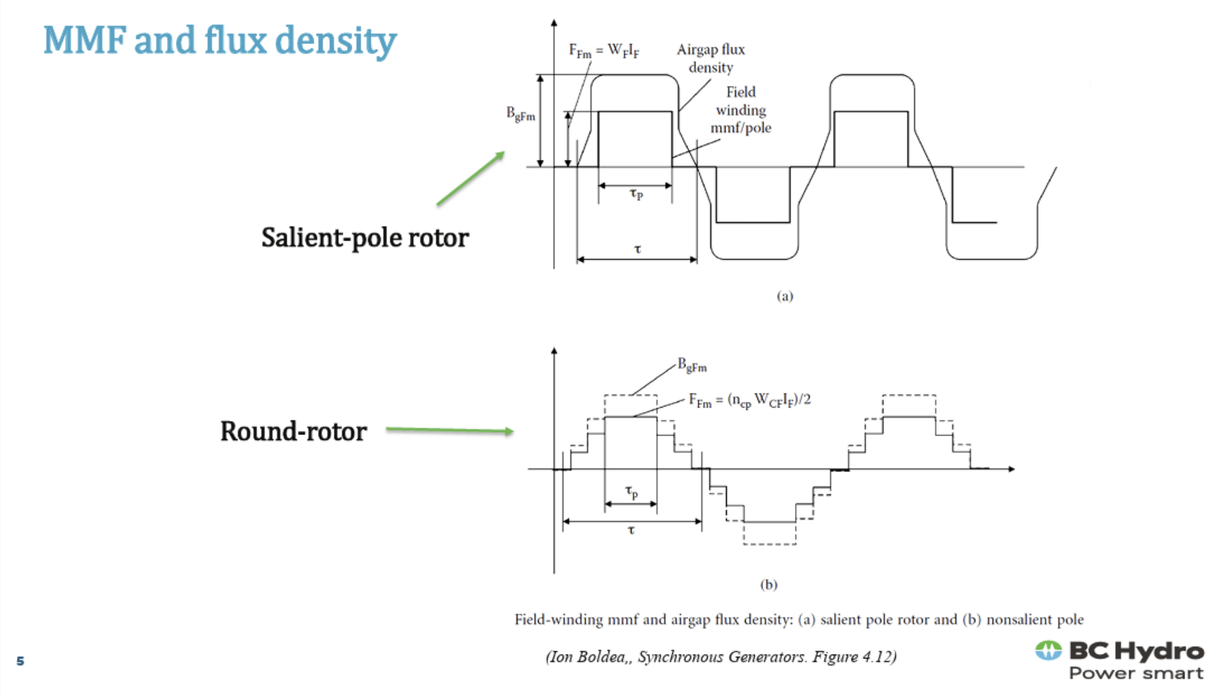
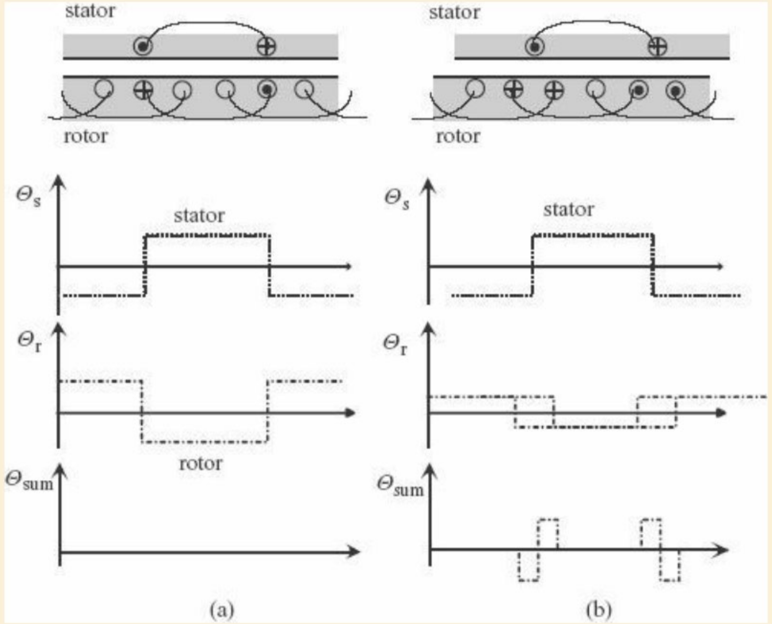


Figure 4.9 Occurrence of an air-gap flux leakage as a result of the spatial distribution of stator and rotor windings in different positions (a) and (b). When the current-carrying parts of the windings are in an aligned position, the resulting sum current linkage is zero, otherwise it deviates from zero.



In Figure 4.9a, the current linkage of the stator winding happens to be fully compensated, because a corresponding current flows at an aligned position in the rotor

Quincy Wang's MVS presentation represents the effects of short pitch tp/t.

Design of Rotating Electrical Machines (Pyrhonen et al., 2013)

SUMMARY

- The GENTPJ Model has been applied to hydroelectric generators for over a decade, this model produces challenges for those producing the generator models (GOP). GENTPJ incorporates a saturation multiplier. It provides an offset to the Vee-Curve. This means similar effects can be made by adjusting XD, Xl or saturation constants. “More knobs to turn”.

- Validation testing work using the GENQEC has so far shown better results to GENTPJ. The GENQEC white paper regarding the application of GENQEC is most insightful. Understanding how to get the models out of the generator is paramount!