Lab 2

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Contents

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1 Equipment

- Dc Power Supply
- Model Transmission Line
- Multi-meters
- Synchronization unit

1.1 Alternator

Table 1.1: *Alternator Nameplate Values*

Stator Voltage (V)	Stator Voltage +20% (V)	Rotor Voltage (VDC)	Power (W) @1500 rpm
41.5	49.8	24	50

2 Setup

- Load Switch Disabled
- 3-Phase power supply connected to load switch
- 3-Phase Wattmeter connected to the three phase supply
- Three Phase supply connected to the stator of the synchronous motor
- Dc power supply connected to synchronous machine rotor
- DC Power supply switched on
- DC Power to motor increased gradually
- DC Motor begins to turn Drive train at V $\approx$ `8-11Vdc`

3 Experiments

3.1 synchronisation

3.1.1 Procedure

- Dc voltage increased until DC motor is running at synchronous speed $\approx$ `1500rpm`
- Second DC Supply turned on to exit the rotor
- Excitation Current increased gradually
- Generator open circuit voltage noted as changing as excitation current to the rotor is increased?
- Machine is Disabled

3.2 Open circuit Test

3.2.1 Procedure

- Name Plate Rating of the Synchronous machine noted
- Additional `20%` margin added to stator voltage rating
- DC Motor restarted
- Synchronous motor spun up to `1500rpm`
- The Generator side of the synchronisation unit is disconnected

- The Rotor excitation current is set to `0A`
- The rotor excitation current is increased in steps of `0.5A` until the measured stator voltage reaches `49.8V` (calculated according to: $1.2 \times V_{\text{stator Name-Plate}}$).
  - for each `0.5A` step the synchronous speed was controlled to `1500rpm` by adjusting the supply to the DC Motor
  - for each step of `0.5A` the open circuit generator voltage was recorded

3.2.2 Results

Table 3.1: *Stator Line voltage Vs rotor Excitation current for open circuit test*

I_{rot} (A)	V_{Line} (V)
0.050	6.71
0.100	12.10
0.150	17.10
0.201	23.10
0.251	28.90
0.302	34.60
0.350	39.60
0.402	44.70
0.451	49.00
0.501	52.90

3.3 Short Circuit Test

3.3.1 Procedure

- The leads leaving the 3 Phase wattmeter which were disconnected Last experiment are now connected together effectively short-circuiting the Generator
- The rotor field supply is set to zero and the supply is switched on
- The DC Motor is turned on and the DC voltage supply is adjusted until the speed of the drive train is at 1500 rpm
- Rotor field excitation current gradually increased in steps of `0.05A`
  - rotor speed is kept constant at `1500rpm` for each step
  - for each step the current flowing out of the generator terminals is noted

3.3.2 Results

Table 3.2: *Stator Current Vs rotor excitation current for short circuit test*

I_{rot} (mA)	I_{stat} (mA)
0	0
52	0
101	350
150	496
200	639
250	786
299	930
325	1010

3.4 Load Tests

3.4.1 Setup (Steps 1-2)

1. Synchronisation - (Step 1)
    - Synchronous machine used as a generator into an infinite bus
    - A 3-Phase Power supply is used to simulate the grid
    - Load switch is set to `Off` on the synchronisation unit
    - The Synchronisation unit is set to `Intensity`
    - The leads between the Synchronisation unit and the 3-Phase Wattmeter are reconnected
    - The DC supply to the DC motor is switched on and the supply voltage is adjusted until the speed of the generator reaches `1500rpm`
    - The DC Rotor supply is now turned on and the current is adjusted until the generator line voltage is `45V` which is the same amplitude of the 3-Phase supply
    - The thee phase supply is now turned on
        - It is noted that the three lights on the synchronisation unit now begin to flash at ≈ `0.5Hz`
    - The motor speed is then adjusted by varying the DC motor current until the lights cease to flash.
    - The Load switch is now set to `On`
        - it is noted that the lights now Cease to flash meaning the synchronous machine is now synchronised with the 3-Phase supply
2. Zero Apparent power flow - (Step 2)
    - The Rotor field excitation current and the DC Motor Current (its torque) is adjusted to minimise the AC stator current
        - the generator is neither motoring or generating with losses supplied by the DC motor (no real power is flowing between the grid and the synchronous machine)

3.4.2 Test 1 - Unity PF (Step 3)

1. Procedure
    - The Current to the DC motor is increased until the stator current is roughly 2/3 I_{nom} which is calculated as `464mA`
        - I Guess this will be primarily real power
    - the rotor excitation current is then adjusted until the stator current is minimised
        - cancelling out the reactive power by altering the magnitude of the EMF?
    - Once the stator current is minimised, the following are recorded
        - Final stator current
        - Prime mover input power
        - rotor excitation current
        - Terminal voltage
        - Power factor
        - rotor angle
    - the synchronous speed of the rotor is then measured with the lamp thing
2. Results

Table 3.3: *Mesurements while operating at zero reactive power*

Measurand	Value	Units
Field Excitation Current	0.478	A
Line Current	0.417	A
Line Voltage	47.2	V
Active Power	33.4	W
Power Factor	1	
Prime Mover Input Power	105.67	W
Rotor (load) Angle	330	degrees

3.4.3 Test 2 - Leading PF (Step 4)

1. Procedure
   - The rotor excitation current is increased until the stator current reaches its nominal value.
     - the Prime-mover torque is kept constant
   - The following are recorded:
     - Final stator current
     - Prime mover input power
     - rotor excitation current
     - Terminal voltage
     - Power factor
     - rotor angle
2. Results

Table 3.4: *Mesurements while operating at rated current with negative reactive power*

Measurand	Value	Units
Field Excitation Current	0.638	A
Line Current	0.689	A
Line Voltage	47.5	V
Active Power	36.0	W
Power Factor	0.63	
Prime Mover Input Power	104.48	W
Rotor (load) Angle	150	degrees

3.4.4 Test 3 - Lagging PF (Step 5)

1. Procedure
   - 24:29
   - DC Motor Power is kept constant
   - Rotor excitation current is reduced to the value measured in step 3: `478mA`
   - Rotor excitation current is continually reduced until the stator current reaches its nominal value
   - The following are recorded at this point:
     - Final stator current
     - Prime mover input power
     - rotor excitation current
     - Terminal voltage
     - Power factor

– rotor angle

- the synchronising switch is opened and all power supplies are turned off

2. Results

Table 3.5: *Mesurements while operating at rated current and positive negative power*

Measurand	Value	Units
Field Excitation Current	0.334	A
Line Current	0.692	A
Line Voltage	47.6	V
Active Power	42.8	W
Power Factor	–0.75	
Prime Mover Input Power	110.2	W
Rotor (load) Angle	150	degrees

4 Deductions

4.1 Synchronous Impedance Plot

The results for the short-circuit and open circuit tests are plotted in Figure 4.1 along with the synchronous impedance calculated from both lines by interpolation. The synchronous impedance is defined according to Formula 4.1 which can be derived according to the equivalent circuit of the synchronous machine.

$$Z_s = \frac{V_{EMF}}{I_{Ph}} \tag{4.1}$$

Since it is impossible to directly measured the $\mathrm{V_{EMF}}$ while current is flowing through the terminals of the synchronous machine, we must first establish $\mathrm{V_{EMF}}$ from the open circuit test. Since it is known that $V_{EMF} \propto I_{rot}$ We record the OC voltage against different rotor excitation currents and similarly record the SC stator currents against rotor excitation current. Since $V_{OCLL}(V_{rot}) \times \frac{1}{\sqrt{3}} = V_{EMF}(V_{rot})$ the SC current at a given $\mathrm{I_{rot}}$ can be assumed to be driven by the $\mathrm{V_{EMF}}$ for that same $\mathrm{I_{rot}}$.

Complicating this somewhat is the fact that the measurements for $\mathrm{V_{EMF}}$ and $\mathrm{I_{Ph}}$ are not taken at the exact same rotor excitation current ($\mathrm{I_{rot}}$), as such a 1D linear interpolation is used over the range of valid[1] Short circuit measurements ($\mathrm{I_{stat}}$). Figure 4.1 attempts to show the interpolation with the dotted red lines showing the x axis points chosen to evaluate $\mathrm{Z_s}$. for simplicity the points are chosen to coincide with the actual measurements of $\mathrm{I_{stat}}$ so interpolation was only conducted on $\mathrm{V_{Ph}}$ [2]. Finally the calculated $\mathrm{Z_s}$ for each point is plotted (shown in red). As can be seen from the flat nature of the line, Calculated $\mathrm{Z_s}$ is basically constant over the selected range of $\mathrm{I_{rot}}$.

[1]Some of the initial measurements of $\mathrm{I_{stat}}$ read zero and as such would lead to a divide by zero in Eq 4.1 and as such have been excluded

[2]the interpolated points on $\mathrm{V_{stat}}$ are highlighted as red markers on the $\mathrm{V_{stat}}$ line

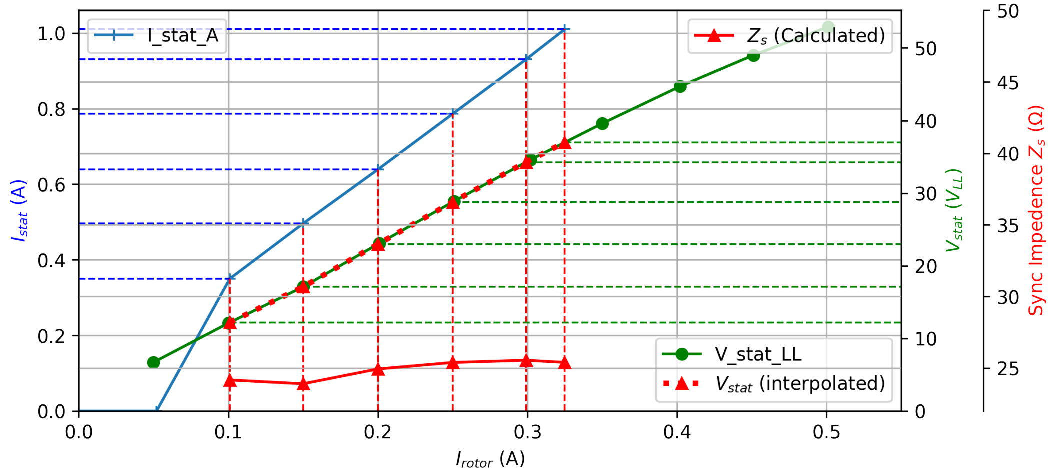

Figure 4.1: *Synchronous Impedance Calculated according to Equation 4.1.*

The final Z_s is calculated by simply taking the value of Z_s where the open circuit voltage is at rated (`41.5V`) yielding:

: 25.0 Ω

4.2 Per-unitisation/Base Values

4.2.1 Base Values

Base Voltage and Power are taken from the nameplate values given in Table 1.1. I_{base} is then calculated according to:

$$I_{base} = \frac{S_{base}}{\sqrt{3} \times V_{base}} \tag{4.2}$$

Yielding: : 0.696 A

$$Z_{base} = \frac{V^2_{rated(LL)}}{S_{rated}} \tag{4.3}$$

From Equation 4.3 and the nameplate values in for rated line voltage and Power in Table 1.1, the base impedance is calculated as.

: 34.0 Ω

4.2.2 Pu Impedance

The base impedance is then used to calculate the per unit impedance according to Equation 4.4, yielding `0.74` Pu.

$$Z_{s(pu)} = \frac{Z_s}{Z_{base}} \tag{4.4}$$

4.3 Calculations

4.3.1 Current angle

The angle of the current with respect to the supply voltage vector at the 3-Phase Wattmeter, can be derived from the power factor:

$$\theta = -cos^{-1}(pf) \tag{4.5}$$

Where pf is positive, and:

$$\theta = cos^{-1}(-pf) \tag{4.6}$$

4.3.2 Voltage drop ($\mathbf{v_d}$)

Since the load impedance is known, the magnitude of the voltage drop can be calculated according to:

$$V_d = I_{stat}\angle\theta^\circ \times Z_s = I_{stat}\angle\theta^\circ \times jX_s \tag{4.7}$$

4.3.3 $\mathbf{V_{EMF}}$ Calculation

From the equivalent circuit diagram and applying Kirchhoff's voltage law we know that V_{EMF} of the generator is given by:

$$V_{EMF} = V_{supply}\angle 0^\circ + V_d \tag{4.8}$$

Where V_{supply} is the complex phasor corresponding to the supply voltage and V_d is the voltage drop over the reactive impedance Z_s. Substituting Equation 4.7 into 4.8 we get:

$$V_{EMF} = V_{supply}\angle 0^\circ + I_{stat}\angle\theta^\circ \times jX_s \tag{4.9}$$

4.3.4 Reacive Power Calculation

Rective power is calculated based on the measured stator current magnitude $|I_{stat}|$, the measured magnitude of stator voltage ($|V_{stat}|$) and the measured power factor accoring to Equation 4.10.

$$Q = \frac{3 \times I_{stat}V_{statLL}}{\sqrt{3}} \times \sqrt{1 - pf^2} \tag{4.10}$$

4.3.5 Real Power Calculation

$$P = \frac{3 \times I_{stat}V_{statLL}}{\sqrt{3}} \times pf \tag{4.11}$$

4.4 Calculation Results

The tabulated calculations of V_{EMF}, I_{rot} and Power for each of the three load tests are displayed in Table 4.1. The corresponding phasor diagrams are shown in Figures 4.2 to 4.4.

Table 4.1: *Results of excitation current and V_{EMF} calculations compared against the mesured excitation current and the Calculated Real and Reacive power*

Test #	Derived V_{EMF}	Derived I_{rot} (A)	Measured I_{rot} (A)	S (VA)	P (W)	Q (VAR)
1	$50.64\angle\ 21.24^\circ$(V)	0.472	0.478	19.682	19.682	0.0
2	$73.56\angle\ 15.05^\circ$(V)	0.766	0.638	32.728	20.618	25.416
3	$35.72\angle\ 39.74^\circ$(V)	0.313	0.334	32.939	24.704	-21.787

4.4.1 Phasor Diagrams

1. Test 1 - Unity Power factor

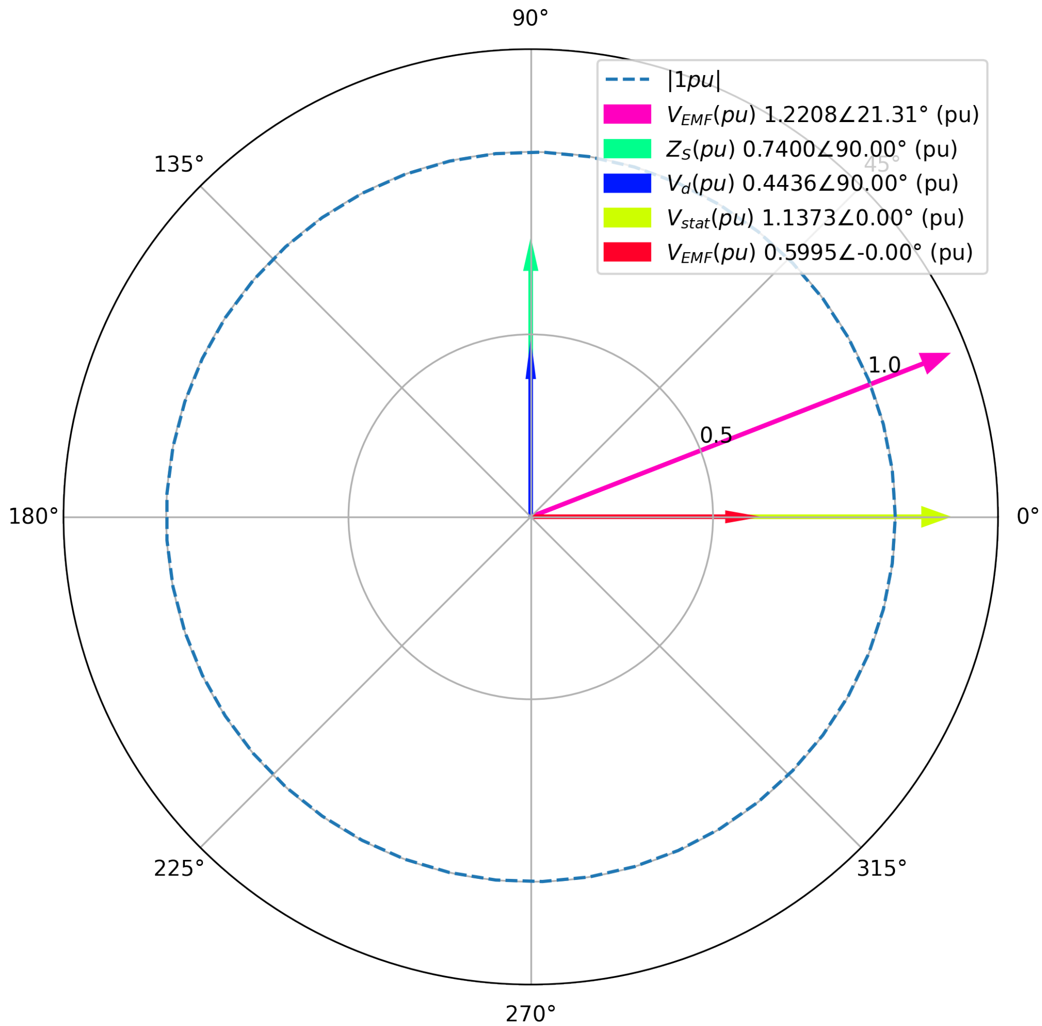

Figure 4.2: *Test 1 phasor plot for unity power factor*

2. Test 2 - Lagging PF

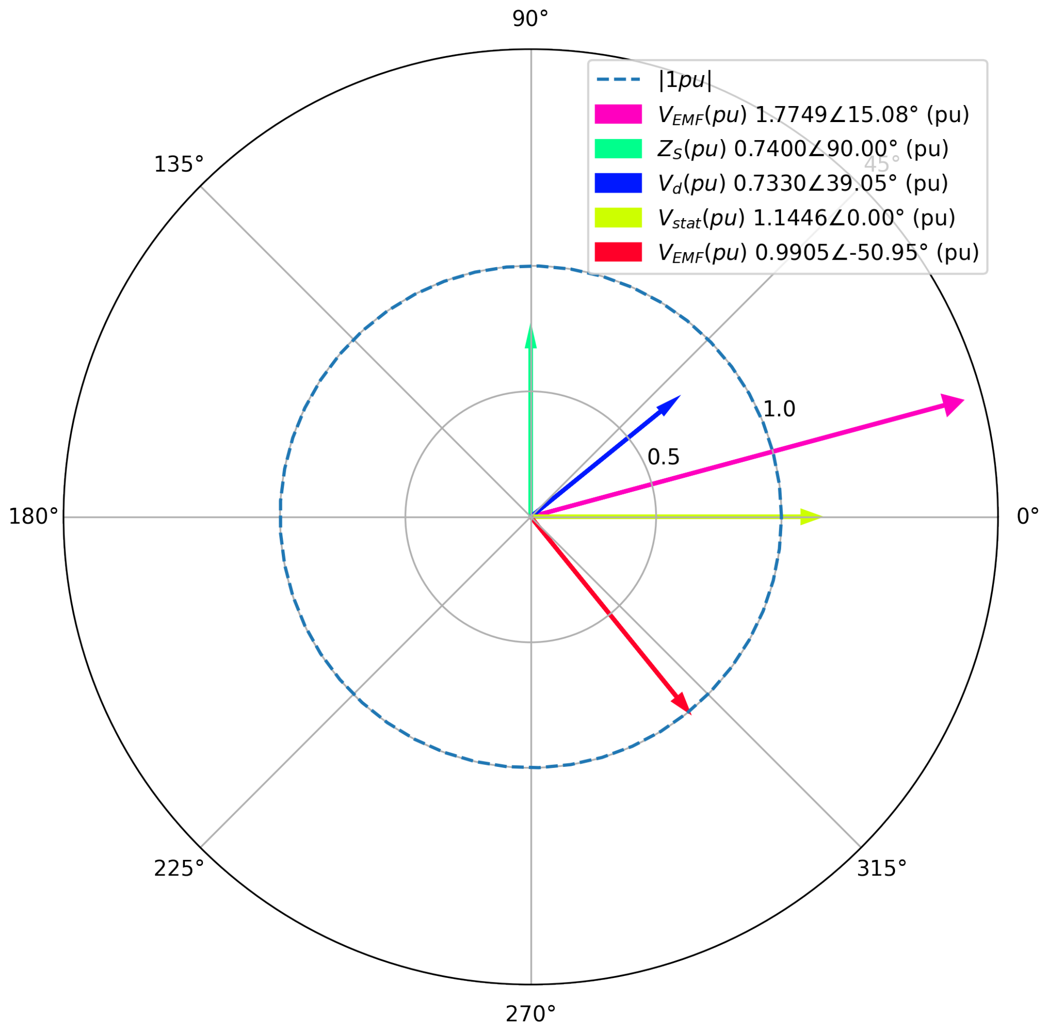

Figure 4.3: *Test 2 phasor plot for lagging power factor*

3. Test 3 - Leading PF

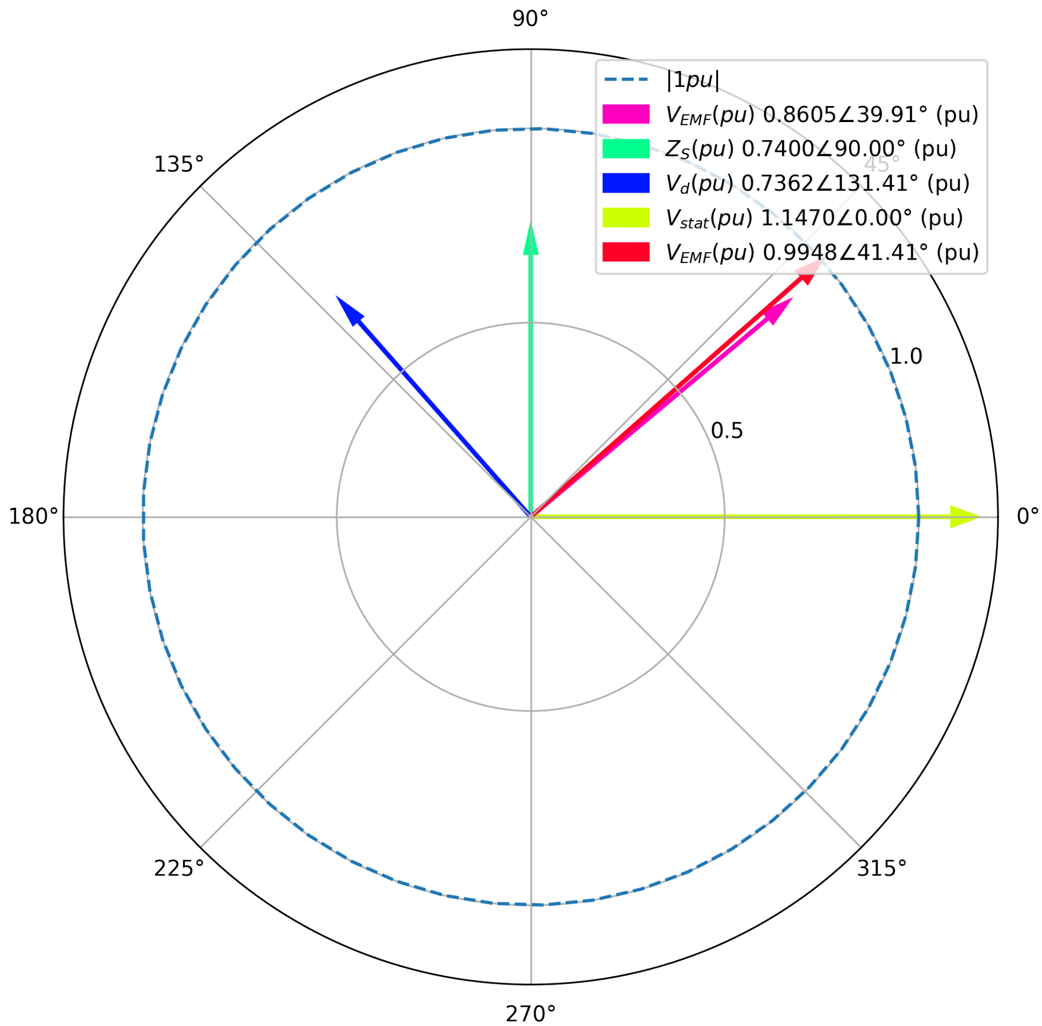

Figure 4.4: *Test 3 phasor plot for leading power factor*

4.4.2 Rotor Angle

The rotor angle is also caclulated implicitly since is is simply the angle of the derived V_{EMF} (Table 4.1).

4.4.3 Field excitation currents

Excitation current is caclulated derived from the magnitude of V_{EMF} and the known relationship between field excitation current and V_{EMF} magnitude establised in Section 4.1. This may then be compared against the measured value as a validations step. From Table 4.1 it is clear that these values match very closely, only differing for test two, possibly due to having to extrapolate outwith the range of the known I_{rot} vs V_{EMF} relationship.

4.4.4 P/Q vs Excitation

Reactive power is calculated according to Equations 4.10 and 4.11, and again found in Table 4.1. It seems clear for the experimental results that the effect of raising and lowering the excitation current affects both the real and reactive power leaving the generator, however reactive power is substantially more sensitive to this than real power. While real power varied only by several % from nominal, the reactive power flipped between ≈ `+0.5pu` reactive power at the high end of excitation and, ≈ `-0.5pu` on the low end of excitation. This implies that higher excitation, and by extension higher V_{EMF} leads to more reactive power export, while conversely low excitation leads to reactive power import.

4.5 Over vs Under excitation

From the results obtained in this lab is can be seen that operating under excited i.e. with lagging power factor, acts to increase the total load angle of the machine. This means that the total stability margin of the machine in steady state is reduced for the same real power.