Power System Quality and Reliability

ECEg-6312

WEEK 16

Final Examination

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Final Examination

- **Final Examination Instructions:** The final examination consists of two parts with a total of 50 marks.
  - **Part I: Multiple-Choice Questions (18 Marks)**
    - This section contains 12 multiple-choice questions.
    - Each question carries 1.5 marks and Total marks for Part I: 18 marks.
    - Students are required to select the single best answer for each question.
  - **Part II: Problem-Solving Questions (32 Marks)**
    - This section contains 4 workout (analytical and calculation-based) questions.
    - Students are required to show all necessary steps, calculations, and justifications where applicable.
    - Marks are allocated based on the accuracy of the solution procedure as well as the final answer.
    - Total marks for Part II: 32 marks.

Part I: Multiple-Choice Questions (18 Marks)

1. A nonlinear load injects harmonic currents into a stiff grid. If the grid voltage THD is observed to increase significantly despite constant harmonic current injection, the MOST probable cause is:
   A. Increase in system short-circuit impedance
   B. Reduction in source impedance
   C. Increase in fundamental load current
   D. Decrease in harmonic order
2. In a parallel redundancy system, system reliability improvement is MOST significant when:
   A. Component reliability is identical and high
   B. Component failure rates are independent
   C. One component dominates failure risk
   D. Repair time is zero

Part I: Multiple-Choice Questions (18 Marks)

3. In IEEE 519 harmonic assessment at PCC, the correct interpretation of current distortion limits is primarily dependent on:
   A. Load voltage level only
   B. Transformer winding configuration
   C. Short-circuit ratio at PCC
   D. Generator inertia constant
4. A reliability improvement strategy that reduces SAIDI but not SAIFI is MOST likely:
   A. Automation of fault isolation
   B. Adding parallel feeders
   C. Increasing generation capacity
   D. Increasing conductor size

Part I: Multiple-Choice Questions (18 Marks)

5. A DVR is most effective in mitigating:
   A. Steady-state harmonics
   B. B.Voltage swells and sags with fast dynamics
   C. Frequency drift
   D. Load unbalance only
6. LOLE (Loss of Load Expectation) is best interpreted as:
   A. Energy not served per year
   B. Expected number of hours/days load exceeds generation capacity
   C. Probability of transformer failure
   D. Voltage collapse frequency

Part I: Multiple-Choice Questions (18 Marks)

7. If a system exhibits high 5th and 7th harmonic dominance, the most appropriate passive filter configuration is:
   A. High-pass filter only
   B. Single-tuned filter for 3rd harmonic
   C. Double-tuned or C-type filter
   D. No filtering required
8. A system with high failure rate but very low repair time will exhibit:
   A. High SAIDI and high SAIFI
   B. High SAIFI but low SAIDI
   C. Low SAIFI and high SAIDI
   D. Low reliability but high availability

Part I: Multiple-Choice Questions (18 Marks)

9. A sudden voltage sag affecting only phase A in a 3-phase system is MOST likely caused by:
   A. Balanced three-phase fault
   B. Single line-to-ground fault
   C. Load switching only
   D. Capacitor switching
10. For a series system, assuming independent failures, system reliability is:
    A. Sum of component reliabilities
    B. Minimum reliability among components
    C. Product of component reliabilities
    D. Maximum failure probability

Part I: Multiple-Choice Questions (18 Marks)

11. Increasing distributed PV penetration WITHOUT control coordination typically leads to:
    - A. Reduced flicker and harmonics
    - B. Increased voltage rise and reverse power flow issues
    - C. Lower system impedance
    - D. Improved fault current levels
12. In a Markov two-state model, the steady-state availability is most directly affected by:
    - A. Load factor
    - B. Failure and repair rates
    - C. Voltage magnitude
    - D. Harmonic distortion

Part II: Problem-Solving Questions (32 Marks)

1. A 15-kV radial distribution feeder supplies a large industrial customer. The feeder consists of three major series components whose reliability data are given below: **(8 Marks)**

System Component	Failure Rate, λ (failures/year)	Average Repair Time, r (hours)
Overhead Feeder	0.35	6
Underground Cable	0.12	12
Distribution Transformer	0.08	18

Part II: Problem-Solving Questions (32 Marks)

a) Determine the equivalent failure rate of the feeder. (1 Marks)

b) Calculate the annual outage duration of the feeder and the contribution by each component (2 Marks)

c) Determine the equivalent average outage duration (repair time) of the feeder. (2 Marks)

d) Compute the feeder availability and unavailability. (1 Marks).

e) The utility plans to automate the feeder and reduce the repair time of the overhead feeder section from 6 hours to 2 hours. Recalculate the annual outage duration and quantify the percentage improvement in availability. (2 Marks)

Part II: Problem-Solving Questions (32 Marks)

2. A nonlinear industrial load connected at the Point of Common Coupling (PCC) produces the following harmonic current spectrum: **(5 Marks)**

Harmonic Order	Current Magnitude (A)	Harmonic Order	Current Magnitude (A)
Fundamental (I1)	150	11th Harmonic (I11)	15
5th Harmonic (I5)	45	13th Harmonic (I13)	10
7th Harmonic (I7)	30	Short-circuit current @PCC	4500

Part II: Problem-Solving Questions (32 Marks)

a) Calculate the Total Harmonic Distortion (THDI) of the load current. (1 Marks)

b) Determine the Total Demand Distortion assuming the maximum demand current is equal to the fundamental curren. (1 Marks)

c) Compute the short-circuit ratio and classify the strength of the system. (1 Marks)

d) Assess whether the installation is likely to satisfy IEEE 519 harmonic current requirements. Justify your answer. (1 Marks)

e) Recommend two technically appropriate harmonic mitigation techniques and explain why they are suitable for this installation. (1 Marks)

Part II: Problem-Solving Questions (32 Marks)

3. A generating station consists of three generating units supplying a regional load with an annual peak load of 90 MW: **(8 Marks)**

Unit	Capacity (MW)	Forced Outage Rate (FOR)/ Unavailability
G1	50	0.04
G2	40	0.05
G3	30	0.08

Part II: Problem-Solving Questions (32 Marks)

a) Construct the complete Capacity Outage Probability Table (COPT) for the generating station. (2 Marks)

b) Determine the probability that the available generation capacity is insufficient to meet the peak load. (2 Marks)

c) Calculate the Loss of Load Probability (LOLP). (2 Marks)

d) Based on the obtained results, discuss whether the generating station satisfies acceptable generation adequacy requirements and identify the most critical generating unit from a reliability perspective. (2 Marks)

Part II: Problem-Solving Questions (32 Marks)

4. A standalone microgrid supplies a critical industrial load, 70 MW (constant). The system consists of: (11 Mark)

Microgrid Unit	Capacity (MW)	Availability
Photovoltaic (PV) plant	40	A_{PV}=0.75
Wind farm	20	Aw=0.65
Diesel generator	30	A_D=1.0

Assume:

i. PV and wind generation are statistically independent

ii. Each renewable source operates in a binary state (available = rated output, unavailable = 0)

iii. Diesel generator is always available and contributes constant output

iv. System operates on a single-bus microgrid configuration

Part II: Problem-Solving Questions (32 Marks)

a) Construct the complete system state space considering all possible combinations of PV and wind availability.

   For each state:

   i. Determine the total available generation (1 Mark)

   ii. Assign the probability of occurrence (1 Mark)

b) Using the state space:

   i. Determine the Loss of Load Probability (LOLP) (1 Mark)

   ii. Compute the probability that the system can fully supply the load (1 Mark)

   iii. Identify the marginal (critical) operating state(s) (1 Mark)

c) For all deficit states: Assume time horizon = 1 hour for interpretation in MW-h units.

   i. Compute the power deficit in MW (2 Mark)

   ii. Determine the probability-weighted expected unserved power (1 Mark)

Part II: Problem-Solving Questions (32 Marks)

d) For each operating state:

   i. Discuss expected voltage profile behavior (Overvoltage / under voltage / nominal) (1 Mark)

   ii. Identify the state with highest risk of voltage instability, frequency deviation, inverter-driven harmonic sensitivity. (1 Mark)

   iii. Explain why the boundary operating state is the most critical from a dynamic stability perspective. (1 Mark)

e) Propose a technically justified improvement strategy that simultaneously enhances: **(Bonus)**

   i. reliability (reduce LOLP) (1.5 Mark)

   ii. power quality (reduce voltage fluctuation and harmonic sensitivity) (1.5 mark)

Good Luck! Read each question carefully and manage your time wisely!!

Answer Key

Part I: Multiple Choice

1. A
2. B
3. C
4. A
5. B
6. B
7. C
8. B
9. B
10. C
11. B
12. B

Part II: Problem Solving

1. **Given**

System Component	Failure Rate, λ (failures/year)	Average Repair Time, r (hours)
Overhead Feeder	0.35	6
Underground Cable	0.12	12
Distribution Transformer	0.08	18

Answer Key

a) Equivalent Failure Rate:

- For a series system

$$\lambda_{eq} = \sum \lambda_i$$

$$\lambda_{eq} = 0.35 + 0.12 + 0.08$$

$$\boxed{\lambda_{eq} = 0.55 \text{ failures/year}}$$

a) Annual Outage Duration

$$U = \sum \lambda_i r_i$$

Overhead feeder:

$$U_1 = 0.35(6) = 2.10$$

Cable:

$$U_2 = 0.12(12) = 1.44$$

Transformer:

$$U_3 = 0.08(18) = 1.44$$

Total: U = U1+U2+U3 = 2.1+1.44+1.44 = **4.98 hours/year**

Answer Key

c) Equivalent Average Outage Duration:

$$r_{eq} = \frac{U}{\lambda_{eq}} = \frac{4.98}{0.55} = 9.05\ hours$$

d) Availability:

$$A = 1 - \frac{U}{8760} = 1 - \frac{4.98}{8760} = 0.9994$$

Unavailability: $Q = 1 - A = 0.000568$

e) Repair Time Reduced to 2 Hours

New outage contribution:

$$U_1' = 0.35(2) = 0.70$$

Total:

$$U' = 0.70 + 1.44 + 1.44$$

$$\boxed{U' = 3.58\ \text{hours/year}}$$

Answer Key

New availability:

$$A' = 1 - \frac{3.58}{8760}$$

$$\boxed{A' = 99.9591\%}$$

Percentage improvement:

$$\%\Delta A = \frac{99.9591 - 99.9432}{99.9432} \times 100$$

$$\boxed{0.016\%}$$

2. Given $I_1 = 150A$ $I_{SC} = 4500A$ $I_5 = 45A,\ I_7 = 30A,\ I_{11} = 15A,\ I_{13} = 10A$

(a) Current THD:

$$THD = \frac{\sqrt{45^2 + 30^2 + 15^2 + 10^2}}{150}$$

$$THD = \frac{\sqrt{3250}}{150}$$

$$THD = 0.3801$$

$$\boxed{THD = 38.0\%}$$

(b) Total Demand Distortion, TDD

$$I_L = 150A$$

$$TDD = \frac{\sqrt{3250}}{150}$$

$$\boxed{TDD = 38.0\%}$$

Answer Key

(c) Short-Circuit Ratio

$$\frac{I_{Sc}}{I_L} = \frac{4500}{150} = 30 \text{ (Medium Strength System)}$$

(d) IEEE 519 Compliance

For:

$$20 < \frac{I_{SC}}{I_L} < 50$$

allowable TDD is typically around 8%. Therefore, the system is not Compliant with IEEE 519 standard.

(e) Mitigation Techniques

Accept any two:

1. Single-tuned passive filter
2. Shunt active power filter (APF)
3. Hybrid active-passive filter
4. Multi-pulse converter
5. PWM converter with lower harmonic injection

Answer Key

3. **Given:** Load=90MW

Unit	Capacity (MW)	Forced Outage Rate (FOR)/ Unavailability
G1	50	0.04
G2	40	0.05
G3	30	0.08

Total Installed Capacity:

$$C_T = 50 + 40 + 30 = 120\ MW$$

Answer Key

(a) Complete Capacity Outage Probability Table (COPT)

State	G 1	G 2	G 3	Capacity Outage (MW)	Avaliable Capacity (MW)	State Probability
S1	UP	UP	UP	0	120	$0.96 \times 0.95 \times 0.92 = 0.83904$
S2	UP	UP	DOWN	30	90	0.96×0.95×0.08=0.07296
S3	UP	DOWN	UP	40	80	0.96×0.05×0.92=0.04416
S4	DOWN	UP	UP	50	70	0.04×0.95×0.92=0.03496
S5	UP	DOWN	DOWN	70	50	$0.96 \times 0.05 \times 0.08 = 0.00384$
S6	DOWN	UP	DOWN	80	40	0.04×0.95×0.08=0.00304
S7	DOWN	DOWN	UP	90	30	0.04×0.05×0.92=0.00184
S8	DOWN	DOWN	DOWN	120	0	0.04×0.05×0.08=0.00016

References

(b) Determine Loss-of-Load States

- Peak Load: L=90MW and the adequate States are: S1 (120MW) and S2(90MW)
- Loss-of-Load States: S3 (80MW), S4(70MW), S5(50MW), S6(40MW), S7(30MW), and S8(0MW)

(c) LOLP Calculation

$$LOLP = P(S3) + P(S4) + P(S5) + P(S6) + P(S7) + P(S8)$$

$$= 0.04416 + 0.03496 + 0.00384 + 0.00304 + 0.00184 + 0.00016$$

LOLP = 0.088 or LOLP = 8.8%

(d) Probability of Adequacy: $P_{Adequate}$=P(S1)+P(S2)=0.83904+0.07296=0.912

(e) Most Critical Unit: The largest generating unit is the most critical plant.

Answer Key

4. Given:

Microgrid Unit	Capacity (MW)	Availability
Photovoltaic (PV) plant	40	A_{PV}=0.75
Wind farm	20	Aw=0.65
Diesel generator	30	A_D=1.0

Load:

$$P_L = 70\ MW$$

Since the diesel generator is always available,

$$P_D = 30MW$$

Answer Key

(a) (i) Total Available Generation (Column 5)

(ii) Probability of Occurrence (Column 6)

State	PV	Wind	Diesel	Total Generation (MW)	State Probability
S1	UP	UP	UP	90	$0.75 \times 0.65 = 0.4875$
S2	UP	DOWN	UP	70	$0.75 \times (1-0.65) = 0.2625$
S3	DOWN	UP	UP	50	$0.25 \times 0.65 = 0.1625$
S4	DOWN	DOWN	UP	30	$0.25 \times 0.35 = 0.0875$

b) (i) Loss of Load Probability (LOLP)

A loss of load occurs whenever: $P_G < P_L$ Therefore, S3 (50 MW) and S4 (30 MW) are deficit states.

$$LOLP = P(S3) + P(S4) = LOLP = 0.1625 + 0.0875 = 0.25 \text{ or } 25\%$$

Answer Key

(b) (ii) Probability of Supplying the Load

- Adequate states: S1 (90 MW) and S2 (70 MW)
- $P_{adequacy}$=P(S1)+P(S2)=0.4875+0.2625=0.75 or 75%

(b) (iii) Marginal (Critical) Operating State

- The critical state is the state where generation exactly equals demand. $P_G = P_L$ which corresponds to: State S2 (PV ON, Wind OFF, Diesel ON)

(c) (i) Power Deficit

- State S3: Deficit=70-50=20MW
- State S4: Deficit=70-30=40MW

Answer Key

(c) (ii) Probability-Weighted Expected Unserved Power

- State S3 Contribution: $EUP3=20\times0.1625 = 3.25MW$
- State S4 Contribution: $EUP4=40\times0.0875 = 3.5MW$
- Total Expected Unserved Power: $EUP=EUP3+EUP4=6.75MW$
- For a one-hour period: $EENS=6.75MW$

(d)(i) Expected Voltage Profile Behavior

- S1: Slight overvoltage possible; S2: Nominal voltage; S3: Undervoltage likely; S4: Severe undervoltage

(d) (ii) State with Highest Risk

- **Voltage Instability:** Occurs when generation is lowest S4; **Frequency Deviation:** Largest generation deficit. S4.
- **Inverter Harmonic Sensitivity:** Highest renewable penetration: PV+Wind=60MW which is S1.

Answer Key

(d) (iii) Why the Boundary Operating State is Critical

- State S2 has: PG=PL=70MW
- There is no spinning reserve.
- Any small disturbance such as sudden load increase, PV fluctuation, frequency deviation, and wind power variation will immediately move the system into a deficit condition.

(e) (i) Reliability Improvement: To reduce LOLP Battery Energy Storage System (BESS) is recommended.

(e) (ii) Power Quality Improvement: Hybrid PQ Improvement Strategy

1. BESS with inverter-based voltage support: voltage regulation and frequency support
2. Shunt Active Power Filter (APF): harmonic mitigation, improved power factor and to reduced THD

Thank You!