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Support Vector Machine (SVM)-Based Synchronized Fault Detection for 100% Renewable Microgrids

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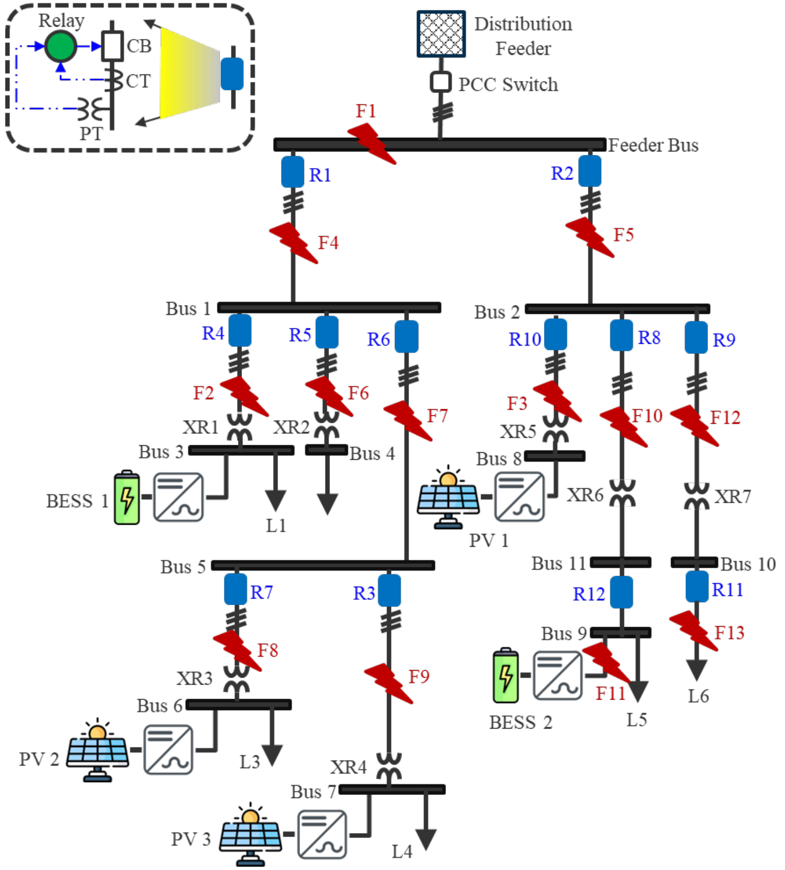
Background and Motivation

Microgrids with 100% renewable sources face significant challenges:

- ✓ Low short-circuit current, inconsistent phase angles
- ✓ Bidirectional power flow
- ✓ Fault current depends on the distributed energy resource (DER)/inverter-based resource (IBR) operation mode.
- ✓ Traditional magnitude-based protection might not function well.

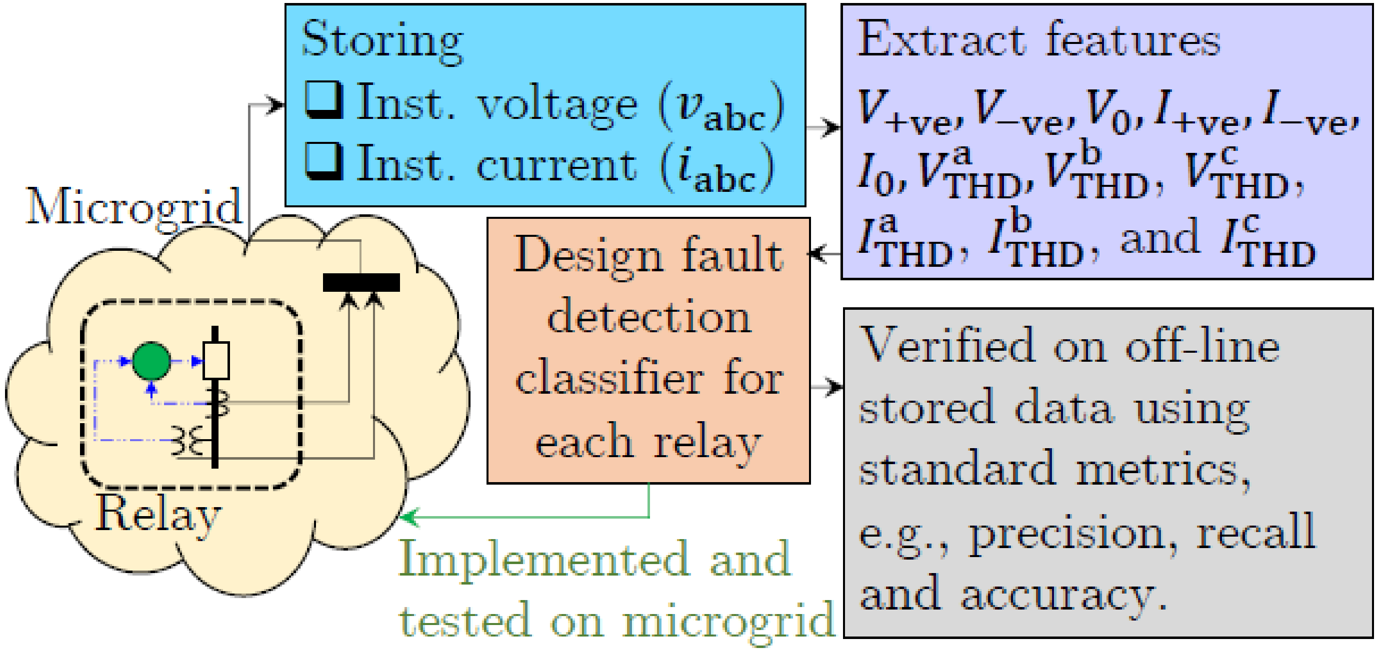
Data-driven-based protection has shown some advantages:

- ✓ Learns the patten of the DER/IBR fault response based on big data and makes the correct decision for the relay.
- ✓ Uses a simple machine learning task to respond quickly.
- ✓ Design proper coordination to avoid false tripping.



Key challenges:
- Asynchronicity issue among relays

Workflow of the Proposed Data-Driven Fault Detection



FAULT DETECTION CLASSIFIER

Stage 1 — Data processing and feature extraction (MATLAB)

→

Stage 2 — Learning SVM classifiers to detect faults (MATLAB)

Features:

- Magnitude of positive-sequence ($V_{+\text{ve}}$), negative-sequence ($V_{-\text{ve}}$) of the voltage waveform
- Magnitude of positive-sequence ($I_{+\text{ve}}$), negative-sequence ($I_{-\text{ve}}$) the current waveform
- Total harmonic distortion (THD) in each phase of the voltage waveforms, i.e., $V_{\text{THD}}^{\text{a}}, V_{\text{THD}}^{\text{b}}$, and $V_{\text{THD}}^{\text{c}}$
- THD in each phase of the current waveforms, i.e., $I_{\text{THD}}^{\text{a}}$, $I_{\text{THD}}^{\text{b}}$, and $I_{\text{THD}}^{\text{c}}$.

Features are extracted based on Stage 1 raw data:

- 10 features are extracted in each power cycle.
- These samples for various test cases are used for the next-stage learning.

Finding classifiers for fault detection based on learning:

- Samples from Stage 2 are used for learning and modeling the classifier.
- A statistical learning theory like SVM with a two-class classification problem is used.
- Classes are (1) no-fault and (2) fault.
- This learning with a large volume of data is done using MATLAB's machine learning environment.

ML Tool: SVM Classifier

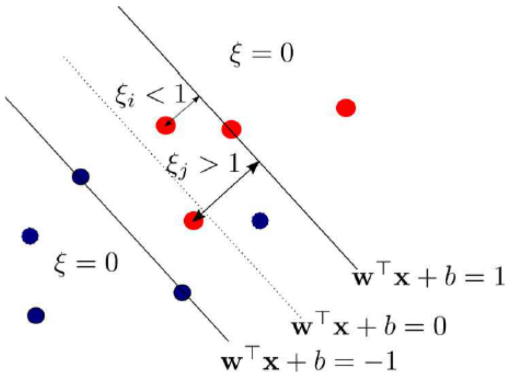
- Support vector machines (SVMs) have been widely used in data-driven classification problems.
- The goal of SVMs is to find a hyperplane that can optimally separate data into two different classes (extendable to multiclass problems).

- **SVM Classifier Mathematical Problem**

$$\min_{w,b,\{\beta_n\}} \quad \frac{1}{2}\|w\|_2 + C\sum_n \beta_n$$

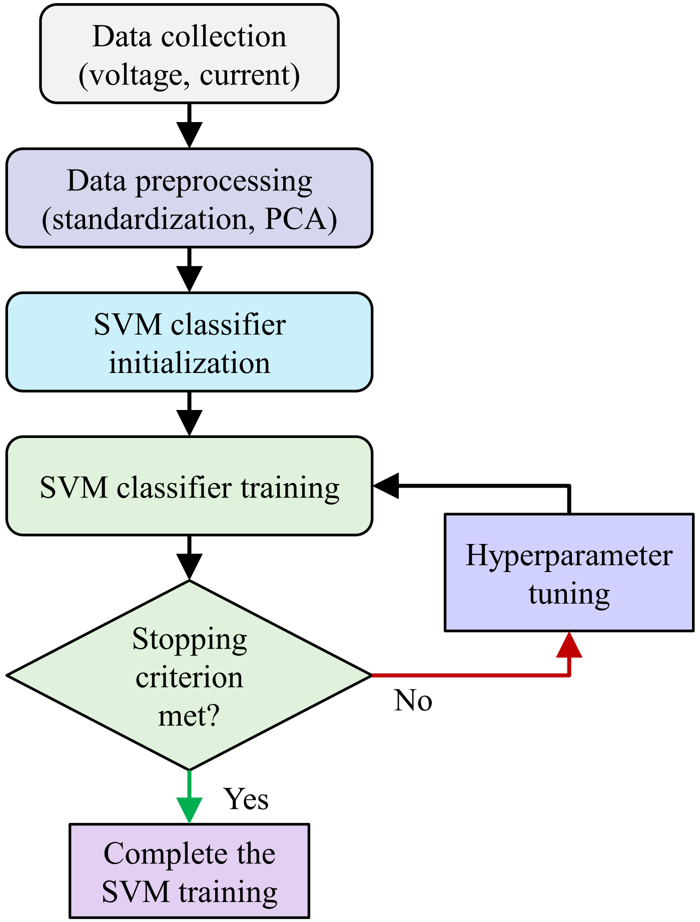
$$\text{s. to} \quad y_n[w^T\phi(x_n)+b] \geq 1-\beta_n \qquad \forall n$$

$$\beta_n \geq 0 \qquad \forall n$$



SVM illustration with a simple kernel function.

- **Flowchart for SVM Training**

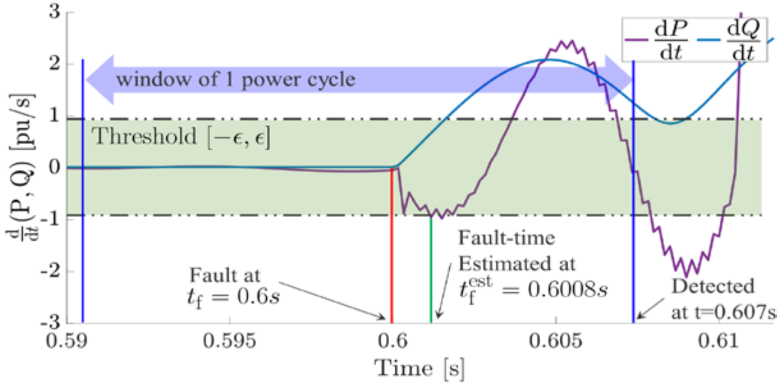


Fault Time Estimation

- Once the fault detection logic detects a fault, it triggers the fault time estimation block.
- The detection trigger signal enables a block that computes the following two quantities:

  $\mathrm{dp(t)/dt}$, and $\mathrm{dq(t)/dt}$

  where $\mathrm{p(t), q(t)}$ are the instantaneous active and reactive power measured by the relay, computed over the previous power cycle only.
- Before and after the fault, there will be a sufficient transient change in $\mathrm{p(t), q(t)}$, as shown in the figure:



Example: During AG fault at F1 with fault impedance of 0.014Ω.

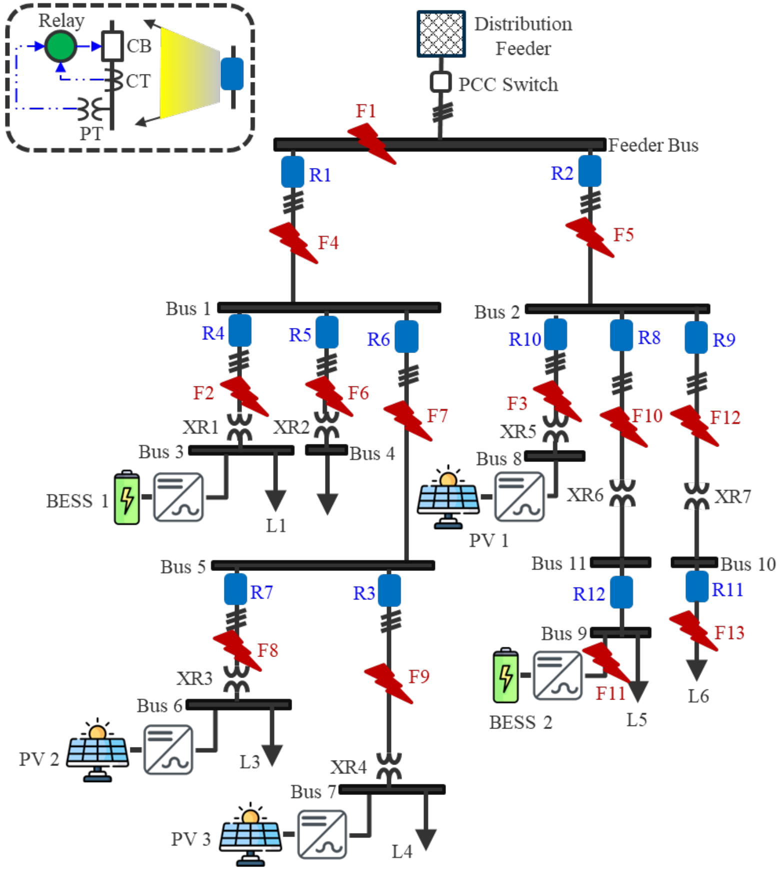
- The logic of the fault time estimation is to find the time stamp when the following condition holds:

  $\mathrm{dp(t)/dt} \geq \epsilon$ Or $\mathrm{dq(t)/dt} \geq \epsilon$

- If t_f^{est} is the instant when the above condition is satisfied, as shown in figure.
- The logic will be triggered only when the fault detection block detects a fault.
- This signifies the triggering fault estimation logic, which will be deactivated if the fault detection logic does not enable the operation.

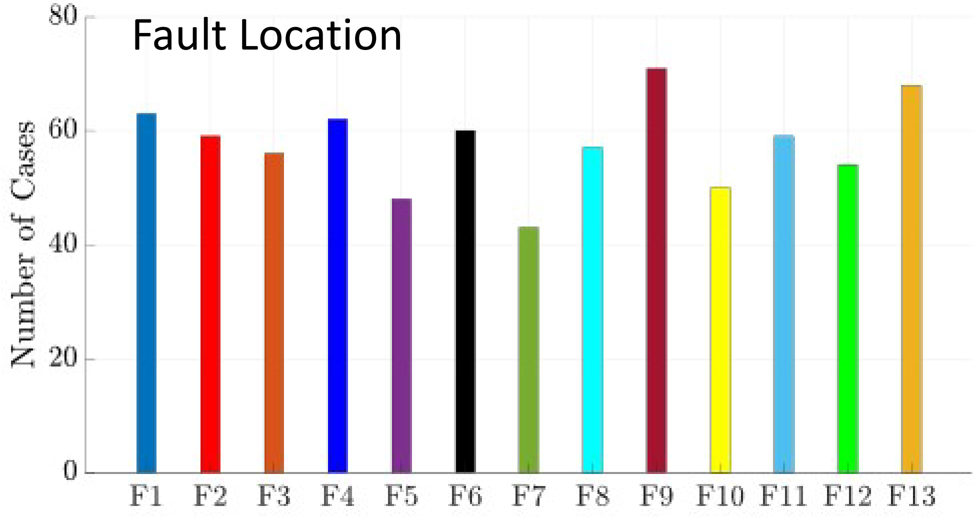
System Under Study

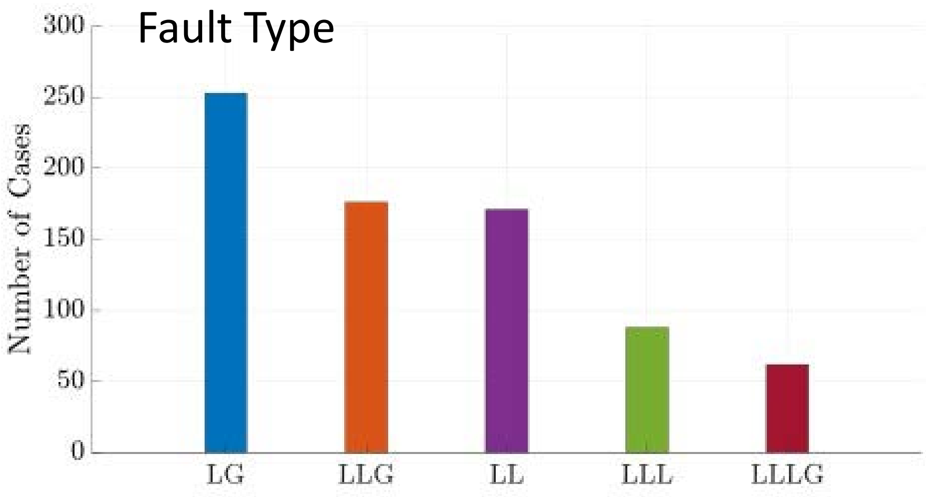
- 100% IBR-based microgrid based on Feeder 2 circuit of Banshee distribution system
- DERs:
  - Battery energy storage system (BESS) 1 of 2 MVA at Bus 3
  - PV 1 of 2 MW at Bus 8
  - Addition of BESS 2 of 1 MVA at Bus 11
  - Addition of PV 2 of 0.5 MW at Bus 6
  - Addition of PV 3 of 1 MW at Bus 7.
- BESS are in grid-forming (GFM) control for both grid-connected and islanded mode:
  - Power tracking for grid-connected mode
  - VF power sharing control for islanded mode.
- PV units are in grid-following (GFL) control with the following three modes:
  - Fixed power factor
  - PQ dispatch
  - Volt-volt ampere reactive (VAR) control with VAR priority.
- Both PV and BESS DERs are IEEE Std. 1547 complaint.
- Constant impedance loads of 4.7 MW with balance and unbalanced loads.
- Circuit breakers have 5 cycles of mechanical delay.

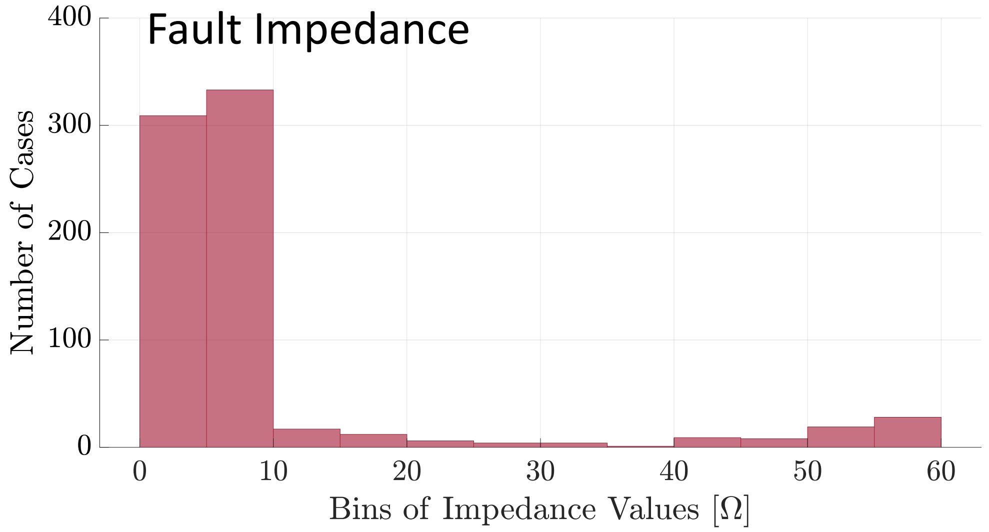


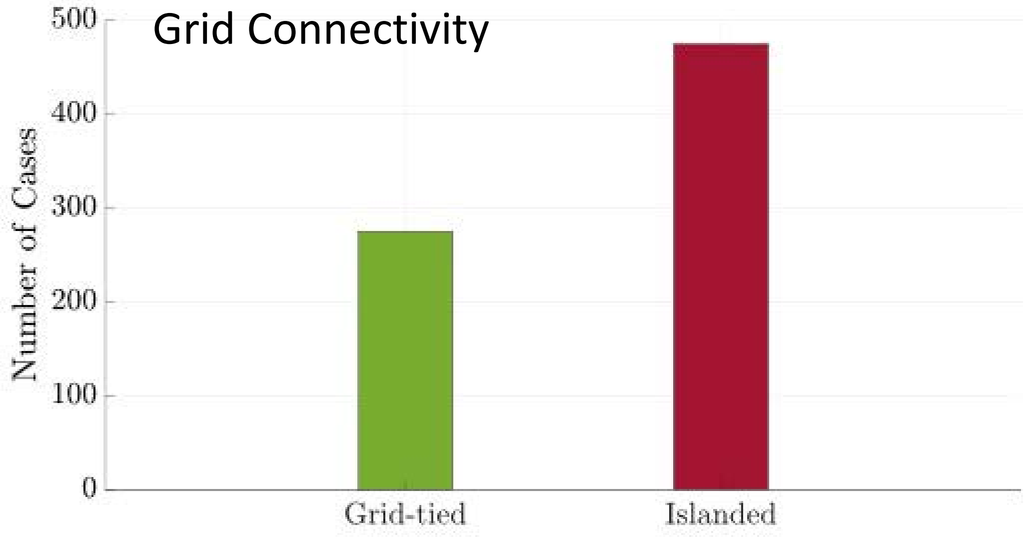
- 13 possible fault locations:
  - Various types: line-to-line, line-to-ground
  - Both low-impedance and high-impedance faults.

750 Testing Cases





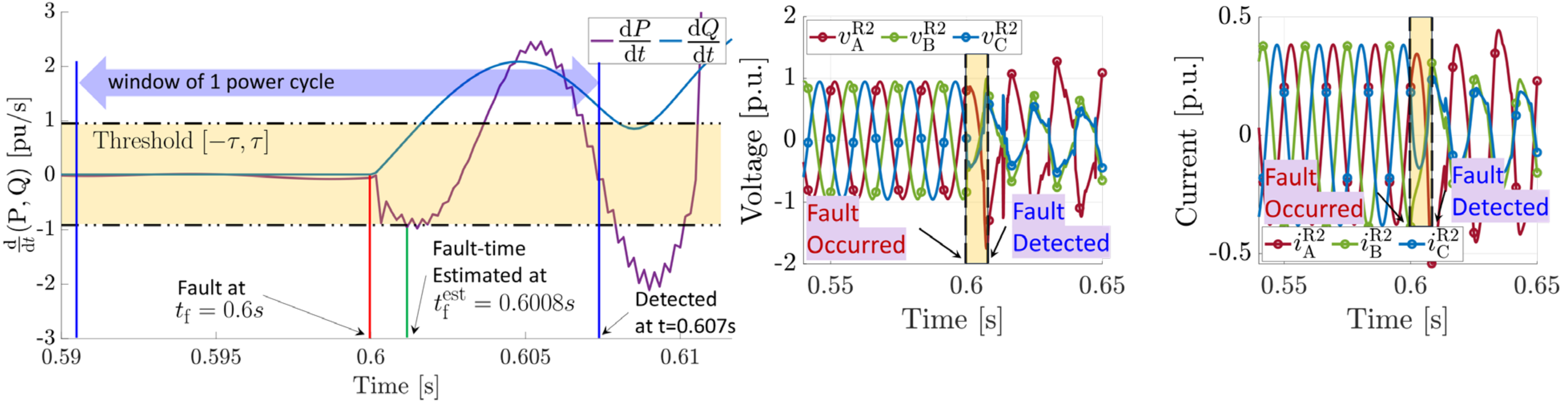




TESTING RESULTS

Case Details: Feature and Diff Quantities measured @ R201

Location	FaultType	FaultImp	FaultRes	Time	PV_Level	Grid_Conn	Load_C3	Load_I3	Load_I4	Load_P3	Load_P2	Load_I5	PV1_mode	PV2_mode	PV3_mode	Season	Day	Time
Fault2	ag	0.014	m	0.6	0.789209	1	0.504637	0.125159	0.055977	0.362516	0.369593	0.058335	0	0	0	Summer	Weekend	N

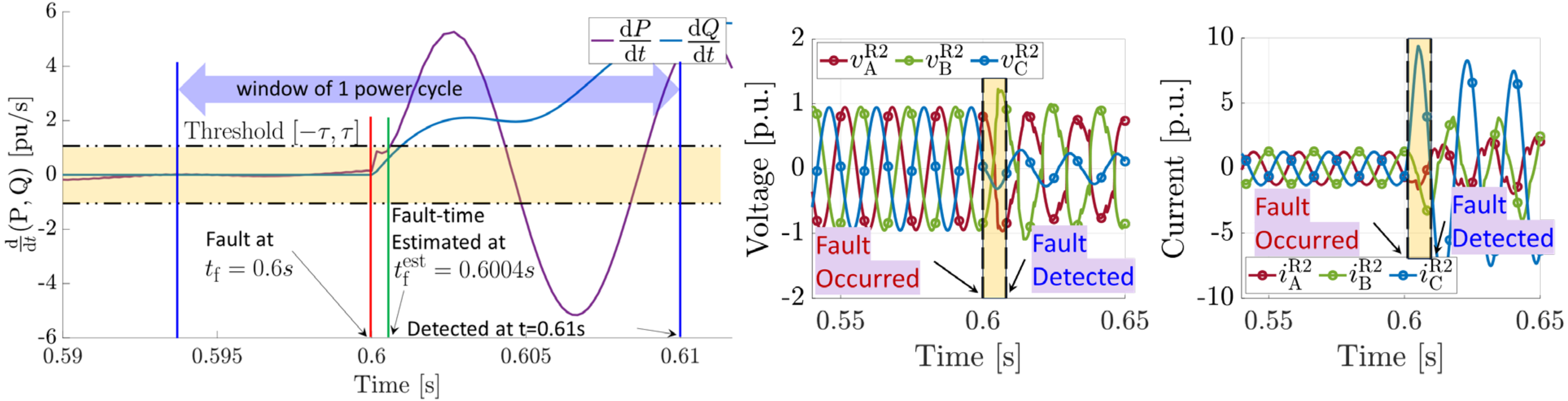


Key observations:

- Can detect and estimate the fault event within half a cycle.

Case Details: Feature and Diff Quantities measured @ R202

Location	FaultType	FaultImp	FaultRes	FaultTime	PV_Level	Grid_Conn	Load_C3	Load_I3	Load_I4	Load_P3	Load_P2	Load_I5	PV1_mode	PV2_mode	PV3_mode	Season	Day	Time
Fault10	abcg	0.187	m	0.6	0.301768	1	0.356582	0.384515	0.312571	0.412276	0.441392	0.388014	1	1	1	Fall	Weekday	M



Key observations:

- Can detect and estimate the fault event within half a cycle.

TESTING RESULTS

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TABLE I: Performance of the SVM-based fault detection method on offline training data. Grtd = grid-tied, Isld = islanded.

Relay	Precision [%]		Recall [%]		Accuracy [%]	
	Grtd	Isld	Grtd	Isld	Grtd	Isld
R_1	97.44	97.31	95.07	96.03	94.63	95.01
R_2	97.89	97.22	95.12	96.52	94.58	95.12
R_3	97.13	97.72	94.96	96.11	94.79	94.97
R_4	97.25	97.11	95.07	95.96	94.88	94.87
R_5	97.69	97.43	95.11	96.03	94.66	95.06
R_6	97.56	97.63	95.26	96.05	94.37	95.12
R_7	97.81	97.56	94.93	96.11	94.33	95.21
R_8	97.52	97.87	95.33	96.16	94.38	95.30
R_9	97.22	97.19	95.03	95.91	94.23	94.98
R_{10}	97.88	97.37	95.18	95.96	94.99	95.11
R_{11}	97.44	97.79	95.01	96.11	95.12	95.13
R_{12}	97.51	97.27	94.93	95.02	95.17	95.18

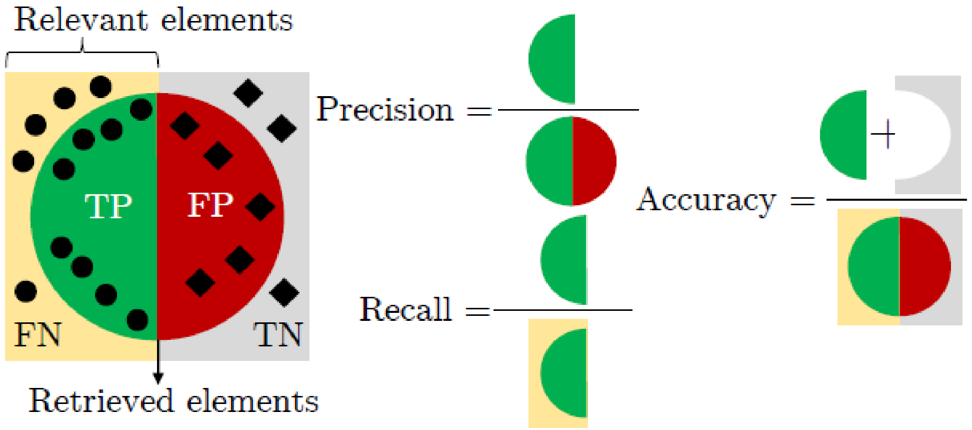

TABLE II: Performance of the fault detection method.

R_1	R_2	R_3	R_4	R_5	R_6
97.87%	97.73%	99.06%	99.06%	98.67%	99.06%
R_7	R_8	R_9	R_{10}	R_{11}	R_{12}
98.67%	99.33%	98.81%	98.93%	98.81%	99.06%

Key observations:

- High accuracy for all inverters for fault detection for both grid-connected and islanded mode
- The average accuracy of all relays is above 97.9%.

CONCLUSIONS

- ✓ Learning based protection requires:
  - Design of simple learning tasks for local machine learning models.
  - The use of representative fault data samples with representative fault signatures
  - The accurate synchronization of the incidence of fault events seen by different relays.

- ✓ The asynchronicity issue is resolved by the fault time estimation algorithm implemented in each relay model with comparing the dP/dt and dQ/dt with the thresholds.

- ✓ The fault event is detected within half a cycle. This is promising for data-driven-based protection.

- ✓ The accurate fault time estimation can be used to coordinate between relays to avoid unnecessary tripping, thus improving the reliability of the power system.

Q&A and Thank You

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