Implementation of a New Algorithm to Detect Turn-to-Turn Faults in Shunt Reactors and Identify the Faulted Phase

Paul I. Nyombi
Xcel Energy
Minneapolis, MN

Zhiying Zhang
General Electric Grid Solutions
Canada

Pratap G. Mysore
Pratap Consulting Services, LLC
Plymouth, MN

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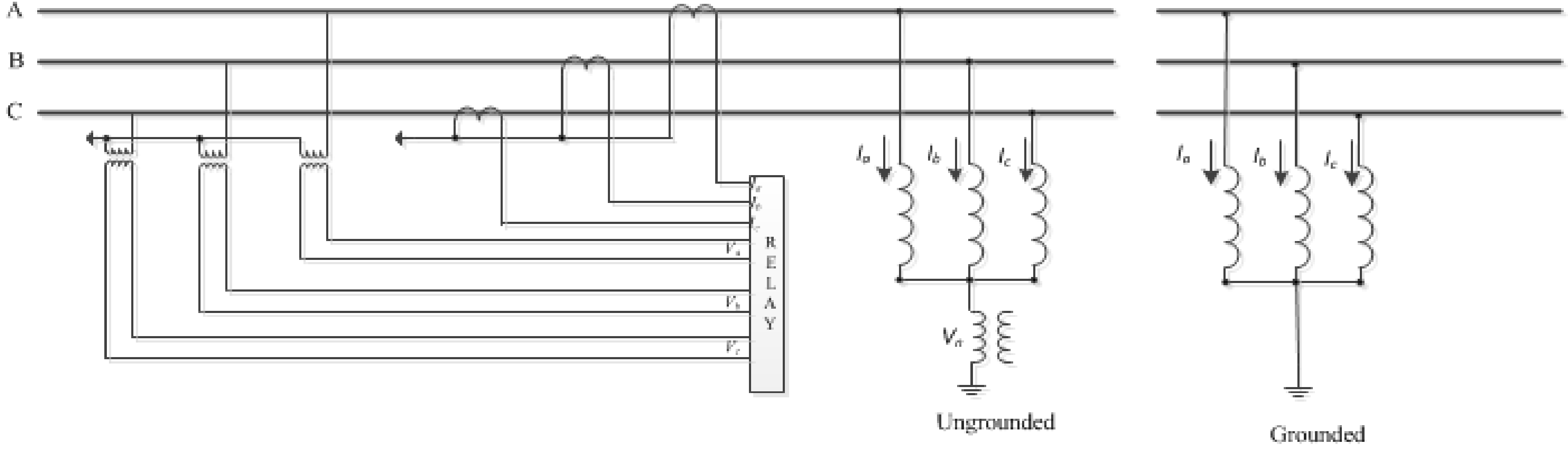
Reactor Configurations Considered

Presentation will mostly be focused on air core reactors in a wye-grounded and ungrounded configuration



Typical Turn to Turn Reactor Fault Detection Schemes

As per, IEEE Guide for the Protection of Shunt Reactors, ANSI/IEEE C37.109-1988, following schemes are generally used for detecting turn-turn reactor faults

- Negative Sequence Time Overcurrent (51Q)
- Voltage Differential Scheme (87V)
- Negative Sequence Directional Element (32Q)

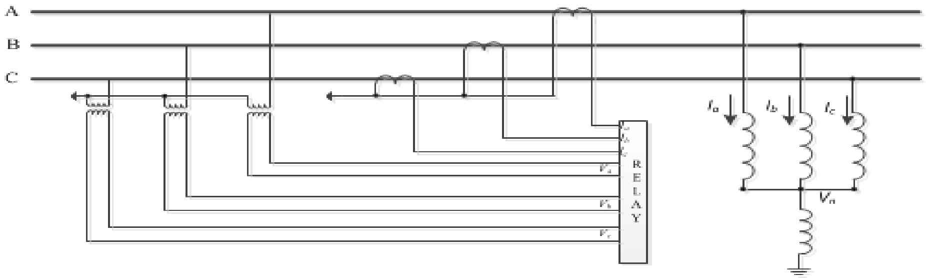
New Algorithm for Turn-to-Turn Fault Detection

Fundamentals of the new algorithm

Negative sequence voltage normalization

$$\frac{V_2}{V_1} = \frac{V_a + a^2 V_b + aV_c}{V_a + aV_b + a^2 V_c} \qquad (1)$$

Where the *operator a* is define as $1e^{120^\circ i}$



Negative sequence current normalization

$$\frac{I_2}{I_1} = \frac{I_a + a^2 I_b + aI_c}{I_a + aI_b + a^2 I_c} \qquad (2)$$

New Algorithm for Turn-to-Turn Fault Detection

Fundamentals of the new algorithm

Consider Z_a, Z_b, & Z_c phases to be reactor impedances for A, B, and C-Phases respectively.

$$\frac{I_2}{I_1} = \frac{\frac{V_a - V_n}{Z_a} + a^2 \frac{V_b - V_n}{Z_b} + a \frac{V_c - V_n}{Z_c}}{\frac{V_a - V_n}{Z_a} + a \frac{V_b - V_n}{Z_b} + a^2 \frac{V_c - V_n}{Z_c}} \qquad (3)$$

Where, V_n, as shown in the previous figure, is zero for solidly grounded reactors.

For $Z_a = Z_b = Z_c = Z$

$$\frac{I_2}{I_1} = \frac{\frac{V_a - V_n}{Z} + a^2 \frac{V_b - V_n}{Z} + a \frac{V_c - V_n}{Z}}{\frac{V_a - V_n}{Z} + a \frac{V_b - V_n}{Z} + a^2 \frac{V_c - V_n}{Z}} \qquad (4)$$

New Algorithm for Turn-to-Turn Fault Detection

Fundamentals of the new algorithm

With $Z_a = Z_b = Z_c = Z$, equation (4) reduces to:

$$\frac{I_2}{I_1} = \frac{V_a + a^2 V_b + a V_c}{V_a + a V_b + a^2 V_c} \qquad (5)$$

Comparing equations (1) and *(5)* gives $\frac{V_2}{V_1} = \frac{I_2}{I_1}$.

This is true for all balanced and unbalanced system voltages as long as reactor impedances are nearly equal.

During turn − to − turn faults, $\frac{V_2}{V_1} \neq \frac{I_2}{I_1}$. The phasor difference between $\frac{V_2}{V_1}$ *and* $\frac{I_2}{I_1}$ will be used to compute the *Operate* quantity

Faulted Phase Identification

- Identification of the faulted phase is based on the phasor angle of the *Operate* quantity.
  - Phasor angle of 180^o indicates an A-Phase turn-to-turn fault
  - Phasor angle of 300^o indicates a B-Phase turn-to-turn fault
  - Phasor angle of 60^o indicates a C-Phase turn-to-turn fault
- Due to the assumptions made during the derivation of the phase identification , a $\pm 30^o$ tolerance is recommended

$Diff_{angle}$	*Phase selection decision*
$150^o \leq Diff_{angle} \leq 210^o$	*Turn to turn fault in phase A*
$270^o \leq Diff_{angle} \leq 330^o$	*Turn to turn fault in phase B*
$30^o \leq Diff_{angle} \leq 90^o$	*Turn to turn fault in phase C*

Application of the New Algorithm

A. Setting Philosophy

- Maximum normal voltage imbalance of *10%*, is considered in determining the tolerances of $\frac{V_2}{V_1}$ and $\frac{I_2}{I_1}$. If the maximum expected PT and CT measurement errors are $\pm$ *5%* of the measured values, the worst expected steady state difference, Diff_{steady}, will be given as:

$$\frac{V_2}{V_1} = 10\ x\ 1.05 = 10.5\%$$

$$\frac{I_2}{I_1} = 10\ x\ 0.95 = 9.5\%$$

$$\text{Diff}_{steady} = \frac{V_2}{V_1} - \frac{I_2}{I_1} = |10.5 - 9.5| = 1.0\%$$

- Diff_{pickup}, can not therefore be set lower than *1.0%.*
- Also as per IEEE Std C57.21-2008, the maximum deviation of the impedance in any of the phases shall be within $\pm$*2.0%* of the average impedance of the three phases. Therefore, all practical purposes, Diff_{steady}, as computed above is sufficient.

Application of the New Algorithm

A. Setting Philosophy

- To protect the reactor, Diff_{pickup} is set to pick up for at least 5% shorting in the reactor. At that fault level,

$$\frac{V_2}{V_1} \ll \frac{I_2}{I_1}$$

- Consider a 5% shorting in B-Phase reactor turns. $\frac{I_2}{I_1}$ is computed as:

$$\frac{I_2}{I_1} = \frac{\frac{V_a}{Z_a} + a^2\frac{V_b}{0.95Z_b} + a\frac{V_c}{Z_c}}{\frac{V_a}{Z_a} + a\frac{V_b}{0.95Z_b} + a^2\frac{V_c}{Z_c}}$$

- If an infinite source is considered, Diff_{pickup} is calculated as:

$$\text{Diff}_{pickup} = \frac{V_2}{V_1} - \frac{I_2}{I_1} \cong \left|\frac{I_2}{I_1}\right| \times 100 = 1.7\%$$

Application of the New Algorithm

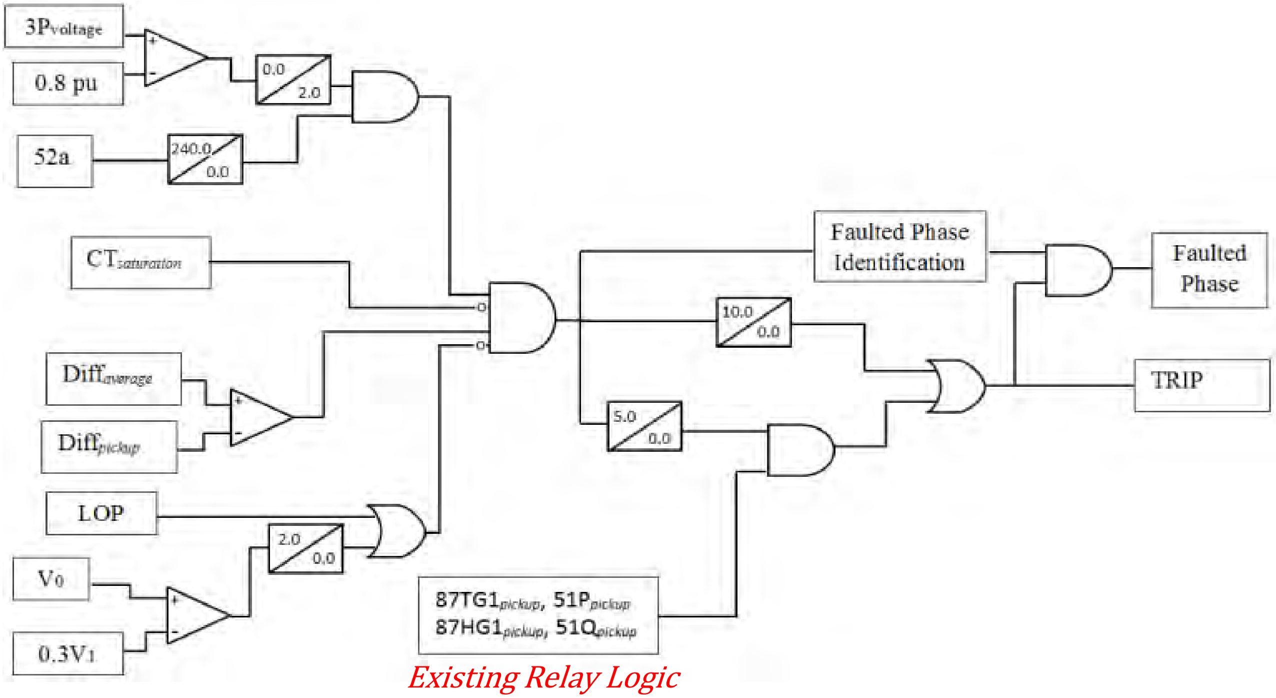
A. <u>Setting Philosophy</u>

- Due to the assumptions involved in this derivation, a safety factor of 2.0 is applied to both $\text{Diff}_{pickup,}$ and Diff_{steady}.
- Diff_{pickup} is selected from $2.0\% < \text{Diff}_{pickup} < 3.4\%$
- The *Operate* quantity is therefore selected so as to be above the normal operating steady state value but below the desired fault pickup value. A pickup value of 2.5% is selected.
- The past eight real-time operating differential values, including the present value are computed and averaged over a power cycle. The averaged differential value, $\text{Diff}_{average}$, is compared against the Diff_{pickup}.

$$Diff_{average}(n) = \frac{1}{p}\sum_{k=1}^{p=8} Diff_{realtime}(n+1-k)$$

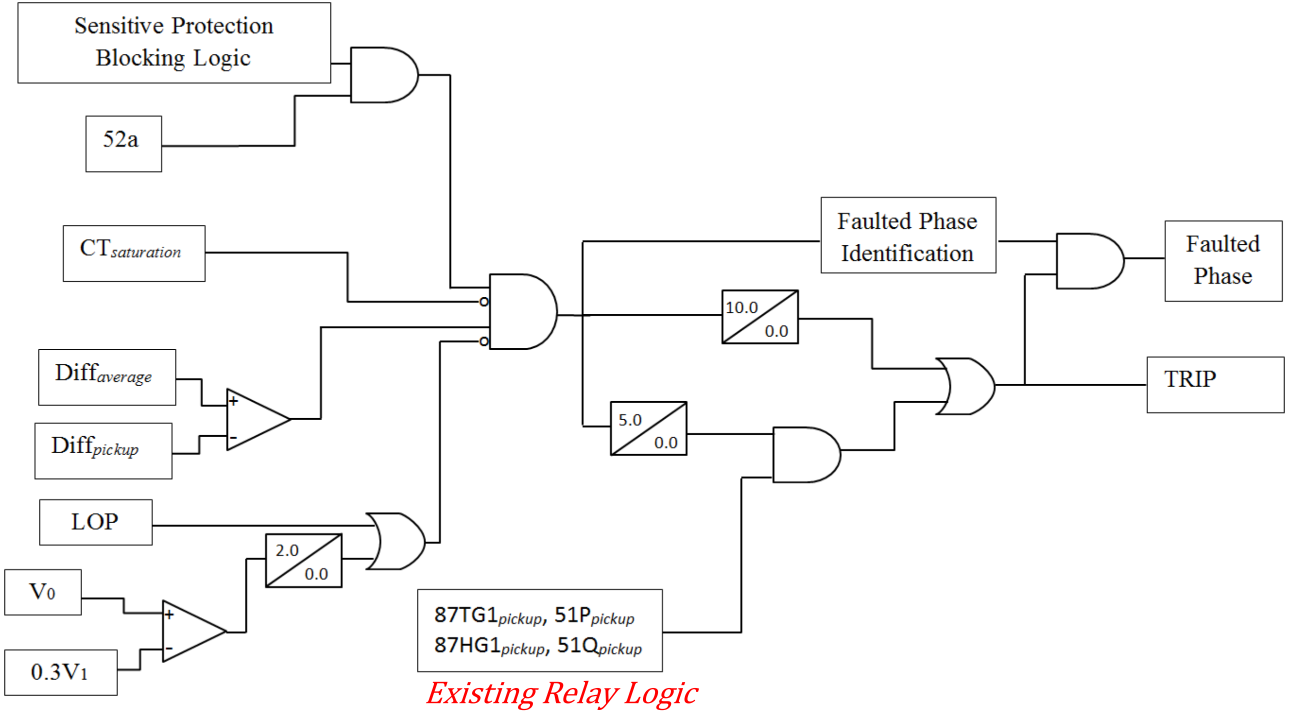
Application of the New Algorithm

B. <u>Logic Implementation</u> – *Ungrounded/Tertiary Connected Reactors*



Application of the New Algorithm

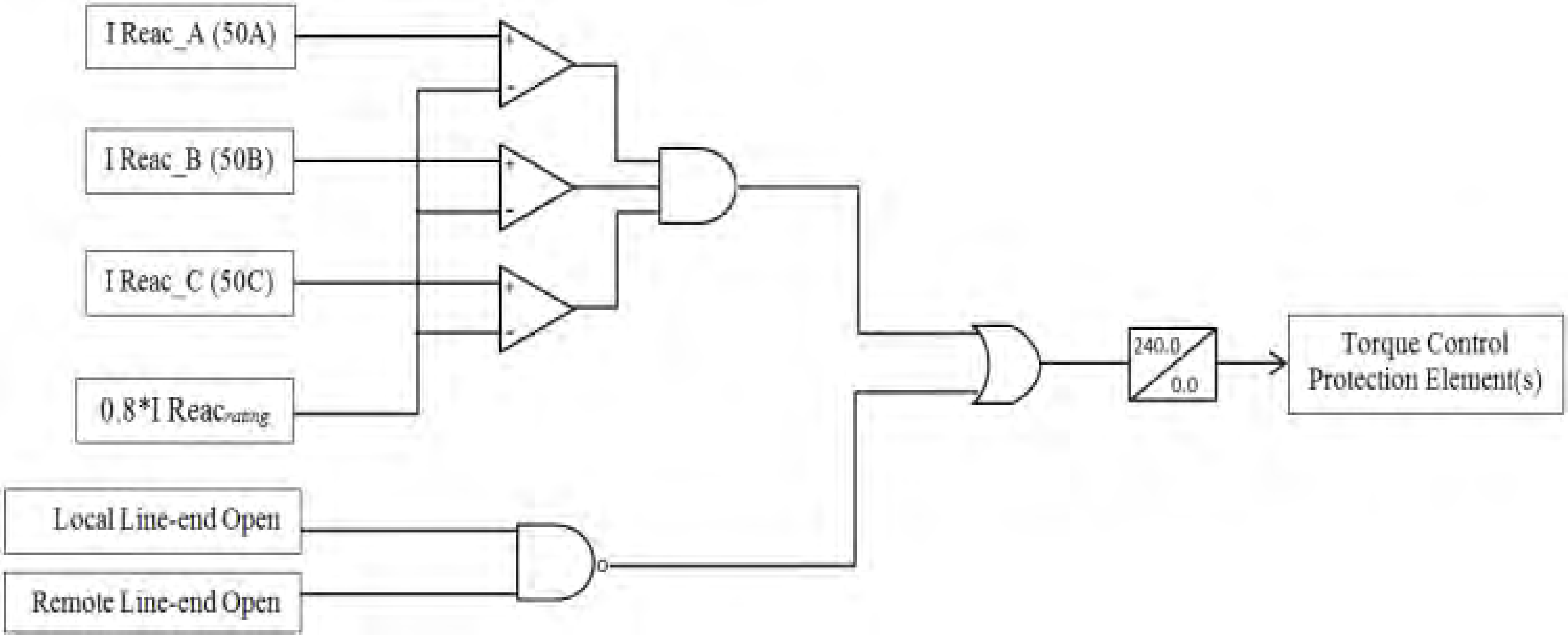
B. Logic Implementation – *Grounded Reactors*



Existing Relay Logic

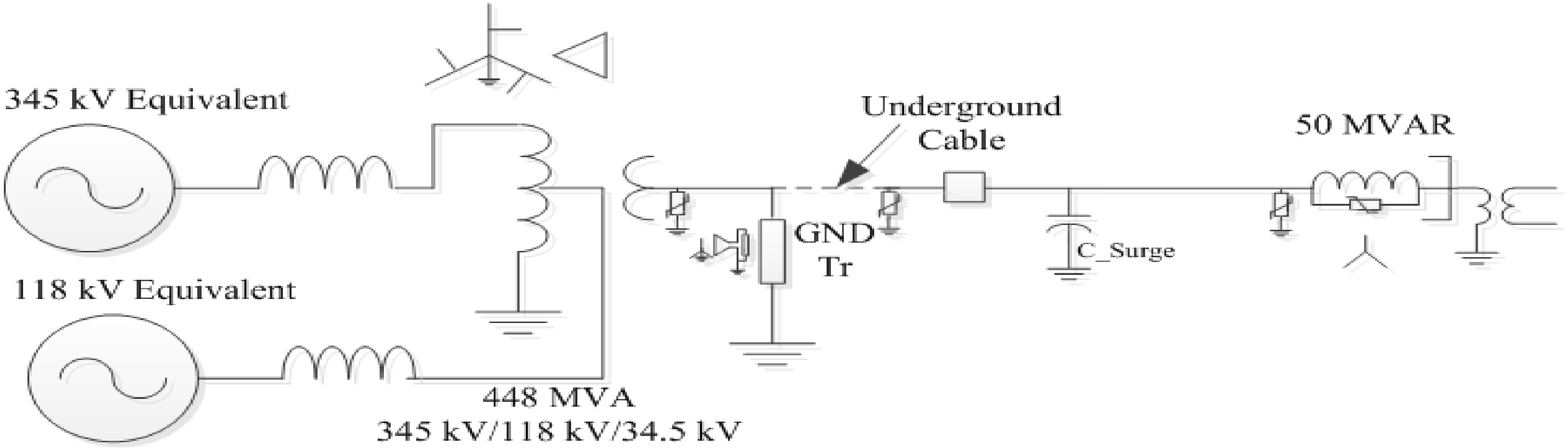
Application of the New Algorithm

B. <u>Logic Implementation</u> – *Sensitive Protection Blocking Logic for Grounded Reactors*



Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

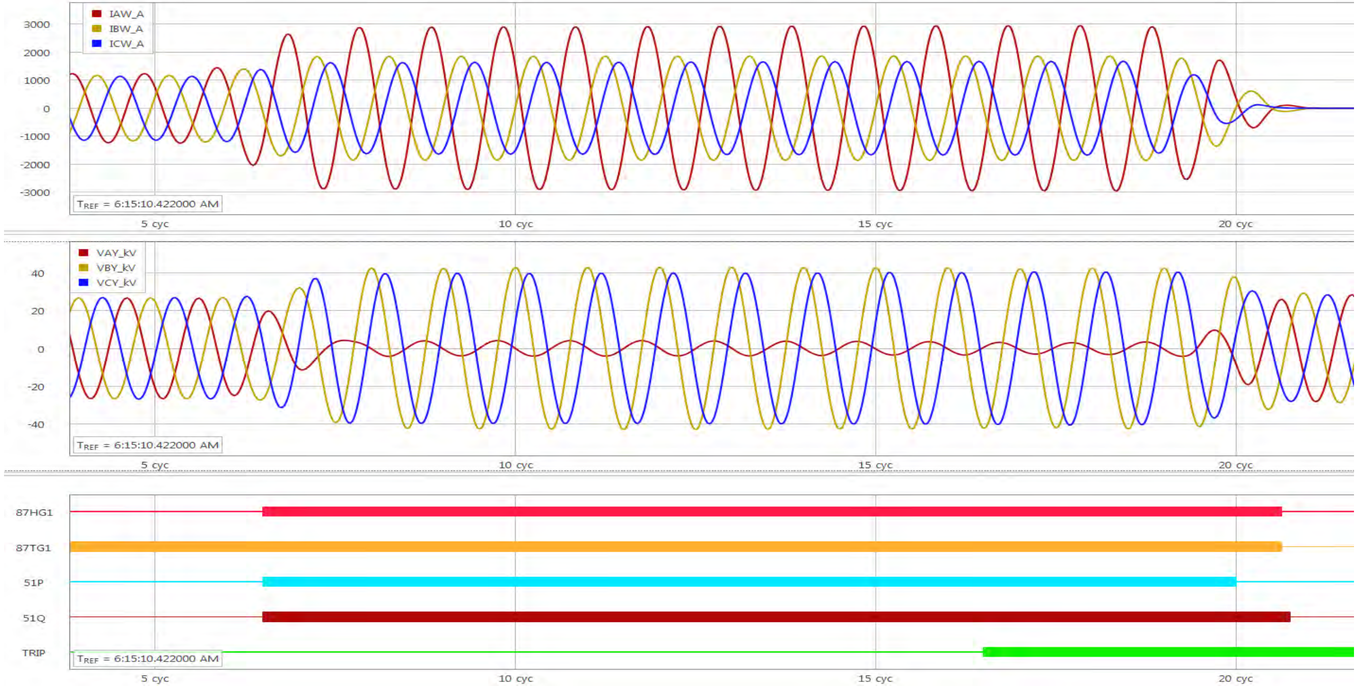


Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

Event: 08/26/2017

Tripped on 87HG1



Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

Event: 08/26/2017

Field Findings: *Failure on A-Phase*

Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

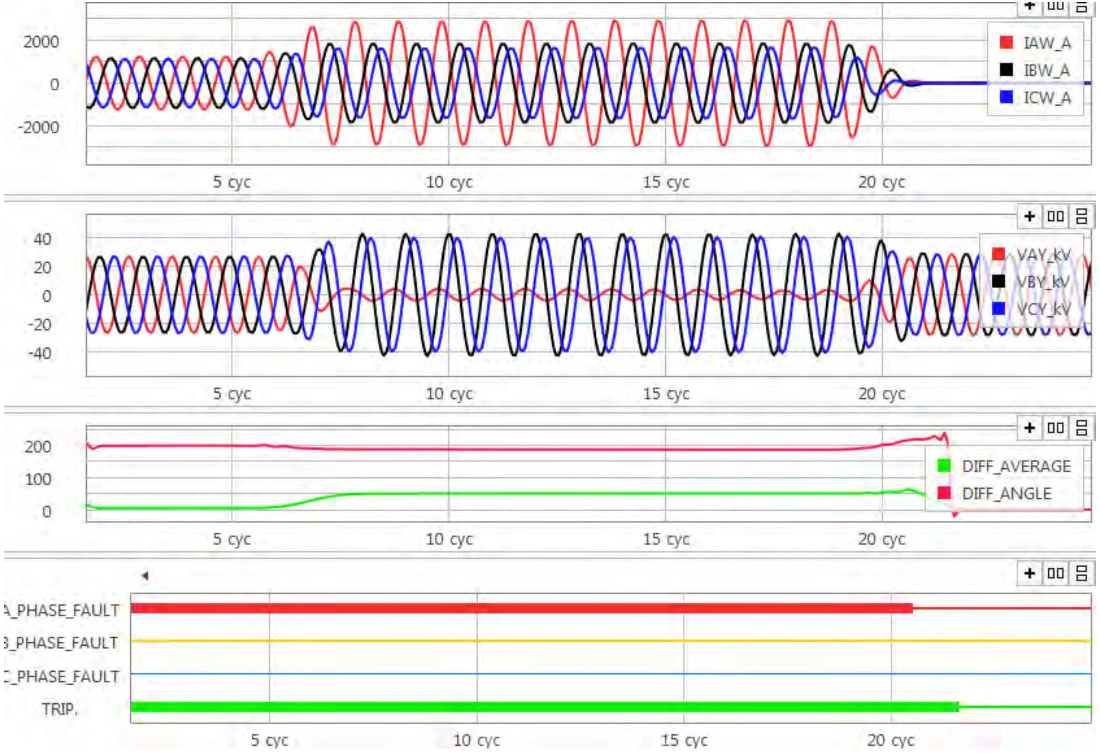
Event: 08/26/2017

With the New Algorithm

Measured (low fault region),

$Diff_{avg} = 5.32\%$

And $Diff_{angle} = 199^{o}$

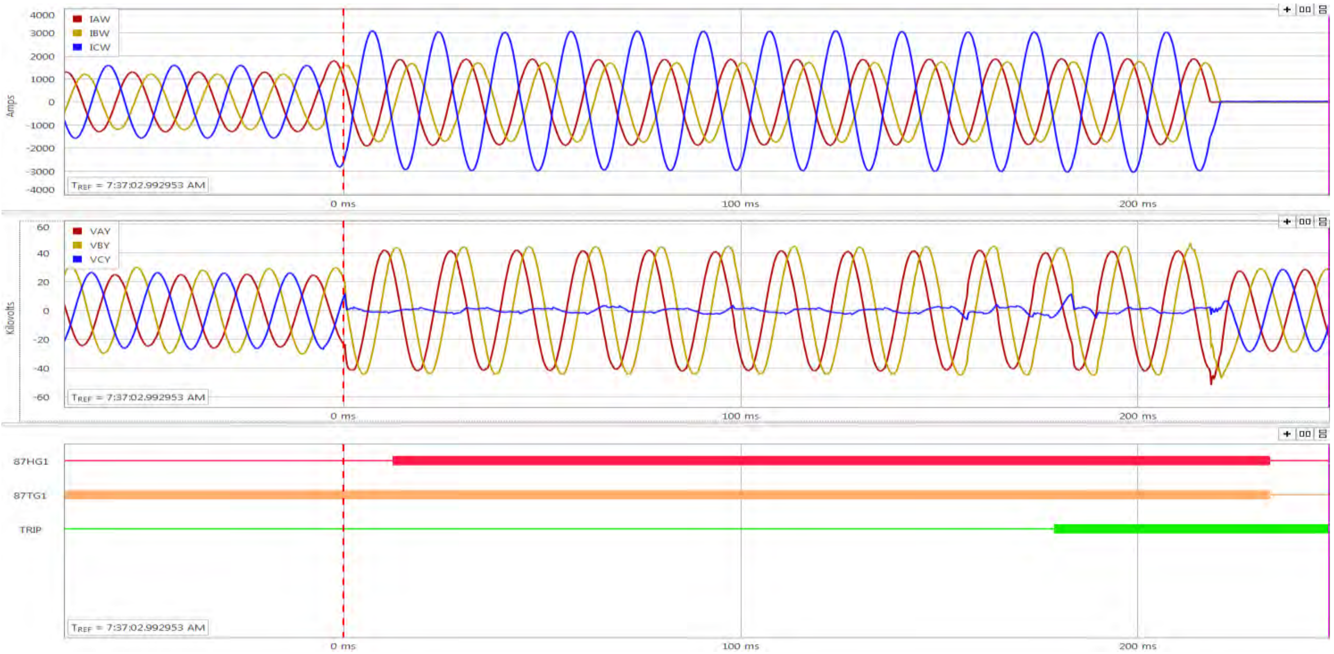


Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

Event: 11/12/2017

Tripped on 87HG1



Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

Event: 11/12/2017

Field Findings: *Failure on C-Phase*

Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

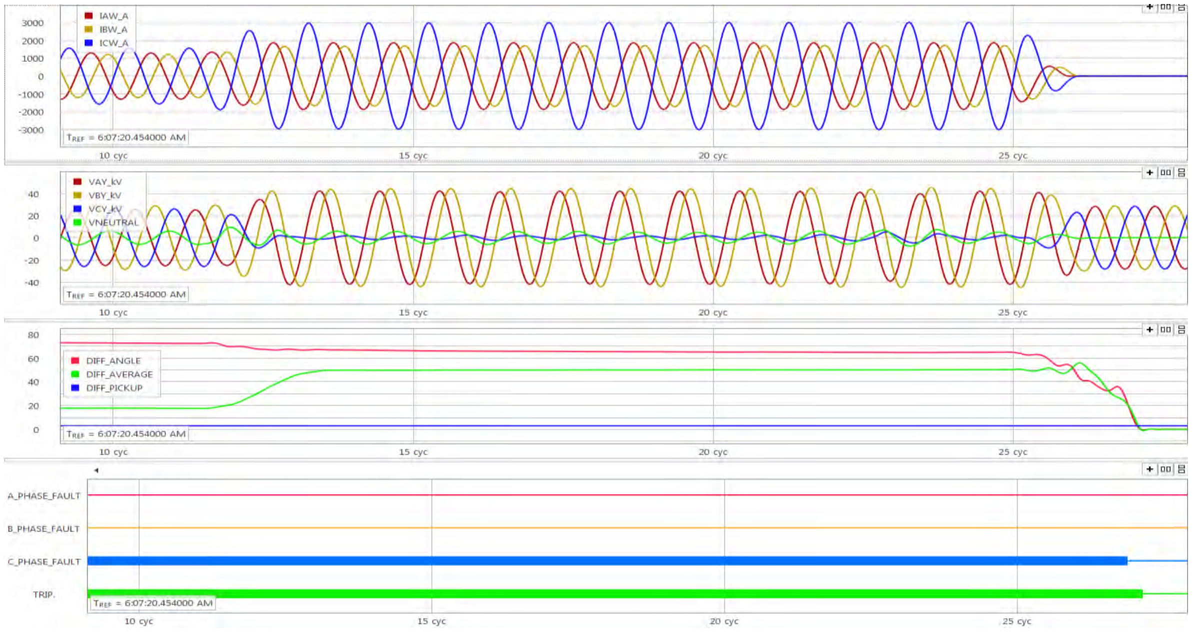
Event: 11/12/2017

With the New Algorithm

Measured (low fault region),

$Diff_{avg} = 17.5\%$

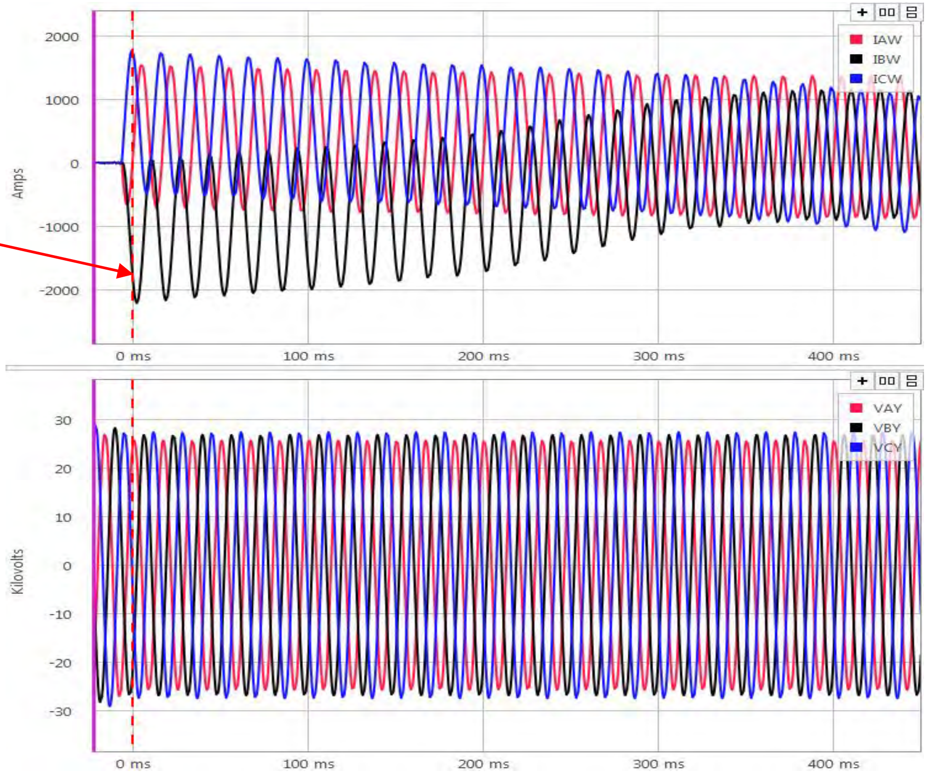
And $Diff_{angle} = 73^{o}$



Field Application of the Proposed Algorithm

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV - *Energization*

Observation: *There's a sudden loss of DC in the B-Phase reactor current.*

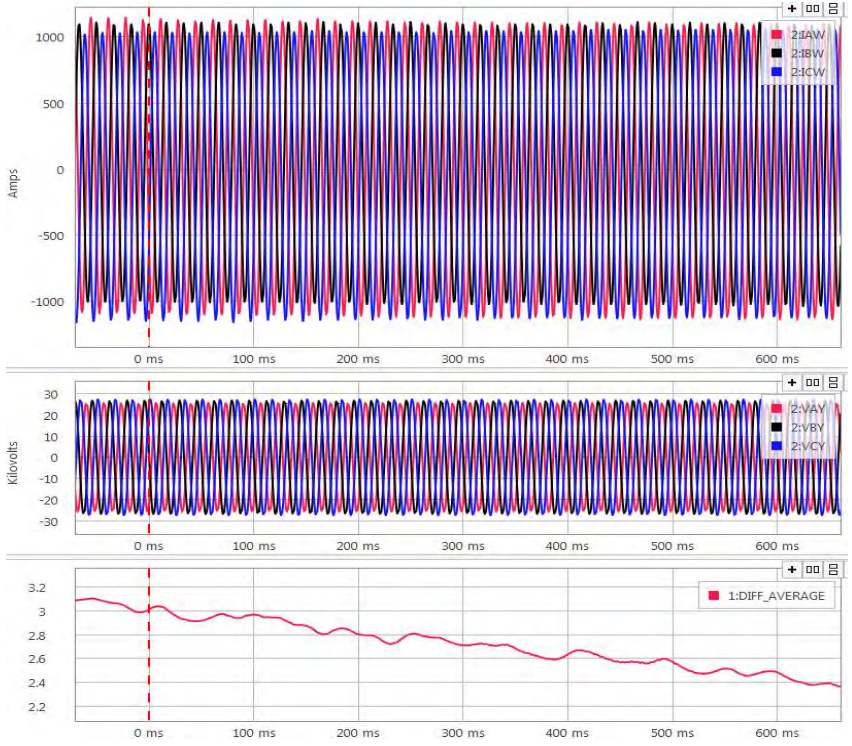


Field Application of the Proposed Algorithm

<u>Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV - *Energization*</u>

Implications

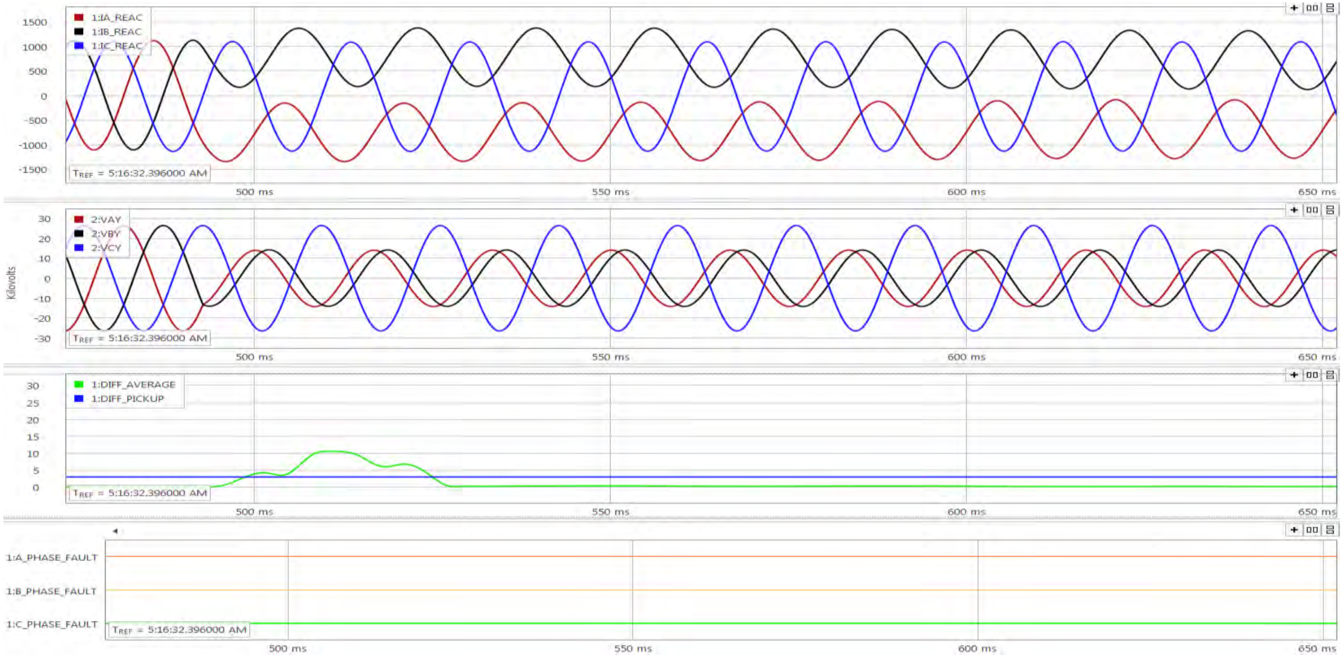
a) *4.0 seconds time delay is recommended. This is longer than the time duration of 3 time constants (X/R = 500) required for the transients to decay down to 95% of their final steady state value for typical Air Core Reactor X/R ratios of 300-500*



Stability of the Algorithm Against External Faults

Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

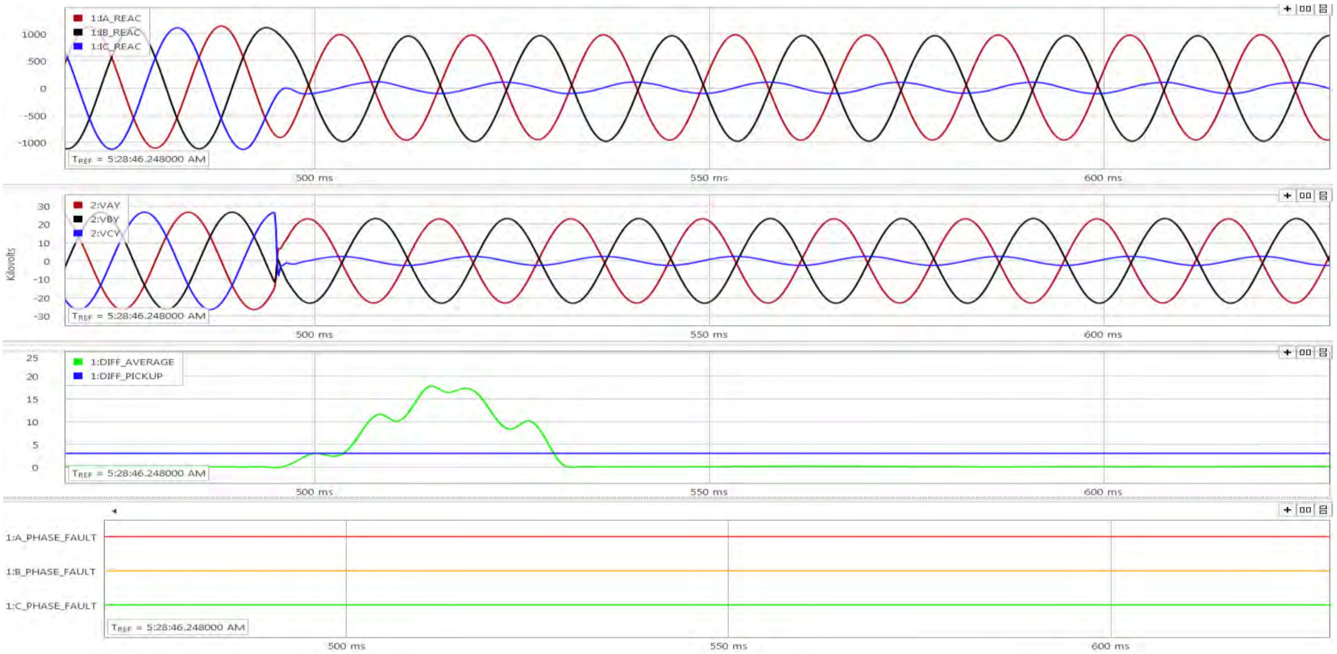
Simulated A-G Bus fault on the 115kV bus



Stability of the Algorithm Against External Faults

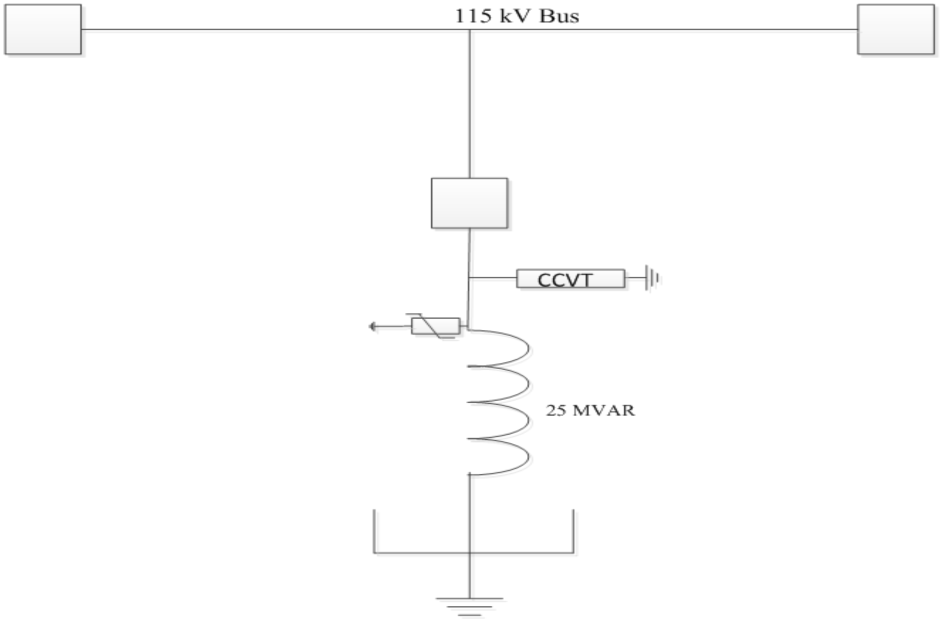
Ungrounded 50MVAR Tertiary Reactor #9, 34.5kV

Simulated B-C Bus fault on the 115kV bus



Field Application of the Proposed Algorithm

25 MVAR Solidly Grounded Reactor #1, 115kV

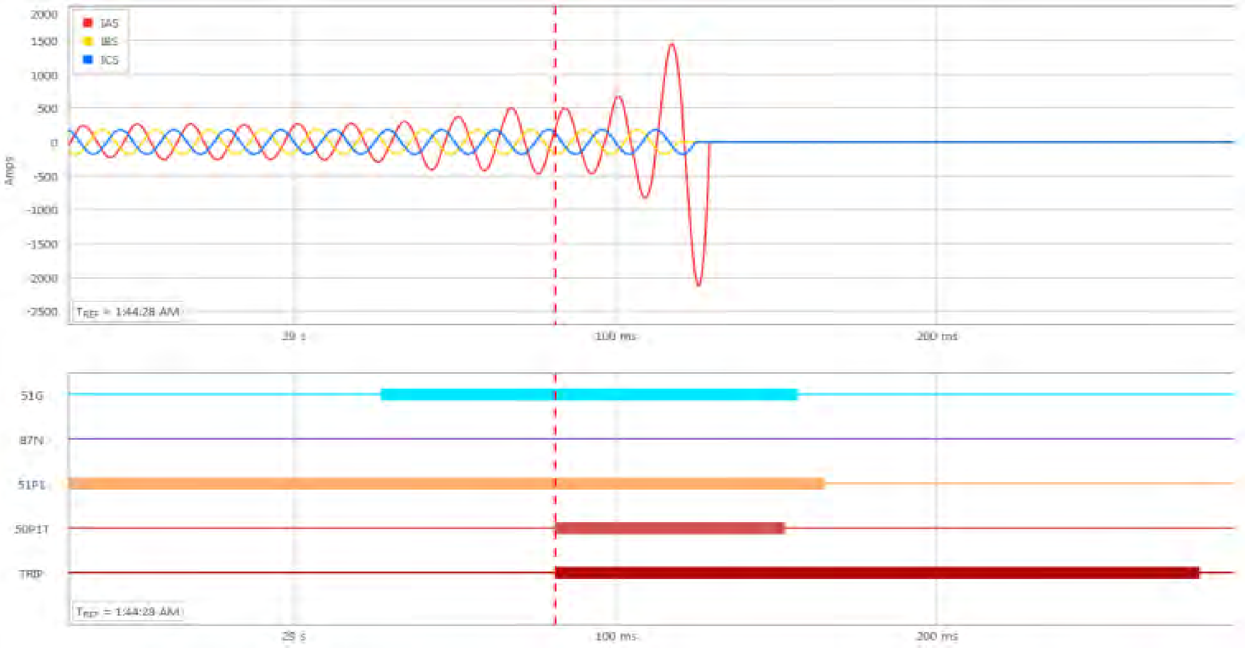


Field Application of the Proposed Algorithm

25 MVAR Solidly Grounded Reactor #1, 115kV

Event: 04/14/2018

51P1T picks up but Reactor trips on 50P1 element



Field Application of the Proposed Algorithm

25 MVAR Solidly Grounded Reactor #1, 115kV

Event: 04/14/2018

Field Findings: *Failure on A-Phase*

Field Application of the Proposed Algorithm

25 MVAR Solidly Grounded Reactor #1, 115kV

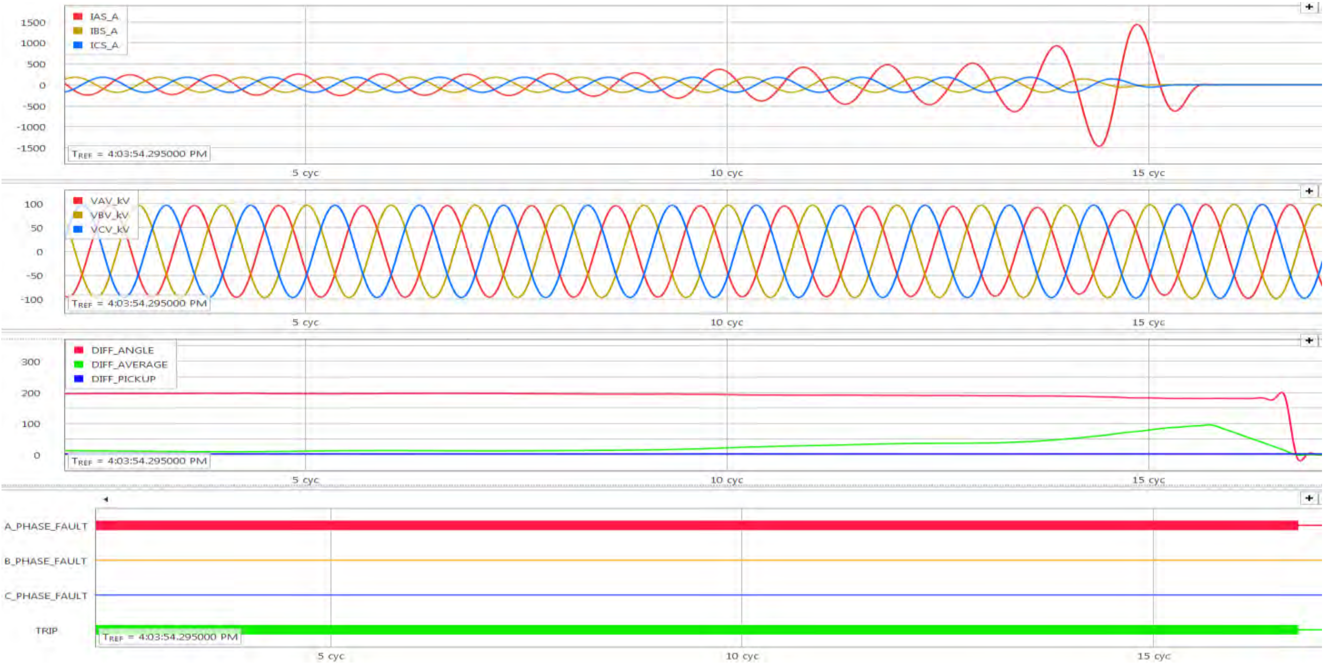
Event: 04/14/2018

With New Algorithm

Measured,

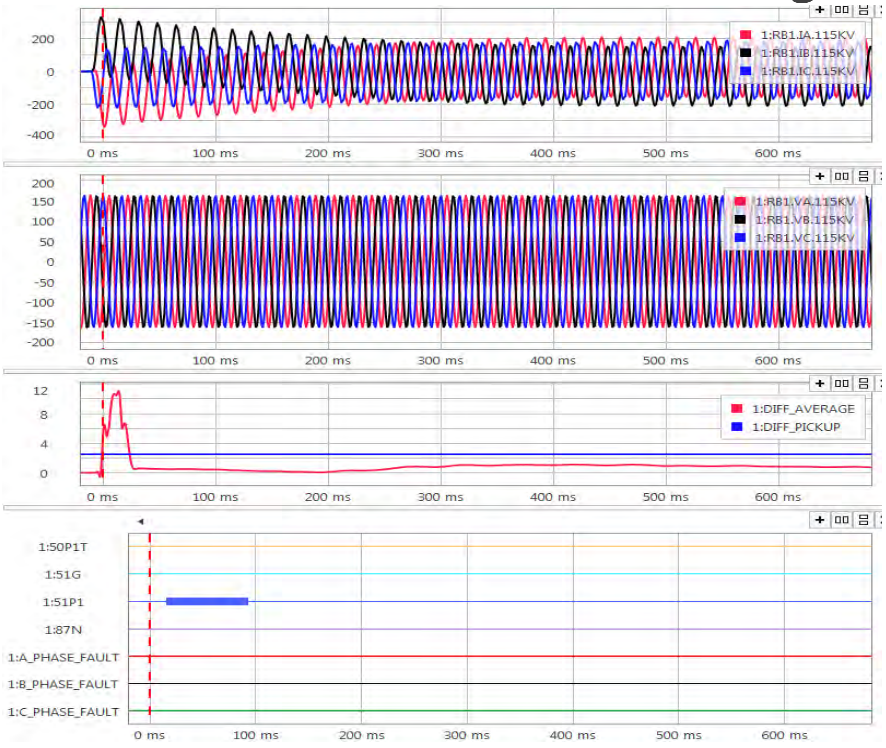
$Diff_{avg} = 10\%$

$And\ Diff_{angle} = 196^{o}$



Field Application of the Proposed Algorithm

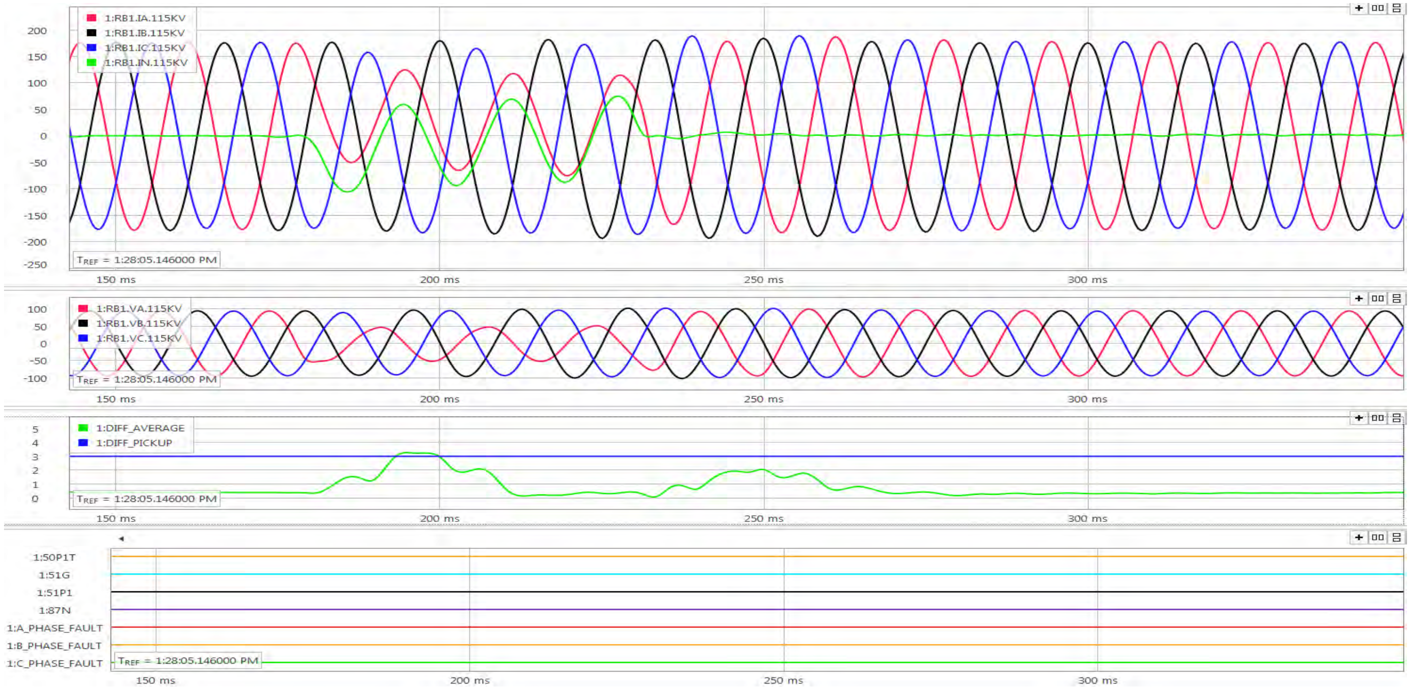
25 MVAR Solidly Grounded Reactor #1, 115kV - *Energization*



Stability of the Algorithm Against External Faults

25 MVAR Solidly Grounded Reactor #1, 115kV

A-G fault 7.5 miles from the substation



Stability of the Algorithm Against External Faults

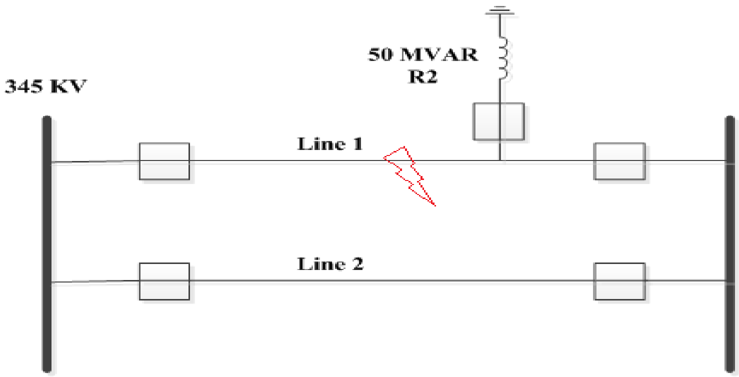
25 MVAR Solidly Grounded Reactor #1, 115kV

A-C fault 5.5 miles from the substation

De-energization of Mutually Coupled Shunt Compensated Line

<u>Simplified Circuit of a 75 mile Double Circuited Line</u>

Fault occurred on Line #1, with no automatic reclosing. Oil filled shunt reactor tripped via negative-sequence time-overcurrent, more than 80 cycles after opening of line-end breakers .



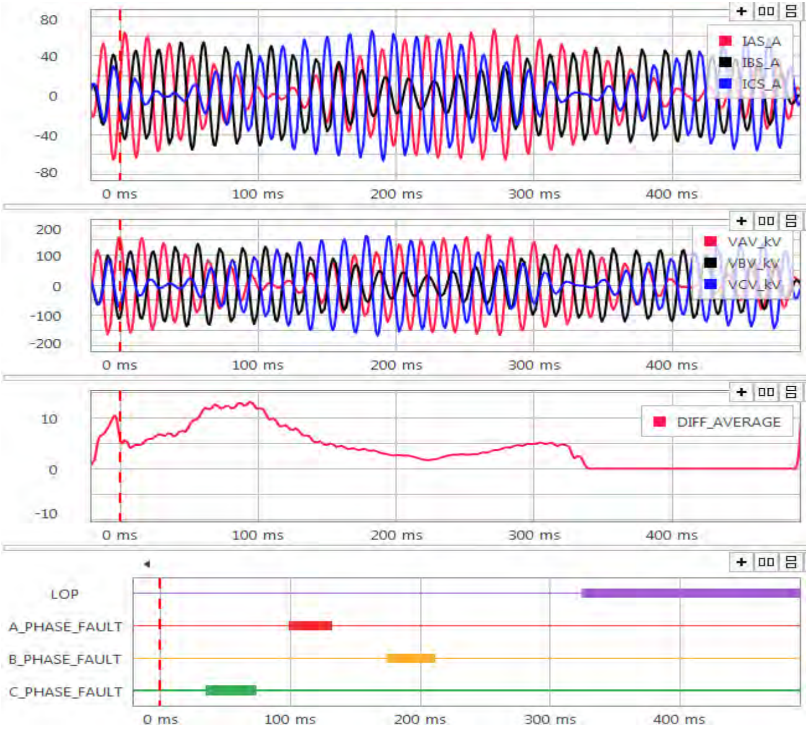
51Q was set to pick up at 20% of the shunt reactor rating.

De-energization of Mutually Coupled Shunt Compensated Line

Evaluation of the algorithm

Observation: *Due to relay's signal processing algorithm, the turn-to-turn fault detection algorithm is not immune to mis-operation*

Recommendation: *Torque control the algorithm using sensitive protection blocking logic*



Conclusions

- 51Q is slow and can't sensitively detect turn-to-turn faults
- 87TG1 does have a definite time delay setting of 5.0s. This is still a very slow element
- Proposed method operates more sensitively and much faster than the current settings standard.
- Faster operation may help save some reactor stacks especially for configurations where more than one reactor is need. High voltage air core reactors are typically stacked together
- Proposed algorithm not only allows for faster detection of reactor turn-to-turn faults, but also allows for the faulty phase identification, which helps minimize time and resources spent on fault location investigations

Questions?