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# Simulation study and experimental results for detection and classification of the transient capacitor inrush current using discrete wavelet transform and artificial intelligence

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**Abstract:** This paper describes the combination of discrete wavelet transforms (DWT) and artificial intelligence (AI), which are efficient techniques to identify the type of inrush current, analyze the origin and possible cause on the capacitor bank switching. The experiment setup used to verify the proposed techniques can be detected and classified the transient inrush current from normal capacitor rated current. The discrete wavelet transforms are used to detect and classify the inrush current. Then, output from wavelet is acted as input of fuzzy inference system for discriminating the type of switching transient inrush current. The proposed technique shows enhanced performance with a discrimination accuracy of 90.57%. Both simulation study and experimental results are quite satisfactory with providing the high accuracy and reliability which can be developed and implemented into a numerical overcurrent (50/51) and unbalanced current (60C) protection relay for an application of shunt capacitor bank protection in the future.

**Keywords:** capacitor switching transient; inrush current; back-to-back capacitor switching; isolated capacitor switching; discrete wavelet transform; fuzzy inference system

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## 1 Introduction

According to the shunt capacitor banks need to be energized and de-energized (switched-in and switch-out) several times in accordance with the behavior of the system load profile, which it is not stable, these banks are created that the switching transient inrush current when they are switched on. The three-phase overcurrent protection relay (50/51) with short time overcurrent and instantaneous functions shall be applied with the desirable minimum pickup of 135% of nominal phase current for grounded wye banks or 125% for ungrounded banks. The operation delay is set long enough to avoid false trips during switching [1, 2]. In modern IEDs (Intelligent Electronic Devices), the time overcurrent functions with fundamental frequency band-pass filters are not sensitive to inrush currents. Successful operation of modern IEDs may be obtained by setting instantaneous relays at a lower value compared with relays without band-pass filters; typically, 3 to 4 times the capacitor bank rated current is sufficient to override back-to-back bank switching [1, 2]. Practically, the minimum pickup is around 15 times the capacitor bank rated current (without band-pass filters) which there is less than the rated short-circuit of the system. It is enough to avoid the relay mal-operation from transient inrush current during energizing the reactive power. However, the suitable pickup setting for instantaneous function shall be 3 to 4 times of the capacitor bank rated current and a few cycles delay because it is convenient for protecting the capacitor in case of the harmonic current presence in the system [3]. Therefore, when designing the shunt capacitor bank protection scheme, it is very important to clearly discriminate between the normal capacitor current and transient capacitor inrush current due to capacitor energizing.

Works of literature on transient classification and discrimination techniques were presented in recent publications [4–11]. These papers have explained a new method for detecting and classifying the power quality disturbance both industries and utilities. The transient classification using various techniques, for instance, using S-Transform and Competitive Neural Network [5], Mathematic morphology [7, 8], Continuous wavelet transform [9], Decision Tree-based Classifiers and Hidden Markov Model [10] and Wavelet-fuzzy logic [11]. The several results of their literatures are effectively detected and classify the transient inrush current from other events. On the other hand, many kinds of literature provide the technique to classify the transient by obtaining the inrush current signal from switching capacitor bank with only a series reactor. Some literatures simulated only the single step switching. It is not enough and does not cover all of the protection schemes. Additionally, some researchers need the voltage signal to investigate the transient oscillation for discriminating the transient capacitor switching. In the meanwhile, the problem of classification and discrimination transient inrush current remains as an open problem for better discussing and improving the solutions. However, the techniques to detect, classify and discriminate the transient inrush current which is occurred from the 6-difference cases of the transient mitigation methods were not presented.

Therefore, this paper proposes a new technique for detection and classification of the high transient inrush current with the 6-difference cases of transient mitigation methods (for instance, pre-insertion resistor, pre-insertion inductor, current limiting reactor, 6% reactor and synchronous closing control) which are normally found in the application of capacitor bank. The DWT is performed to extract the high-frequency component which is contained in the transient inrush currents. The wavelet coefficients of the scale 1-30 from the DWT will be used for detection. Then, the standard deviation of wavelet scale coefficient will be determined for classifying the possible case of normal switching (isolated) or back-to-back capacitor switching [4]. The total case studies of 244 cases have been tested and verified with various 12 switching inception angles. The results from DWT are an input to the Artificial Intelligence (AI). The type of intelligence is a “Fuzzy Inference System (FIS)”. In order to discriminate the transient inrush current which is occurred from the 6-difference cases of the transient mitigation methods will be used by the fuzzy inference system. The results show that the proposed technique can effectively perform the detection, classification and discrimination of the transient inrush current during capacitor switching which provides the high accuracy more than 90%. It can be developed to overcurrent (50/51) and unbalanced current (60C) protection relay for avoiding the relay mal-operation from high transient inrush current in the future. In addition, the proposed methods can help an engineer who works in the field of protective relay to identify the type of transient signals.

# 2 System simulation study

## 2.1 System modeling

The substation shunt capacitor bank used as a model is shown in Figure 1 [12]. The 4th-steps capacitor bank which is rated 72 Mvar, 230 kV is used to simulate the high transient inrush current and classify the possible cases of switching. The three-phase voltage source model is represented by equivalent circuit with a short circuit value of 10 kA [4]. The transient mitigation method for 6-difference cases was numerically simulated: a base-case, with a pre-insertion resistor, with a pre-insertion inductor, with a current limiting reactor, with a series 6% reactor and using synchronous closing control [3]. The inrush current with variation of the inception angle for capacitor bank switching at 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 and 330 degrees were recorded. The switching transient patterns were varied into 6 different cases as following:

- Simulations using a base case (uncontrolled transient energization)
- Simulation using the pre-insertion resistors; each with a resistance value of approximately 86 Ω.
- Simulation using the pre-insertion inductors; each with a reactance value of approximately 119 mH.
- Simulations using the current limiting reactors; each with inductance value of approximately 1 mH/phase.
- Simulations using the series 6% reactors; each with an inductance value of approximately 166 mH per phase.
- Simulations using synchronous closing control for the controlled shunt capacitor bank.

## 2.2 High transient inrush current

To design a protection scheme of capacitor bank able to detect and classify the transient inrush current. Each kind of transient inrush current is very important to be prepared. The PSCAD/ EMTDC [13] was used for simulation by using the sampling frequency of 250 kHz. These recorded signals were used to be an input for wavelet analysis. The example of high transient inrush current form 6-difference cases of transient mitigation methods was shown in Figure 2.

The inrush current has been increased while the last step switching. The typical amplitude of the inrush current for back-to-back energization is several kAs with a

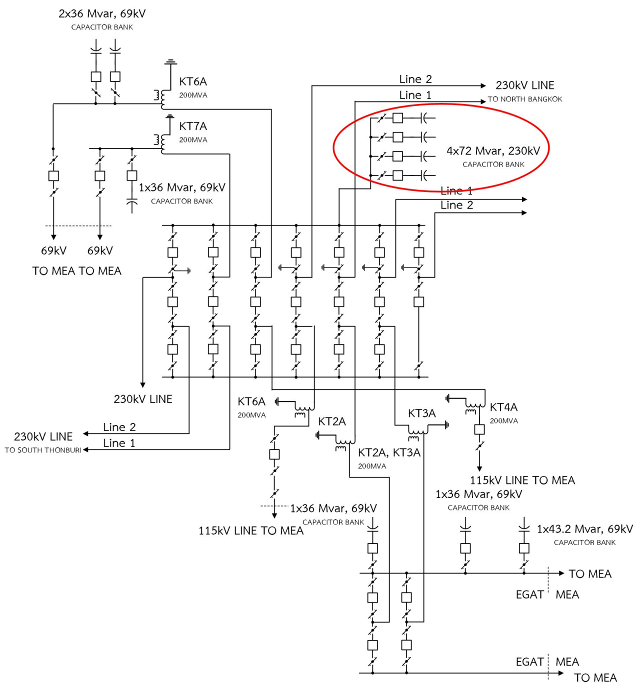



**Figure 1:** The system used in this simulation studies in case of isolated and back-to-back capacitor switching transients [12]

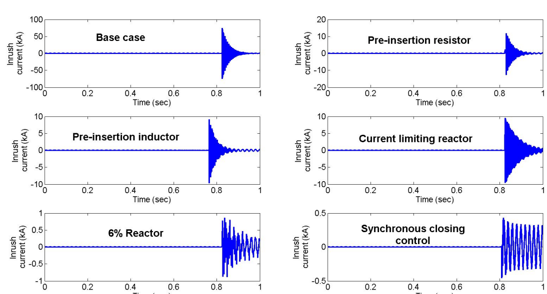



**Figure 2:** High transient inrush current which is energized by the capacitor bank in 4th-step switching (back-to-back switching) [4]

frequency of more than 2 kHz. The magnitude and frequency of this inrush current is, therefore, much higher than that of an isolated bank. Generally, the isolated capacitor bank switching has an inrush frequency between 300 Hz to 2 kHz and not exceed 20 times of capacitor rated current because the large impedance of network can reduce this inrush current.

# 3 Proposed techniques

## 3.1 Discrete wavelet transform for detection and classification

The discrete wavelet transforms based on Daubechis wavelet has been used to detect and classify the high transient inrush current [14]. Figure 3 shows the structure of the proposed techniques for the transient inrush current classifier. The structure is composed of the discrete wavelet transform, wavelet scale analysis, maximum scale selection and transient classification from the inrush current 6-difference cases of transient mitigation methods in order to investigate the possible cause of capacitor bank switching. The DWT is used to analyze the transient signal at scale selecting between 1 to 30 scales only. The mother wavelet, db4 is also used to analyze the transient disturbance owing to less time requirement to do the calculation and provide the classification more correctly than others [10]. The wavelet coefficient from each scale will be determined by Equation (1) [15, 16]. The discrete wavelet transforms (DWT) is used to analyze the transient signal at scale selecting from first scale to thirty scales only.

$$E_{\psi}(s) = \sum_{m=0}^{n} \left| DWT(m,n) \right|^{2} (1) \tag{1}$$

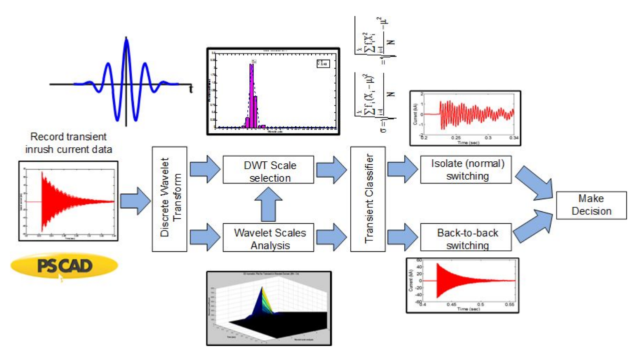



**Figure 3:** The structure of transient inrush current detection and classification system with DWT

The wavelet coefficient in each phase during capacitor switching will be conducted for detection the high transient inrush current by using an if-then statement which will be compared with the wavelet coefficient during capacitor rated current (threshold, steady state) as follows.

If (IA,max) > (1.3xThreshold),1,0),
If (IB,max) > (1.3xThreshold),1,0),
If (IC,max) > (1.3xThreshold),1,0),

If (Imax,positive) > (1.3xThreshold),1,0)
and
If (AND (Imax,positive) = 1,
SUM (IA:IB:IC,max) ≥ 2),"Abnormal","Normal")

The above if-then statement is designed to match the high transient inrush current phenomena and the philosophy of the protective relay setting accordance with IEC 60871-1:2014, IEC 60871-3:2015, IEEE Std. 1036-2010 and IEEE Std. C37.99-2012. The capacitor units shall be suitable for continuous operation at an r.m.s. current of 1.30 times the normal rated current that occurs at rated sinusoidal voltage and rated frequency, excluding transients. Therefore, for banks with separate overload and short-circuit protection, the overload protection is normally set in the range of 1.3 and 1.4 times rated current. The operating delay time is set long enough to avoid false trips during switching. The short-circuit protection is set above 3In and a few cycles delay. Refer to the if-then statement as above, the 130% or 1.3 times is from the maximum of capacitor overloading condition. If current phase A, B, C and positive sequence current are higher than the 1.3 times. It is a risk for capacitor damage and exposure due to capacitor overloading. This criterion is the pick-up current setting for overcurrent relay protection. During capacitor switching to close state, the transient inrush current phase A, B, C and positive sequence current will be increased rapidly and higher than the threshold. Therefore, the result of a proposed algorithm is the abnormal condition. Moreover, if the summation of wavelet coefficient of the positive sequence current is higher than the threshold and the summation of wavelet coefficient in each phase can detect more than 2 phases. We can conclude that these signals are abnormal. The criteria of the summation of wavelet coefficient in phase A, B and C shall be used equally or more than 2-phase detection because some of the switching devices are closed nearly to 0 degrees. Thus, the inrush current is very low signal. However, we cannot judge the transient signal whether it is the inrush current switching or normal capacitor rated current. The algorithm of standard deviation will be performed in order to find the type of these transients.

In the section of classification algorithm, the standard deviation is very important features to distinguish the transient disturbance classification [9]. Therefore, the equation to calculate the standard deviation is shown in Equation (2).

$$\sigma = \sqrt{\frac{1}{N}\sum_{s=1}^{N}\left(E_{\psi}(s) - \mu\right)^2 \, (2)} \qquad (2)$$

The standard deviation of the discrete wavelet scale analysis and the number of maximum scales to detect in wavelet scale analysis can be used to classify the possible cause and origin of transient inrush current both isolate and back-to-back capacitor switching by using the if-then statement. The flowchart diagram of the proposed algorithm can be shown in Figure 4.

IF (AND (STDEV,inrush,positive) > (1.3*STDEV,threshold,positive), Wavelet,scale max < (Wavelet,scale threshold), “Normal switching",“Back-to-Back switching")

As the above algorithm, the standard deviation must be multiplied with 1.30 times to be setting the pick-up current (threshold). The capacitor unit can withstand for continuous operation at an r.m.s. current of 1.30 times the normal rated current that occurs at rated sinusoidal voltage and rated frequency, excluding transients. The variable “STDEV, inrush, positive” is the standard deviation which is calculated from the wavelet coefficient of positive sequence current by using the equation (2). This variable will be calculated the standard deviation totally 30 scale wavelet analysis. The variable “STDEV, threshold, positive” is the standard deviation which is calculated from wavelet coefficient of positive sequence current during normal capacitor switching totally 30 scale wavelet analysis.

## 3.2 Fuzzy logic inference system for discrimination

To solve the protective relay of capacitor bank maloperation from transient switching inrush current, a fuzzy-based approach is proposed. The fuzzy logic rules evaluate the multi-resolution features as well as electric characteristics in order to identify the power quality disturbances in network. The fuzzy inference system with two linguistic variables that defines 2-concept, the maximum wavelet scale detection is acted as input 1, the standard deviation is acted for input 2. Then, the output is the type of 6-difference cases for transient mitigation methods. The structure of fuzzy classifier based on the fuzzy inference system (FIS) diagram for discrimination of high transient inrush current is shown in Table 1.

Before building the fuzzy interference system, the standard deviation will be multiplied by 100 in order to easily create the membership function and can be designed a system cable of detecting and classifying the high transient inrush current as shown in Figure 5. A fuzzy inference system (FIS) is a system that uses fuzzy set theory to map inputs to outputs. Type of fuzzy inference system which is Mamdani [17, 18]. Mamdani’s fuzzy inference

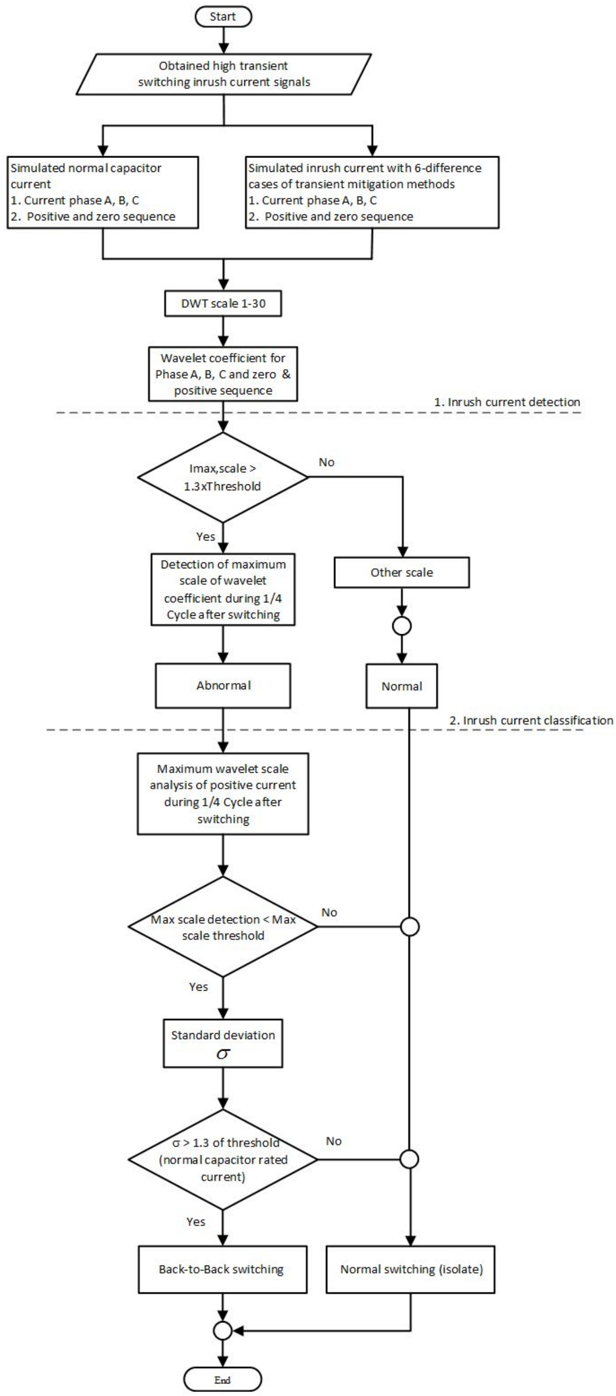
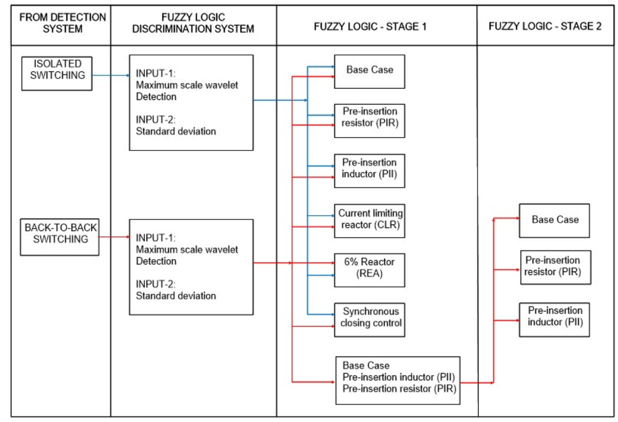



**Figure 4:** Flowchart diagram for detection and classification by using the discrete wavelet transforms

method is the most commonly seen fuzzy methodology using fuzzy set theory. The Mamdani type rules to discriminate the information provided by the two linguistic variable inputs. Figure 6 shows the block diagram of transient inrush current discrimination with FIS scheme based on Mamdani type rules.

**Table 1:** Discrimination system based on fuzzy inference – Mamdami rules



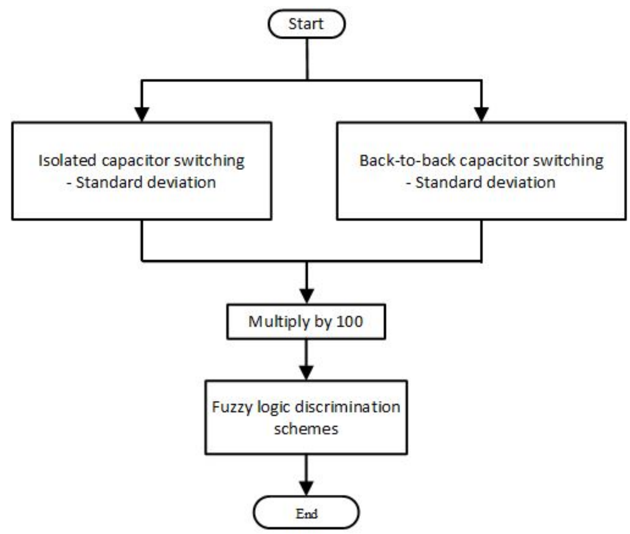




**Figure 5:** The flowchart diagram for transient inrush current discrimination by using fuzzy rules

## 3.3 Experiment test unit

A single line diagram of the experimental test unit is shown in Figure 8. The power supply of the system is taken from the university laboratory at a voltage level of 380 V and then connecting to a step-up voltage transformer to be 415 V. The switching capacitor in each step uses the magnetic contactors k1, k2, and k3. The switched capacitor bank can be operated by push button and a power factor controller (PFR). The HRC fuses will be mainly used for short-circuit protection.

The current transformer connected to main incoming phase A to be an input of the controller. The three-phase PQ analyzer is used to do the measurement of the voltage at main bus-bar and transient inrush current in each step. The 3-step capacitor switching will have the reactive power

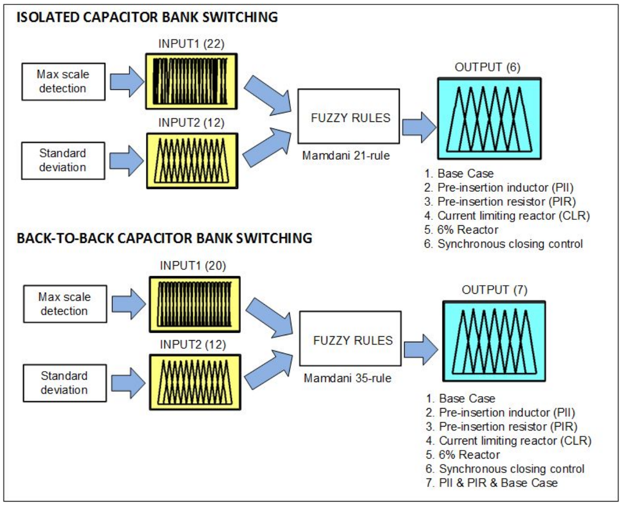



**Figure 6:** The block diagram of transient inrush current discrimination with Fuzzy inference schemes based on Mamdani type rules

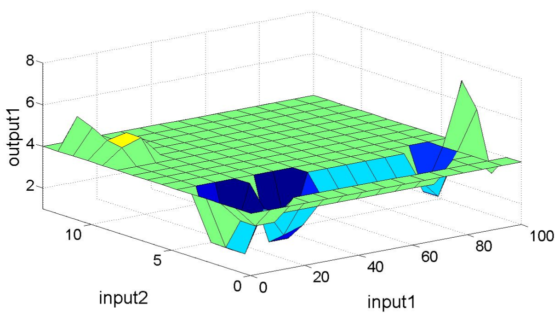



**Figure 7:** Example of the fuzzy inference surface viewer based on Mamdani type in case of back-to-back capacitor switching

at 5.0 kvar per step including the series 7% reactor. The inductance rating of series reactor is 0.653 mH per phase. The shunt capacitor bank series with the 7% reactor can be used in high distribution loads (loads with more than 4-steps of capacitor banks) and in industrial applications. The inductor size is normally estimated by 7% of the capacitive reactance of the capacitor bank. The picture of experimental test unit is shown in Figure 9.Voltage and current were measured at a location in the front of the magnetic contactor. The measurement of the oscillation overvoltage and high transient inrush current was done using a power quality analyzer. However, the operation of a capacitor bank in experiment test unit will be controlled by manual mode via push button in the front side of the unit.

The controller unit receives voltage and current measurements from the potential transformer (PT) and current transformer (CT) to calculate the power factor of the system and then compares these data with the power factor

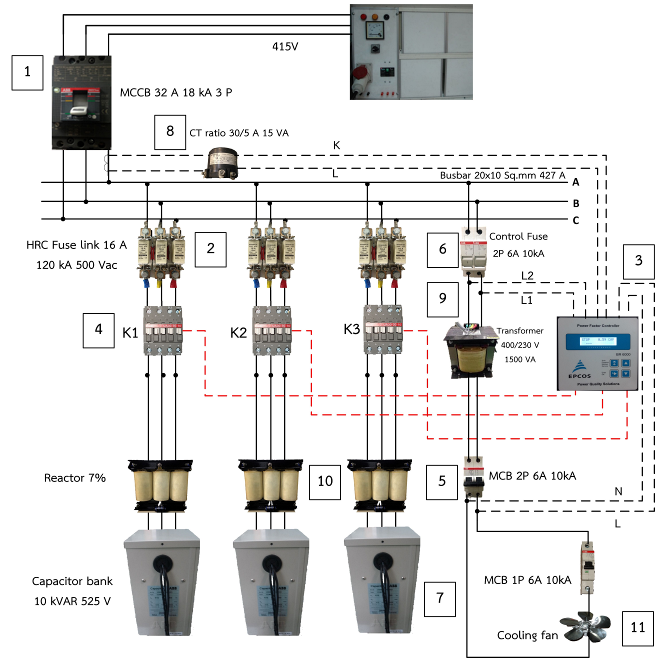



**Figure 8:** A single line diagram for experimental test unit in laboratory

value that is set inside the unit. After that, it sends an on/off signal to the magnetic contractor to close or open the capacitor bank circuit in each step. This test setup is downscale from the capacitor bank system in the 115-kV substation with a reactive power of 48 MVar in each step. This experimental test unit is downscaled from 115 kV to 415 V in the laboratory by using per-unit calculation to determine the size of the capacitor and other devices or equipment for the test unit.

# 4 Simulation of the proposed algorithm

## 4.1 Inrush current detection and classification using DWT

The isolated capacitor bank switching provides the maximum wavelet coefficient as the ninth scale (1st step switching). In the meanwhile, the back-to-back capacitor switches as the third scale only. This characteristic will be used to classify the transient inrush current in order to find the possible causes and origin of transient inrush current. The comparison of the wavelet scale coefficients is shown in Figures 10 – 13. The comparison of the wavelet scale coefficients by Equation (1) is considered as illustrated in Figures 12 and 13. As in the figure, the wavelet scale analysis of

**Figure 9:** Photography of the experimental test unit in a university laboratory

all step capacitor switching is plotted on the wavelet scale versus wavelet coefficient. The wavelet scale coefficient in case of the threshold obtained from discrete wavelet transform during capacitor was already energized for a period more than 100 msec. It means that the capacitor current is in a stable stage.

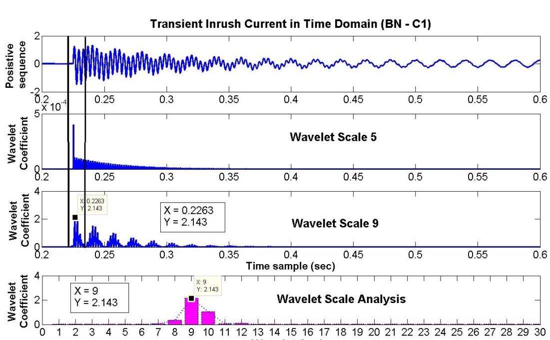



**Figure 10:** The wavelet scale analysis for detection & classification the transient inrush current in case capacitor bank the 1st-step switching (base case)

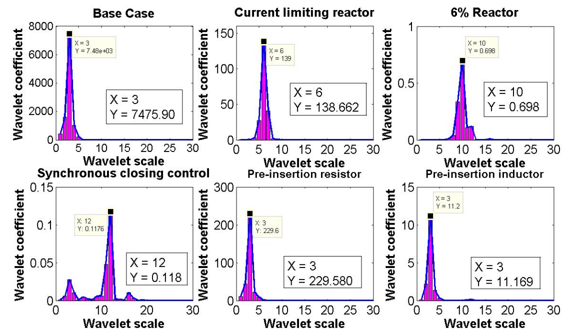



**Figure 11:** Maximum wavelet scale analysis for transient inrush current in case of the 4th-step switching with the 6-different cases of transient reduction control

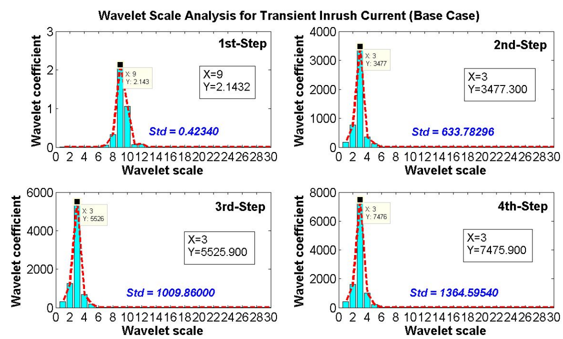



**Figure 12:** The transient inrush current in maximum wavelet scale analysis for all the step capacitor bank switching in case of base case (no transient control)

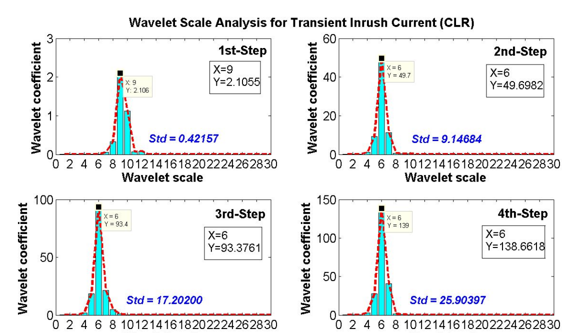
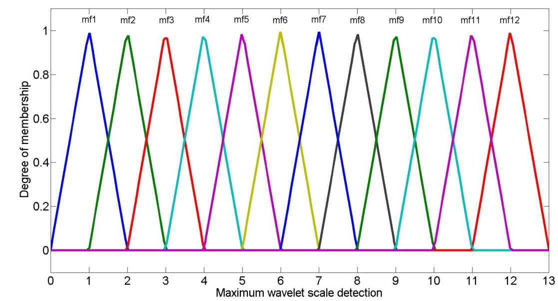



**Figure 13:** The maximum of wavelet scale analysis and standard deviation of 30 scale wavelet coefficients for all step capacitor bank switching in the base case (with series current limiting reactor 1.0 mH)

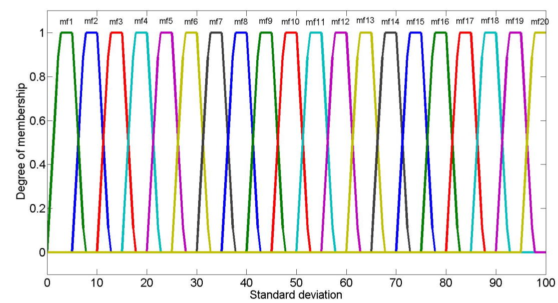
## 4.2 Inrush current discrimination using Fuzzy Inference

The discrimination system was tested with 244 cases of transient inrush current signals which were generated with the PSCAD simulation. Due to the standard deviation for linguistic variables input 2 is very low. So, they will be multiplied by 100 in order to easy for create the membership functions and Mamdani rules in FIS. In Figure 11, the maximum wavelet scale detection is a triangular membership function defined as input 1. The standard deviation is a trapezoidal membership function defined as input 2. Then, the output is as a triangular membership function.

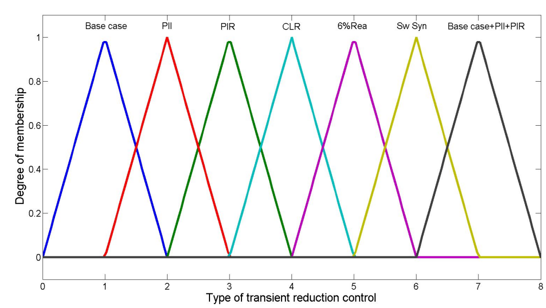
The scheme of FIS can be shown in Figure 14. Index of membership function for first and second input are defined by triangular (trimf) and trapezoidal (trapmf) respectively. Output is represented by a triangular (trimf). The surface viewer is shown as in Figure 14. A three-dimensional curve represents the mapping from maximum wavelet scale detection (input1) and standard deviation (input2) to the type of transient reduction control (output). The fuzzy rules for isolated and back-to-back capacitor switching will be established by Mamdani 21-rule and Mamdani 35-rule respectively.




**(a)** Definition of the linguistic variable for input 1 – max scale detection




**(b)** Definition of the linguistic variable for input 2 – standard deviation




**(c)** Definition of the output FIS – type of transient reduction control

**Figure 14:** Definition of the membership functions in case of back-back switching

## 4.3 Experimental test set

For the experiment, the system's normal case has been recorded to evaluate switching transients occurred when the energized capacitor back phenomena taken into account are inrush current and voltage transients. The current signals measurement will be acted as input for wavelet transform in order to verify the proposed algorithm. The inrush current waveform and oscillation overvoltage at the bus are shown in Figure 15 and 16, respectively. In the case of a capacitor bank system without an installed reactor (base case), when considering the system current after switching in the first step, the inrush current magnitude rises to approximately 7-8 times the normal current magnitude due to the energizing current to the capacitor bank. Inrush current in the next step is higher than the previous one due to the inrush current occurring when the energizing capacitor bank combines with the current from the energized bank. It causes an increase in magnitude of the inrush current accordance with the theory.

In Figure 15, the inrush current signal for phase A, B, and C will be calculated to determine the symmetrical component of positive, negative and zero sequence. The positive sequence current of each phase will be acted an input of discrete wavelet transform to detect and classify the transient inrush current behavior as shown in Figure 17. Then, the output from wavelet classifier will be used to input for fuzzy inference for discrimination the type of transient reduction control between base case and 7% reactor. The wavelet scale analysis to detect and classify the signals whether transient created from isolated switching or back-to-back switching was shown in Figure 17. The result shows that maximum wavelet coefficient can be founded in the 2nd scale.

The fuzzy inference system for discriminating the type of transient mitigation method in case of an experimental test unit can be built in the same method as the simulation study case. But the membership function for output

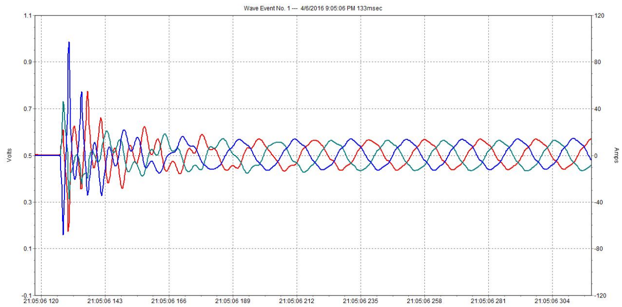


**Figure 15:** The 3-phase inrush current waveform measured by the PQ analyzer in a university laboratory

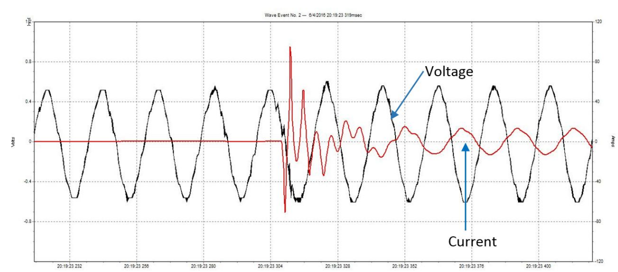



**Figure 16:** The transient inrush current and voltage at bus signals from an experimental result when the 2nd-step switching with series 7% reactor

variable is different. It is only 2-output between 7% reactor and base case. The maximum wavelet scale detection is a triangular membership function defined as input 1. The standard deviation is a trapezoidal membership function defined as input 2. Then, the output is as a triangular membership function.

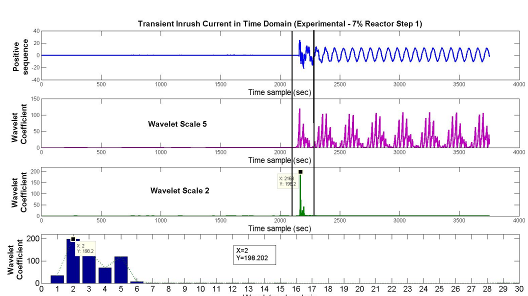



**Figure 17:** The wavelet scale analysis for detection and classification of the transient inrush current in case capacitor bank the 1st-step switching (experimental – 7% reactor).

# 5 Results of proposed algorithm

## 5.1 Simulation study results

The proposed algorithm has shown satisfactory performance to detect, classify and discriminate the transient inrush current in the various types of capacitor switching transient. The errors of an algorithm will have occurred when switching at reference voltage phase A as 0 degree and 180 degrees because this switching inception angle provides the zero voltage across the circuit breaker [4]. So, the transient inrush current does not occur.

## 5.2 Experimental results

The experimental results are shown in Table IV and V. The proposed algorithm shows excellent performance to detect, classify and discriminate the high transient inrush current.

The results of the proposed algorithm were shown in Table 2, 3, 4 and 5 respectively. The wavelet coefficient corresponds with the switching sequence. The wavelet coefficient will be increased when the number of step-switching is increased. The last step-switching provides the highest of wavelet coefficient which is corresponding with the inrush current in the system as the capacitor switching theory (Isolated & Back-to-Back capacitor switching). Each of the wavelet coefficient from the 6-difference cases of transient reduction control can be found that the switching capacitor bank without transient reduction control (base case) have the highest value of wavelet coefficient, but the maximum of wavelet scale detection is very minimum. In the meanwhile, the switching capacitor bank with synchronous closing control has the lowest value of wavelet coefficient, but the maximum of wavelet scale detection is so high. It is concluded that if the maximum of wavelet scale analysis is high, the inrush current is very low. Contrarily, if the maximum of wavelet scale analysis is very low, it has the meaning that the inrush current is very high. On the other hand, if the wavelet coefficient is so high, the inrush current is so high too. Therefore, the wavelet coefficient value is corresponding with the high transient inrush current signal by the wavelet coefficient which will be highest value when the capacitor bank switching in the last step. Regarding the fuzzy inference system, it shows the high accuracy to discriminate the high transient inrush current in case of the transient mitigation method of synchronous switching control and pre-insertion inductor respectively. In the meanwhile, the pre-insertion resis-

**Table 2:** Detection and classification using DWT

| Type of inrush current | Performance Conclusion for Inrush Current Classification | | | | % Accuracy |
|---|---|---|---|---|---|
| | 1st-Step | 2nd-Step | 3rd-Step | 4th-Step | |
| Base Case | NS | BBS | BBS | BBS | 100% |
| PIR | NS | BBS | BBS | BBS | 100% |
| PII | NS | BBS | BBS | BBS | 100% |
| CLR | NS | BBS | BBS | BBS | 100% |
| 6% Reactor | NS | BBS | BBS | BBS | 100% |
| SW Syn | NS | NS | NS | NS | 100% |

Note:
NS = Normal switching
BBS = Back-to-back switching

**Table 3:** Discrimination using fuzzy inference system

| Type of inrush current | No. event | Transients inrush current signals | | | | | | Errors % | Acc. |
|---|---|---|---|---|---|---|---|---|---|
| | | Base case | PIR | PII | CLR | 6% REA | SW SYN | | |
| Base case | 48 | 43 | 0 | 0 | 5 | 0 | 0 | 5 | 89.58 |
| PIR | 48 | 0 | 37 | 3 | 4 | 4 | 0 | 11 | 77.08 |
| PII | 48 | 0 | 0 | 48 | 0 | 0 | 0 | 0 | 100.00 |
| CLR | 48 | 2 | 0 | 0 | 45 | 1 | 0 | 3 | 93.75 |
| 6% Reactor | 48 | 0 | 0 | 2 | 0 | 44 | 2 | 4 | 91.67 |
| SW Syn | 4 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 100.00 |
| ALL Transients | 244 cases | | | | | | | | |
| Performance | ISOLATED CAPACITOR SWITCHING 78.69% | | | | | | | | |
| | BACK-TO_BACK CAPACITOR SWITCHING 94.54% | | | | | | | | |
| | ALL CAPACITOR SWITCHING TRANSIENTS 90.57% | | | | | | | | |

**Table 4:** Detection and classification using DWT

| Type of inrush current | Performance conclusion for inrush current classification | | | % Accuracy |
|---|---|---|---|---|
| | 1st-Step | 2nd-Step | 3rd-Step | |
| Base Case | NS | BBS | BBS | 100% |
| 7% Reactor | NS | BBS | BBS | 100% |

Note: NS = Normal switching
BBS = Back-to-back switching

tor has the highest of error discrimination because each of transient mitigation method that provided with the value of standard deviation and max scale detection had nearly value in each mitigation method. It is quite difficult to discriminate the type of transient mitigation method with FIS. However, the proposed algorithm provides the accuracy more than 90% for classifying the all capacitor switching transient inrush currents.

# 6 Conclusion

This paper presents the technique of detection, classification and discrimination of the high transient inrush current during capacitor bank switching occurring on the substation shunt capacitor bank in order to avoid the overcurrent relay (50/51) and unbalanced current relay (60C) maloperation due to failed trip from high transient inrush current. This paper described the approach to detect and classify high transient inrush current, which occurs from the energization of an HV substation shunt capacitor bank, rated 4×72 Mvar/230 kV, in a Thailand's substation system. The main purpose of the new algorithm in this paper is clear to discriminate between the normal capacitor current and transient capacitor inrush current only. The protective relay can be known that the type of transient signals is the inrush current or normal capacitor rated current. Thus, the relay will not be tripped (block function) from the type of transient inrush current signal.

**Table 5:** Discrimination using fuzzy inference system

| Type of inrush current | No. events | Transients inrush current signals Base case | 7% Reactor | Errors | % Accuracy |
|---|---|---|---|---|---|
| Base case | 3 | 3 | 0 | 0 | 100.00 |
| 7% Reactor | 3 | 0 | 3 | 0 | 100.00 |
| ALL Transients | 6 cases | | | | |
| Performance | ISOLATED CAPACITOR SWITCHING 100%<br>BACK-TO_BACK CAPACITOR SWITCHING 100%<br>ALL CAPACITOR SWITCHING TRANSIENTS 100% | | | | |

PSCAD/EMTDC was used to simulate transient inrush current with the transient mitigation methods in six different cases. Wavelet scale analysis can be used to detect and classify the possible cause of transient inrush current both isolate and back-to-back capacitor switching. The type of Artificial intelligence is a Fuzzy Inference System which will be used to discriminate and distinguish the type of capacitor switching in the 6-different cases of transient reduction control. The proposed techniques show the highest accuracy and satisfaction for detection, classification and discrimination in both the experimental test unit and simulation study. It can be developed to the numerical protective relay in the protection scheme of the HV shunt capacitor bank.

However, the next research will be a further study on how to discriminate between short-circuit current and inrush current signals. The protection algorithm will be conducted. Finally, the author expected that the software engineer who was responsible to develop the computer processor in IED have an idea to classify the type of transient signal during capacitor switching.

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## References


[1] IEEE Standard 1036, IEEE Guide for Application of Shunt Power Capacitors, 2010.

[2] IEC Standard 60871-1, Shunt Capacitors for A.C. Power Systems Having a Rated Voltage above 1000V – Part 1: General, 2014.

[3] IEEE Standard C37.99, IEEE Guide for the Protection of Shunt Capacitor Banks, 2006.

[4] Patcharoen T., Ngaopitakkul A., Pothisarn C., Leelajindakrairerk M., Simulation analysis of the switching of 230 kV substation shunt capacitor banks with a 6% series reactor for limiting transient inrush currents and oscillation overvoltage, Electrical Engineering (2017), (in press), DOI:10.1007/s00202-017-0516-4.

[5] Mokryani G., Siano P., Piccolo A., Detection of Inrush Current Using S-Transform and Competitive Neutral Network, International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) (20-22 May 2010, Brasov, Romania, Romania), IEEE, 2010, 191-196.

[6] Farias P.E., de Morais A.P., Cardoso G., Oliveira A.L., Transients Detection and Classification in Distribution Networks for High Impedance Faults Identification, International Universities Power Engineering Conference (UPEC) (2-5 September 2014, Cluj-Napoca, Romania), IEEE, 2014, 1-6.

[7] Buggaveeti S.K., Brahma S.M., A Morphological Filter to Distinguish a Fault from Capacitor Switching, IEEE PES Transmission and Distribution Conference and Exposition (19-22 April 2010, New Orleans, LA, USA), IEEE, 2010, 1-5.

[8] Buggaveeti S.K., Brahma S.M., Improved Overcurrent Protection of Capacitor Banks Using Mathematical Morphology, IEEE Transactions on Power Delivery, 2011, 26, 3, 1972-1979.

[9] Tan R.H.G., Ramachandaramurthy V.K., Capacitor Bank Switching Classification using Scale Selection Continuous Wavelet Transform, International Conference on Power Electronics and Drive Systems (2-5 November 2009, Taipei, Taiwan), IEEE, 2009, 950-955.

[10] Perera N., Rajapakse A.D., Power System Transient Classification for Protection Relaying, International Conference on Harmonics and Quality of Power (28 September - 1 October 2008, Wollongong, NSW, Australia), IEEE, 2008, 1-6.

[11] Chacon M. I., Duran J.L., Santiesteban L.A., A Wavelet-Fuzzy Logic Based System to Detect and Identify Electric Power Disturbances, IEEE Symposium on Computational Intelligence in Image and Signal Processing (IEEE CIISP (2007) (1-5 April 2007, Honolulu, HI, USA), 52-57.

[12] Transmission System Operation Planning Department, Switching and Transmission Line Diagram, Electricity Generation Authorization Thailand Press., Thailand, 2010.

[13] Manitoba HVDC Research Centre, EMTDC: Transient Analysis for PSCAD Power System Simulation, Manitoba HVDC Research Centre Inc., Manitoba, Canada, 2003.

[14] Masoum M.A.S., Jamali S., Ghaffarzadeh N., Detection and classification of power quality disturbances using discrete wavelet transform and wavelet networks, IET Science, Measurement & Technology, Measurement and Technology, IET, 2010, 4, 193-205.

[15] Rodrfguez A., Aguado J., Martin F., Mufioz J., Medina M., Ciumbulea G., Classification of Power Quality Disturbances using Wavelet and Artificial Neural Network, International Conference on Power System Technology (POWERCON) (24-28 October 2010, Hangzhou, China), IEEE, 2010, 14-7.
[16] Wavelet Toolbox User's Guide (R2016a), MathWorks, Inc., 2016.
[17] Fuzzy Logic Toolbox User's Guide (R2016a), MathWorks, Inc., 2016.
[18] Mielczarski W., Fuzzy Logic Techniques in Power Systems, Physica-Verlag Heidelberg, 1998