Improved Protection and Maintenance for Shunt Capacitor Banks

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***Abstract*—Field experience shows that impedance-based protection (21C) can be safely and efficiently used to complement or replace voltage differential protections (87V) for shunt capacitor banks. One important consideration is that bank capacitance varies with temperature. This variation is not even across the bank because of variations in sun and shade. Moreover, it affects not only impedance measurements but also most forms of unbalance relay measurements. This paper presents a novel time-based temperature compensation algorithm that overcomes this variation. This compensation algorithm works without requiring an external temperature probe. It leverages the long-time constants associated with thermal variations to reliably trip for capacitor failures and faults, while securely avoiding misoperation for power system events or temperature changes. Results show that this compensation algorithm improves impedance protection sensitivity. In addition to protecting the capacitor bank, impedance measurement can provide health information for individual strings or phases in the capacitor bank, which can be used for planning, maintenance, or to better target emergency repairs.**

***Index Terms*— Protection, Capacitor Bank, Impedance, Temperature compensation, Condition-based monitoring**

I. INTRODUCTION

Protection of shunt capacitor banks is often implemented by the use of voltage differential (87V and 87VN) elements, often referred to as unbalance protection. While this protection scheme has a proven record, it is showing its limitations in some cases. For example, some utilities note misoperations in fuseless shunt capacitor banks used in high voltage power systems; those misoperations result from having detection thresholds that are very close to the measurement tolerance of the protective relay. In the past, impedance-based protection was proposed as a mitigation technique [1]. While this technique is not in widespread use, field experience shows that impedance-based protection element (21C) can be safely and efficiently used to complement or to replace traditional voltage differential elements.

One drawback of impedance protection is that bank capacitance varies throughout the day as temperature changes. Moreover, this variation is not even across the bank because of variations in sun and shade. For these reasons, this paper proposes an algorithm to mitigate the effect of temperature that leverages the long time constants associated with thermal variations to reliably trip for capacitor failures and faults, while securely avoiding misoperation for power system events or temperature changes.

This paper will first present the origins of impedance-based protection (21C), highlight the effect of temperature on impedance, and present a novel algorithm to mitigate its effects.

II. ORIGINS OF IMPEDANCE-BASED PROTECTION (21C)

Impedance-based protection was first introduced for fuseless shunt capacitor banks. It was proposed to overcome limitations of traditional voltage differential protections (87V).

A. Limits of Voltage Differential (87V)

To illustrate the limits of a voltage differential protection element (87V), consider the following case of a fuseless shunt capacitor bank. In this type of bank, failure mode of capacitor units is expected to be a short circuit. When this occurs, a voltage increase occurs on the remaining elements of the string. Those capacitor banks are usually designed to withstand a few number of capacitor element failures. However, protection should trip the bank when the voltage on capacitor units reaches 110% of their nominal rating [2].

This primary protection can be achieved using voltage differential protection. The aim of this protection is to sense failures in capacitor elements in order to limit the overvoltage on the remaining elements of the capacitor bank.

Figure 1shows a capacitor bank grounded through a low voltage capacitor. The protection is implemented using a voltage differential element (87V) that compares the voltage across the low voltage capacitor relatively to the bus voltage. This protection is applied on each phase. While perfectly valid, this approach has some drawbacks.

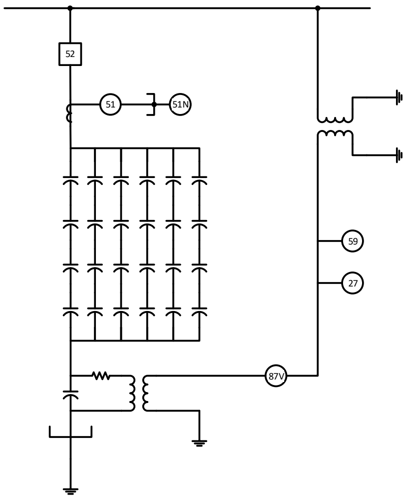


Figure 1 Example of voltage differential protection (87V) applied to a fuseless shunt capacitor bank

To illustrate this, consider a bank made of 6 strings containing 4 capacitor units each containing 12 capacitor elements, resulting in strings of a total of 48 capacitor elements. Before the voltage across an element reaches 110% of the voltage measured on elements of a healthy string, 5 elements must fail in the same string. This is shown using the following formula, from table 10 of IEEE C37.99 [2]:

$$V_e = V_{ln} \times \frac{E}{E-e} = 1.0 \times \frac{48}{48-5} = 1.1163 \tag{1}$$

With up to 4 elements failed, a string is still safe to operate, the voltage increase on each element being limited to roughly 9%. The increase in current flowing through the string have the same magnitude.

However, the voltage differential protection has to account for multiple strings. In order to trip the bank for a string containing 5 failed elements, the differential threshold has to be set to the following voltage:

$$V_{thr} = V_{nom} \times \frac{(n+p)}{n} = 1.0 \times \frac{6+0.1}{6} = 1.0167 \tag{2}$$

Thus, a voltage increase of 1.67% on the low voltage capacitor should trip the bank. The first downside of this approach is that such a small increase in voltage is very close to the tolerance of the voltage inputs of a typical protection relay. Alarming upon one or two capacitor element failures would prove difficult to perform securely and reliably.

Second drawback of the approach is that it does not differentiate between capacitor element failures occurring in the same string. A string with only one capacitor element failed will result in a current increase of 2.13% in the string, and a 0.36% increase of voltage for the differential protection. A rough estimation shows that the bank would also trip for 5 strings containing each a faulty capacitor element, while those strings would still able to operate safely. This protection scheme thus has a high probability of operating while the bank is still safe to be kept energized.

B. *Principle of Operation for Impedance-Based Protection (21C)*

String-based impedance protection (21C) is briefly described in IEEE C37.99 [2]. It is particularly sensitive when the protection monitors each string of the bank individually. The following figure illustrates such protection scheme.

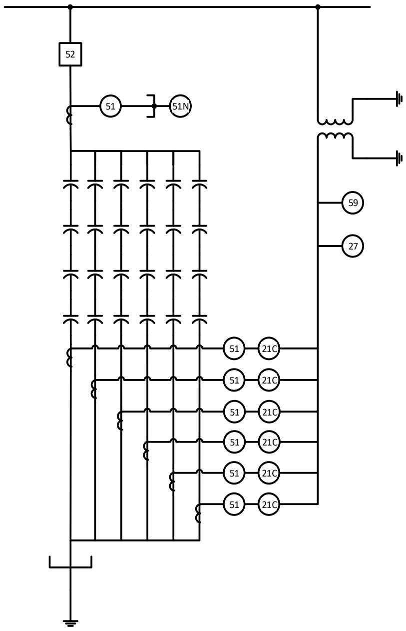


Figure 2 Example of impedance-based protection (21C) applied to a fuseless shunt capacitor bank

The 21C protection element calculates impedance of the string using the bus voltage (V_{bus}) and the current flowing through a given string (I_n where n identifies the string), using Ohm's law.

$$Z_n = \frac{V_{bus}}{I_n} \tag{3}$$

This impedance is then compared to the expected impedance of the capacitor string as defined by configuration and commissioning. Figure 3 shows an example of expected string impedance with the configured alarm and trip thresholds.

During normal operation of the bank, the measured impedance will be found near the expected impedance. When the measured string impedance (Z_n) goes outside one of the configured impedance circles for a duration longer than the specified operating time, an alarm or trip signal is asserted. Three alarm and two trip thresholds are configurable for the protection element. Each threshold radius is defined as a percentage of the expected impedance.

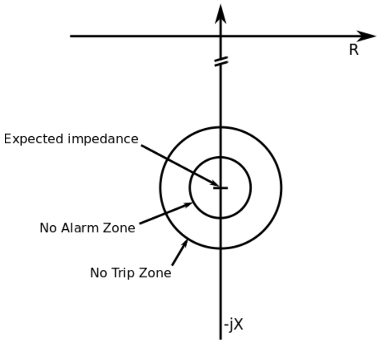


Figure 3 Operating principle of the 21C protection, based on complex string impedance

To determine which thresholds are exceeded, the protection element for each string calculates an error ratio between the measured string impedance (Z_n) and the expected string impedance (Z_{exp})

$$\Delta Z_n(\%) = \frac{|Z_{exp} - Z_n|}{|Z_{exp}|} \times 100\% \tag{4}$$

When ΔZ_n is greater than one of the configured alarm or trip threshold for at least the specified operating time, an alarm or trip signal is asserted. The asserted signal will stay activated as long as the condition persists, and prolonged for the configured hold time. To prevent operation or alarming when the bank is de-energized, the operating mechanism is disabled if the current is smaller than a configurable minimum threshold.

To demonstrate how this type of protection is more sensitive than traditional voltage unbalance, consider the following example. In a capacitor bank comprising 48 capacitor elements per string, a failure of one capacitor element will decrease impedance by approximately 1/48 or 2.1% of nominal impedance. This is significantly above the noise level of the protection relay. Hence, the detection of such a defect is guaranteed. As each string impedance is measured, it is possible to identify the specific strings which have defective capacitors. Furthermore, from the impedance measurement it would theoretically be possible to infer the number of defective capacitors elements.

C. *Downside of 21C*

A cause of concern with the impedance-based protection is temperature variation. The capacitance variation due to temperature can easily reach ± 2% for a temperature range of -30ºC to 60ºC [3]. These temperatures are to be expected when factoring in the sun exposure. Moreover, sun exposure will result in uneven variation across the bank.

When the number of capacitors elements per string is high, for example more than 30, the impedance variation of ± 2% is in the same order as a single capacitor element failure. Thus, compensation of temperature-induced impedance variation becomes a desirable feature for any protection scheme using impedance as operating value.

III. TEMPERATURE COMPENSATION

To address the issue of temperature and sun exposure effect on string impedance, a temperature compensation mechanism must be used. We will first present existing methods, followed by the novel algorithm we propose to mitigate the problem.

A. *Existing methods*

Different methods are proposed to compensate for impedance changes induced by temperature variations. The following present the two most widespread.

1) *Use of a temperature transducer*

The most obvious method consist in using a temperature transducer to measure temperature in the surroundings of the capacitor bank [1]. This requires the protective relay to be equipped with an extra input for this sensor. In practice, this input takes the form of a 4-20mA input. This measurement allows adjustment of the mho characteristic along the y axis, proportional to the deviation of temperature. The protective relay must also be parametrized with a coefficient that relates the measured current in the temperature transducer input to the variation in impedance.

While this method is straightforward, requiring an external transducer puts an additional burden on commissioning. It is also an extra piece of hardware that could be subject to failure. Finally, since only one input is used, the method can only compensate for the average variation of ambient temperature of the bank. The difference of temperature between units placed in the sun and those in the shade will be left out of the equation.

2) *Averaging of deviation*

In order to avoid the use of an external probe to measure temperature, Day and Roth proposed a method that performs temperature compensation on the impedance of a string based on the average impedance of the neighboring strings [4]. For example, if a capacitor bank is composed of 10 strings per phase, the method measures how the average impedance of the strings in the group diverts from the nominal impedance of the bank. The measured delta can be then used to calculate a compensation for all the strings of the group.

This method is based on the assumption that temperature variation will mostly affect the impedances of the strings equally. This proves to be invalid, considering that the sun and shade on the capacitor bank will result in different temperatures on different areas of the bank, as discussed previously in II.C.

B. *Presentation of the algorithm*

In order to mitigate the temperature-induced impedance variation, the following temperature compensation algorithm is proposed.

Figure 4 shows the principle of temperature compensation for the string impedance-based protection. When a temperature change is detected, the expected impedance will be adjusted in order for the element thresholds to follow normal variations in the impedance.

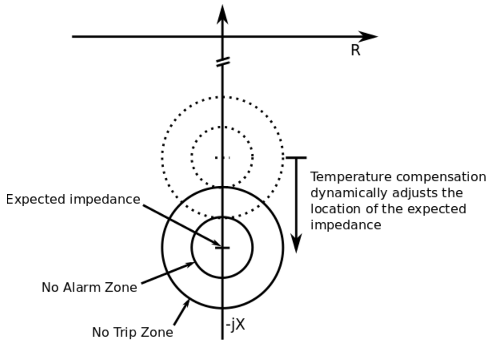


Figure 4 Temperature compensation principle of operation

In order to perform compensation, a time-based temperature compensation algorithm is used. This compensation is used in combination with the thresholding logic of the protection element.

Instead of comparing the measured impedance value to a fixed expected impedance, the 21C element compares it to a temperature-compensated expected impedance value. This value is generated by an algorithm that behaves according to the following guidelines:

- Any slow variation in the impedance is considered to be related to temperature. If a slow increase or decrease is measured, the expected impedance will be moved accordingly
- If the impedance varies quickly, either a grid disturbance is under way, or we are in the presence of a capacitor element failure. The following rules apply:
  - If the measured impedance stabilizes near the same point it was prior to the event, the event is ignored
  - Else, a capacitor element has failed. Thus, the difference between impedance prior and after the event will be calculated and summed up into a cumulative error register. Temperature-compensated expected impedance will be adjusted in a way that capacitor element failures will never be considered as a normal operating value.

The algorithm used for temperature compensation of the expected impedance is illustrated in the block diagram shown in the next figure. This algorithm meets the general requirements described above.

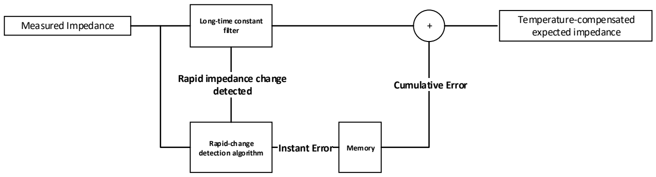


Figure 5 Block diagram of the temperature compensation algorithm

In order to track the slowly-varying impedance due to temperature changes, a long-time constant low-pass filter is used. This filter uses a 5 minutes time-constant. Thus, the output for this long-time constant filter will not be affected by a rapid impedance variation, it will only be affected by slow changes such as impedance variation due to temperature.

When a capacitor element fails, the foils weld together and short-circuit [5]. Capacitor failures happen quickly, within milliseconds [6]. Therefore, a rapid-change detection algorithm is used to detect quick and significant changes in impedance. For example, a sudden variation of 90 Ω that happens within 100 milliseconds will be detected and memorized.

The rapid-change detection algorithm is based on a filtered-derivative algorithm [7] with an integrating filter and a 500-ms window. The use of the filtered-derivative algorithm prevents the detection of false events that would occur if one simply used the derivative. The threshold for the jump of the mean, is set to a fraction of the nominal impedance of a capacitor element in order to prevent false detections. Once a jump of the mean has been detected, the amplitude of this jump is estimated using the data samples in the 500-ms window. The amplitude of the jump is the rapid impedance change.

The rapid impedance change is then summed up into a memory that contains the sum of the previous rapid change events yielding the cumulative error. For example, if a first event of 80 Ω and a second event of 90 Ω has been detected after, the cumulative error will be set to 170 Ω.

After a rapid impedance change has been properly detected, the long-time constant filter is reinitialized with the current impedance value. Otherwise, the temperature-compensated expected impedance value would change. This expected value must stay constant for a constant temperature even if errors have been detected. On the other hand, an impedance variation of 90 Ω that happens over an hour, due to temperature change, will be ignored and therefore not be memorized. This variation will contribute to the slowly varying temperature-compensated expected impedance.

As a failsafe measure, the temperature-compensated expected impedance is constrained to ±3% of the commissioned impedance. This is enough to cover typical variations associated with temperature [3].

In the case where the capacitors drift due to aging, the time-based temperature compensation algorithm will accumulate some error with time as the compensation works by observing the actual measured value. However, other temperature compensation techniques still show the same problem, as well as traditional unbalance protection. While the relay does not proceed to evaluate this drift by itself, it can provide valuable information about actual measured impedance that can be gathered on a long-term basis in order to evaluate this drift for maintenance purposes.

C. Operation results

The following present the results obtained when applying the proposed temperature compensation algorithm to an impedance-based protection element in a few operating conditions.

1) Temperature variation

The first case presented here shows the behavior with a temperature variation over a day, from -30ºC to 25ºC. First figure displays the measured impedance and the temperature-compensated expected impedance calculated by the relay.

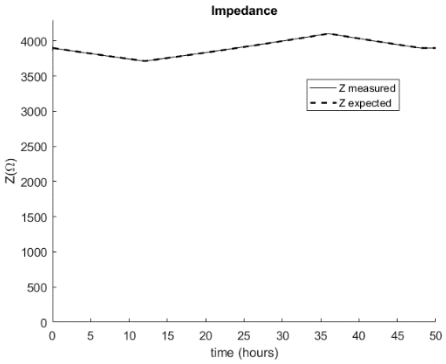


Figure 6 Variation of the bank impedance over time

The figure shows that the impedance varies in magnitude more than the configured threshold for alarm, which is set to 1% of the commissioned impedance of 3900 Ω. However, thanks to temperature compensation, the following figure also shows that no alarm signal is raised.

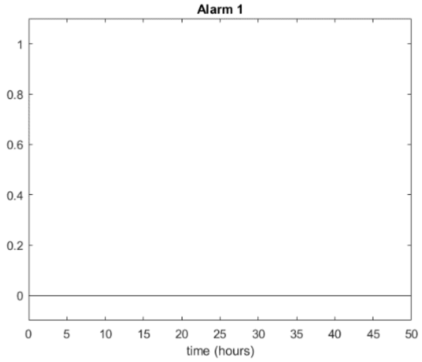


Figure 7 Absence of alarm in a scenario where the impedance varies along with temperature

2) *Capacitor failure*

The second case highlights an actual capacitor failure in the bank. The following figure shows the event relative to the impedance thresholds.

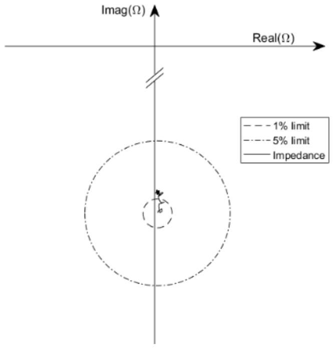


Figure 8 Impedance of a string affected by a capacitor failure

The next figure compares the magnitude of the measured impedance and the actual temperature-compensated expected impedance.

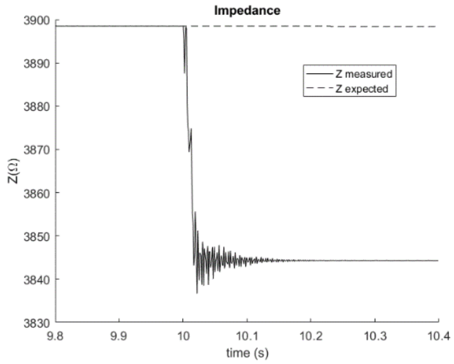


Figure 9 Magnitude of impedance during a capacitor failure, over time

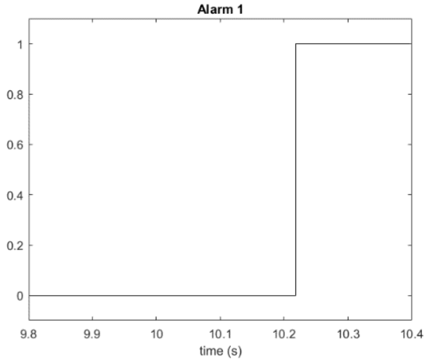


Figure 10 Alarm signal is asserted when the measured impedance exits the alarm range after capacitor failure

After the measured impedance exits the alarm impedance circle for the configured operating time (200 ms), the alarm signal raises, as shown in Figure 10. This is not a typical operating time for the first alarm level, but this delay was chosen to simplify the view of the behavior.

Figure 9 also showed that even if a capacitor fails and the measured impedance falls, the temperature-compensated expected impedance that is output from the algorithm still stays the same. In the algorithm, the cumulative error detected now compensates for the long time-constant filter drop.

3) *Grid disturbance*

In case of a grid disturbance, the protection element is expected to behave without operation. Figure 11 shows an example of such event.

During the event, the measured impedance exits the alarm threshold but comes back in it shortly after. Figure 12 shows the measured impedance relative to temperature-compensated expected impedance.

During such an event, the protection does not operate, as shown in Figure 13.

D. Comparison between 87V and 21C

For comparison purposes between 87V and 21C protection elements, we consider the case of the capacitor bank presented in section II.A, a bank comprising 48 capacitor elements per string. The following sections provide comparison of behavior between the two protection schemes.

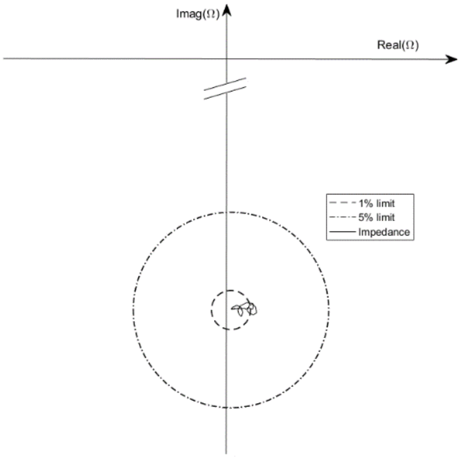


Figure 11 Impedance of a string during a grid disturbance

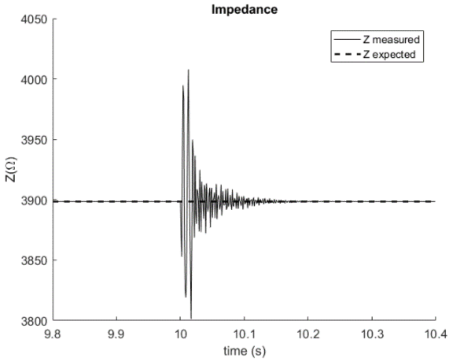


Figure 12 Magnitude of impedance during a grid disturbance, over time

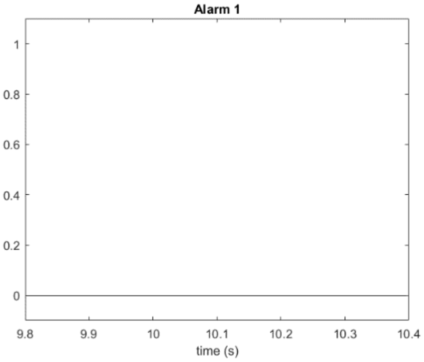


Figure 13 Absence of alarm in a scenario of grid disturbance

1) *Sensitivity to distributed failures vs cumulative failures*

In order to compare the effect of the location of capacitor failures, a first scenario where one capacitor element failure is applied on each string of a given phase is considered. Failures are applied at the same time for illustration convenience, although they would not typically occur at the same time. The effect of such a scenario on an 87V element is illustrated on the following figure.

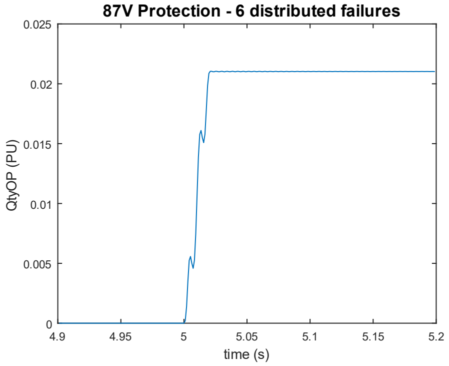


Figure 14 Effect of distributed failures on an 87V element

In a second scenario, we consider the case of 5 capacitor element failures occurring on the same string of a given phase while the other strings have no failures. The following figure shows the resulting effect on the 87V element.

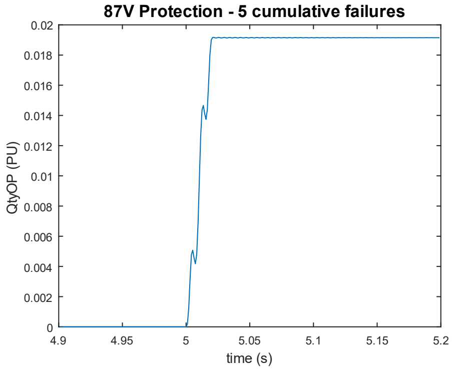


Figure 15 Effect of cumulative failures on an 87V element

As shown in the figures, both scenarios result in approximately the same effect (0.021 p.u. vs 0.019 p.u.) on the operating quantity of the 87V element. While in the first case, operation would still be safe, it would clearly be hazardous in the second scenario, thus requiring the trip threshold of the element to be set close to the operating quantity shown in Figure 15. This would translate to misoperation for distributed failures in the bank.

The following figures show the behavior of the impedance for 21C elements distributed over the strings of the bank.

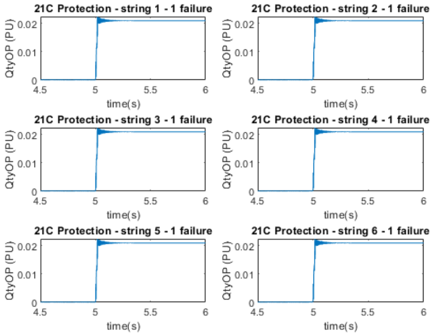


Figure 16 Effect of distributed failures on a 21C element

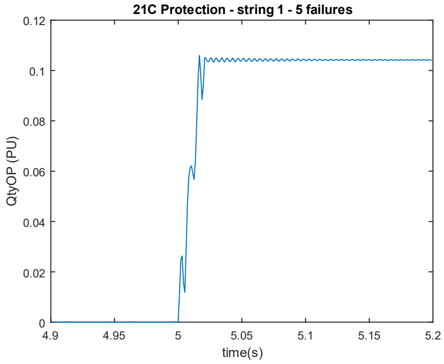


Figure 17 Effect of cumulative failures on a 21C element

The previous figures show that the scenario with cumulative capacitor failures translates on a string impedance measurement delta 5 times greater, approximately 0.1 p.u. for the string impedance, whereas the distributed failure scenario results in a variation of around 0.02 p.u. This protection scheme clearly allows to discriminate the location of failures within the bank.

2) *Temperature effect on 87V elements*

Voltage differential elements (87V) are also affected by temperature because the design of the power capacitors used in the bank differ from the design of the low-voltage capacitors used for measurement. Their capacitance-temperature curves will be different [8]. Furthermore, the capacitor bank temperature is typically not uniform because of shading. In the typical case, the 87V protection operating quantity will vary significantly due to temperature as shown in the next figure.

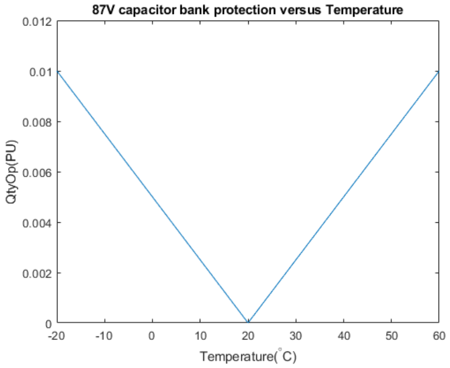


Figure 18 Effect of temperature on an 87V protection element operating quantity

In the case of the 21C, temperature variation is expected by the proposed temperature compensation algorithm. Therefore, the behavior of the 21C protection will be the same whether the temperature in the bank is uniform or not.

IV. CONSIDERATIONS ABOUT FIELD USAGE

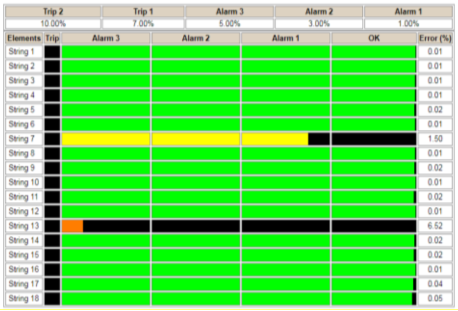
A. *Configuration and Commissioning*

As seen previously, impedance-based protection for capacitor banks (21C) operates on a threshold based on a relative error value, in percentage of the nominal impedance of the bank. This requires the expected impedance of the bank to be configured in the protection relay prior to energization. However, the actual impedance of the bank might be slightly different than the nominal. First, the tolerance of the capacitor units themselves will differ from the nameplate value. Second, the instrumentation used, either for voltage or current measurement, will be another source of error. Then, the accuracy of the inputs of the relay will add to the imprecision.

All these tolerances sum up and will result in some relative error reading upon first energization, which leaves less security margin for the operation of the protection relay. Thus, it is recommended to calibrate the real impedance of the bank at commissioning to get an impedance measurement as close as possible to the target value configured for a given string. This calibration can be implemented in the protection relay as a command used during commissioning that allows to take a snapshot of the actual impedance of the strings. This way, the initial error reading for each of the strings after commissioning should be close to 0%.

B. *Condition-based monitoring*

The 21C protection scheme involves measuring the impedance of each string in the capacitor bank. By displaying the measurements locally on the protection relay, or through a remote interface to the relay, like a web page, an operator can quickly get the health of the bank during operation.



Trip 2	Trip 1	Alarm 3	Alarm 2	Alarm 1
10.00%	7.00%	5.00%	3.00%	1.00%

Elements	Trip	Alarm 3	Alarm 2	Alarm 1	OK	Error (%)
String 1						0.01
String 2						0.01
String 3						0.01
String 4						0.01
String 5						0.02
String 6						0.01
String 7						1.50
String 8						0.01
String 9						0.02
String 10						0.01
String 11						0.02
String 12						0.01
String 13						6.52
String 14						0.02
String 15						0.02
String 16						0.01
String 17						0.04
String 18						0.05

Figure 19 Example display of the bank relative error on impedance measurements for each string.

The same measurements can also be retrieved remotely using SCADA communication like IEEE 1815 (DNP3) or IEC 61850. If this information is gathered globally, a utility can in turn prioritize maintenance activities on banks that are most affected by capacitor failures. At the same time, maintenance can be focused on the strings that really require repairs, speeding up the intervention.

C. *Retrofit of existing installations*

We previously demonstrated that the use of a 21C on each string of a bank provides better sensitivity of the protection while helping with fault location. However, it is also possible to retrofit existing installations of 87V protections and replace the 87V protection shown on Figure 1 with a 21C protection. This replacement requires the usage of low-voltage capacitor shown as a shunt capacitor to measure the combined current of all strings. This allows a quick retrofit of an existing installation to benefit from the advantages of the proposed temperature compensation mechanism. Such a retrofit would still be unable to discern distributed capacitor faults from cumulative capacitor faults in a given string.

V. CONCLUSION

This paper presented the principles of operation behind impedance-based protection for shunt capacitor banks. It highlighted the issue of impedance variation due to temperature, as well as exposure to sun. Then we presented a proposed temperature compensation mechanism that can act without any external probe.

Results indicate that the proposed mechanism allows safe and reliable use of the 21C protection element under varying temperature conditions. Moreover, the usage of this mechanism gives an advantage over the use of traditional voltage differential elements (87V).

While this method improves the reliability of protection, it can also provide valuable information to speed up repairs on capacitor banks affected by faults, and can be used for condition-based monitoring in order to better target maintenance.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of Felix Pelletier and Rene Lord in the development of the impedance-based protection element (21C) and the proposed temperature compensation mechanism presented in this paper.

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BIOGRAPHIES

Eric Thibodeau is a Product Manager for Protection Relays at Gentec. He also acts as a technical resource about communication network protocols and cybersecurity. He is involved in the activities of the IEEE Power System Communications and Cybersecurity Committee (PSCCC) and IEEE Power System Relaying and Control Committee (PSRCC). Prior to Gentec, he was a Software Engineer at Cooper Power Systems. Formerly, he obtained its B.Ing. in Computer Engineering, as well as M.Sc.A. and Ph.D. degrees from Universite de Sherbrooke. While a graduate student, he was also a lecturer in this same institution about network protocols specification and design, network components and architecture as well as electronic power supply design. His main areas of expertise are TCP/IP networking, SCADA communication and cybersecurity, and digital protective relaying. He is a registered professional engineer in the Province of Quebec.

Benjamin Couillard is a specialist in digital signal processing and control systems at Gentec. He is responsible for designing and implementing digital signal processing algorithms for protection relays. He also implements digital control loops for inverters, rectifiers and battery chargers. Prior to Gentec, he received the B.S.E.E. degree from Universite de Sherbrooke in 2004.

Dean Sorensen received a B.S. degree with distinction in Electrical Engineering in 1984 and an M.S. degree in Power Systems Management in 2002 both from Worcester Polytechnic Institute (WPI). Dean has over 30 years of experience in the power industry serving in various engineering capacities in transmission, distribution and generation primarily in the areas of protection and controls and power quality. Dean is a principal engineer in the Department of Protection Policy and Support at National Grid. Dean has also been on the faculty of WPI since 2011 as an adjunct instructor teaching graduate courses related to power system protection. He is a member of IEEE and is an active member of the Power System Relaying Committee (PSRC) currently active serving on the IEEE Std. C37.99 working group. Dean is also registered professional engineer in the state of Massachusetts.

Song Ji is a principal engineer in the Department of Protection Policy and Support of National Grid, where he analyzes system disturbances on transmission and supply networks, develops & reviews protection related standards and applications. Song has more than 20 years’ experience in the power system studies, substation & power plant design, protection and control for utility and industrial systems ranging from 4.16 kV to 500 kV. Prior to joining National Grid, Song spent 4 years with Worley Parsons Canada as a power system specialist and 9 years with Henan Electric Power of China State Grid as a power system engineer. He received BSEE in power system from Zhengzhou University in China and a MSEE in power system from Royal Institute of Technology in Sweden. He is a member of IEEE and a registered professional engineer in Alberta Canada.