A Method for Evaluating Loadability of Incremental-Quantity Distance Elements

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A METHOD FOR EVALUATING LOADABILITY OF INCREMENTAL-QUANTITY DISTANCE ELEMENTS

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Abstract

This paper presents a method for evaluating the loadability of incremental-quantity distance (TD21) protection elements. Responding to changes in voltages and currents, the TD21 elements are not impacted by heavy load or power swings. However, switching operations that result in sudden changes in load, including both load pickup and load rejection, may impact security of the TD21 elements. Traditional methods of evaluating protection element loadability do not apply to incremental quantity-based protection elements and schemes. This paper closes the gap by introducing a simple and practical method of evaluating TD21 loadability. The paper provides a short overview of the key TD21 design details and describes a TD21 loadability evaluation method.

1 Introduction

First introduced a few decades ago in a static generation of line protective relays [1] [2], the incremental-quantity underreaching distance (TD21) protection element has been recently re-introduced in microprocessor-based relays and is now available in products from several manufacturers [3] [4]. The TD21 element has a potential for half-cycle operating speed, and in some implementations, it operates in a quarter of a cycle or faster [3]. Even though the design details may differ, the TD21 element operating principle is similar across a range of implementations [5].

Load encroachment and power swings do not compromise the TD21 element security. A slowly changing load and a power swing in high-inertia systems create only small incremental signals and by extension, only a small TD21 operating signal. However, a large sudden load change may cause the TD21 element to misoperate. Traditionally, loadability verification for line protection elements considers a static load [6] and a stable power swing [7]. Evaluating the impact of sudden load changes on incremental-quantity protection is a new problem.

The paper starts with reviewing the TD21 operating principle and presenting several design variants used in products today.

Next, the paper introduces a practical method for evaluating the loadability of the TD21 element during load switching. The method is based on the phase angle synchronism-check settings for lines in the vicinity of the protected line and the source-to-impedance ratio (SIR) for the protected line. The method shows how to verify security of a TD21 reach setting for given system conditions and how to calculate the maximum secure reach setting.

The paper presents several examples and illustrates them by showing test results from a relay [3] that incorporates the TD21 element. The method can be refined to analyze the loadability of TD21 implementations that are different than [3].

2 TD21 Element Design

The TD21 element derives a change in voltage at the TD21 element reach point by using the change in the measured voltage and current at the relay location and the line impedance data. The change in reach-point voltage during a fault at the reach point cannot be greater than the pre-fault voltage at the reach point. If the derived change in voltage is greater than the pre-fault voltage, the fault must be short of the reach point and the TD21 element operates. Otherwise, the fault is beyond the reach point and the TD21 element restrains. The following text, taken from [5], further explains the TD21 operating principle.

2.1 TD21 Principle [5]

With reference to Fig. 1a, consider a line between Terminals S and R with a TD21 element at Terminal S. A distance element is required to operate for faults between Terminal S and the reach point, but not beyond. The element measures the local voltages (v) and currents (i) and derives their incremental quantities (Δv, Δi). We represent the line as a resistive-inductive circuit (RL model).

Assume a metallic fault is located at the reach point. With reference to Fig. 1b, a metallic fault that occurs when the pre-fault voltage is v_{PRE} causes a change in voltage at the reach point (Δv_{REACH}) that is equal to $-v_{PRE}$. In other words, the greatest possible change in voltage at the reach point is the pre-fault voltage at the reach point. This observation allows us to derive the operating equation of an incremental-quantity distance element as follows.

Consider a fault that is located short of the reach point, as shown in Fig. 2a. If you calculate the change in voltage at the reach point for this fault, you will obtain a value greater than the pre-fault voltage at the reach point. Now consider a fault that is located beyond the reach point, as shown in Fig. 2b. If you calculate the change in voltage at the reach point for this fault, you will obtain a value less than the pre-fault voltage at the reach point.

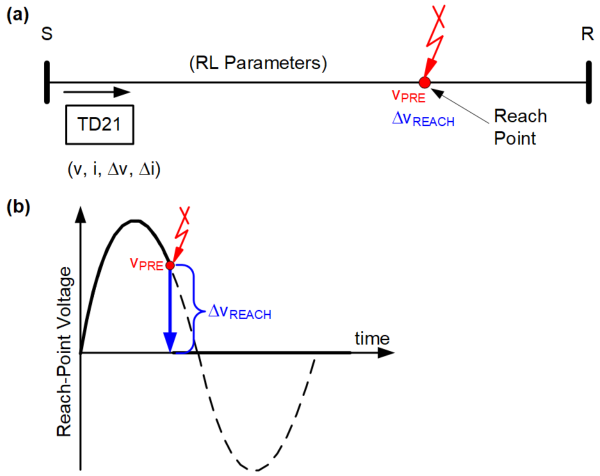

Fig. 1. Measurements and data for TD21 element operation (a) and voltage at the reach point for a metallic fault at the reach point (b).

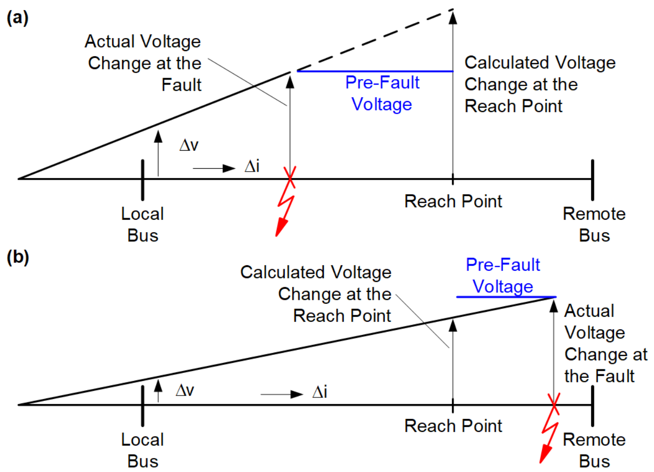

Fig. 2. Actual and TD21 element calculated change in voltage at the fault location: in-zone fault (a) and out-of-zone fault (b).

The above observations allow us to write the key operating equation for the incremental-quantity distance element:

$$\mathrm{OPERATE} = (|\Delta v_{\mathrm{REACH}}| > |v_{\mathrm{PRE}}|) \qquad (1)$$

The operating signal in (1) is calculated as the voltage change at the reach point, which can be summarized as:

$$\Delta v_{\mathrm{REACH}} = \Delta v - \mathrm{TD21M} \cdot |Z_1| \cdot \Delta i_Z \qquad (2)$$

where:

$|Z_1|$ is the magnitude of the positive-sequence line impedance.

TD21M is the per-unit reach of the element.

i_Z is the instantaneous replica current.

Δ is the incremental-quantity symbol.

Equations (1) and (2) use symbolic references to an incremental quantity (Δ), voltage (v), voltage magnitude (| |), and comparison (>). These operations can be implemented in a variety of ways, yielding different versions of the original TD21 principle of operation.

Different implementations use different approaches to:

- Derive the voltage change signal (high-pass filtered transient [1] [2], instantaneous [3] [5], half-cycle phasor, integrated half-cycle phasor magnitude [4]).
- Derive the pre-fault voltage signal (nominal, instantaneous, integrated half-cycle phasor magnitude).
- Implement the logic for comparing the two signals in (1).

Reference [5] provides a comprehensive review of these design choices.

2.2 TD21 Restraining Signal [5]

The TD21 operating signal in (1) is a change in voltage at the reach point, and as such, it is a common concept in all TD21 implementations. The TD21 restraining signal in (1) is the pre-fault voltage at the reach point and can be selected arbitrarily, as is the case with many restraining signals used in protective relaying in general. The TD21 restraining signal plays an important role in TD21 loadability. Implementation [3] compares the instantaneous operating and restraining signals in the time domain, without averaging or using any other method of deriving the magnitude information. We refer to this method of restraining as *point-on-wave* restraining.

To use the concept of point-on-wave restraining, we calculate the instantaneous voltage at the reach point:

$$v_{\mathrm{PRE}} = (v - \mathrm{TD21M} \cdot |Z_1| \cdot i_Z)_{\mathrm{PRE}} \qquad (3)$$

We know that the restraining voltage calculated with (3) is not perfectly accurate because of the finite precision of line impedance data, line charging current, line transposition, and so on. Nonetheless, (3) is a good approximation of the actual voltage at the reach point. Of course, we need a time-delayed value of (3) to represent the voltage at the reach point prior to the fault.

Fig. 3 explains our implementation. The logic multiplies the absolute value of the voltage (3) by the factor k (slightly greater than 1) to add a small amplitude margin. It buffers this signal and extracts one-period-old data and two extra sets of data – one before and one after the exact one-period-old data – to add a small phase margin to the restraining signal. The maximum value among the minimum restraint level and the three values becomes the final restraint, V_{RT}. The logic uses the minimum restraint constant to ensure that the TD21 restraint does not fall to zero for points on wave near the zero crossings (i.e., during time intervals when the restraining signal (3) is very small or zero).

Fig. 3b illustrates the rationale of the way we calculate the TD21 restraining voltage. Our goal is to create a signal that 1) envelops the actual reach-point voltage while assuming various sources of errors yet 2) still reflects the instantaneous value of the voltage to maximize the speed and sensitivity inherent in the time-domain implementation.

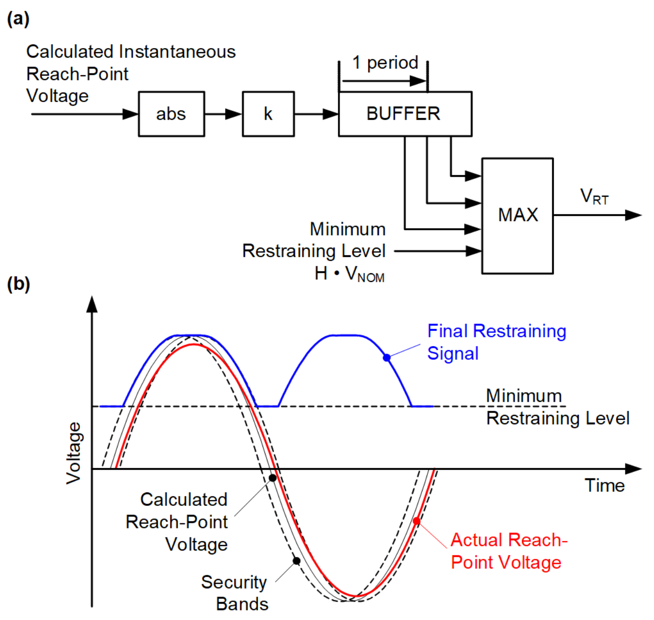

Fig. 3. Point-on-wave TD21 restraining signal: logic diagram (a) and example of operation (b).

2.3 *TD21 Comparator Logic*

The TD21 restraint in implementation [3] is more than just the restraining signal depicted in Fig. 3. The TD21 element operates if the integral of the difference between the operating and restraining signals is above a certain threshold. The TD21 logic compares the polarity of the operating signal with the polarity of the pre-fault voltage at the reach point (a true fault moves the faulted-loop voltage toward zero not away from zero). A faulted-loop selection logic based on incremental quantities is used. The element is supervised with an incremental-quantity overcurrent element to check that the voltage profile depicted in Fig. 2 slopes enough to allow secure distance protection. This overcurrent supervision limits the TD21 application to lines with a local SIR less than about 2.5. Also, the TD21 comparator logic uses an arming logic to verify the predisturbance steady state and a time window to effectively shut down the TD21 element several milliseconds into the disturbance.

3 Static Load and Power Swings

Static or slowly changing load does not pose security concerns for the TD21 element. If the load does not change, the incremental voltage and current at the relay location are zero, yielding an operating signal of zero in (1). If the load changes slowly (the time constant of a load change is much longer than a power cycle), the operating signal is very small, well below the minimum restraint in Fig. 3. From this perspective, the TD21 element meets the loadability requirements defined in [6], regardless of the TD21 reach setting.

During a power swing, the incremental voltage and current at the relay location are small and the TD21 element remains secure and dependable. If the swing accelerates, the incremental signals increase gradually with the frequency of the swing. Before these incremental signals become large enough to jeopardize the TD21 security, the arming logic embedded in the TD21 implementation [3] detects standing incremental signals and disarms the TD21 element. This guarantees security during power swings that are fast and create standing incremental signals. From this perspective, the TD21 element meets the power-swing requirements defined in [7], regardless of the TD21 reach setting.

4 Load Switching

Fig. 4 illustrates load rejection – a switching operation outside of the protected line that entirely interrupts the power flow in the protected line. Fig. 5 illustrates load pickup – a switching operation outside of the protected line that loads the line.

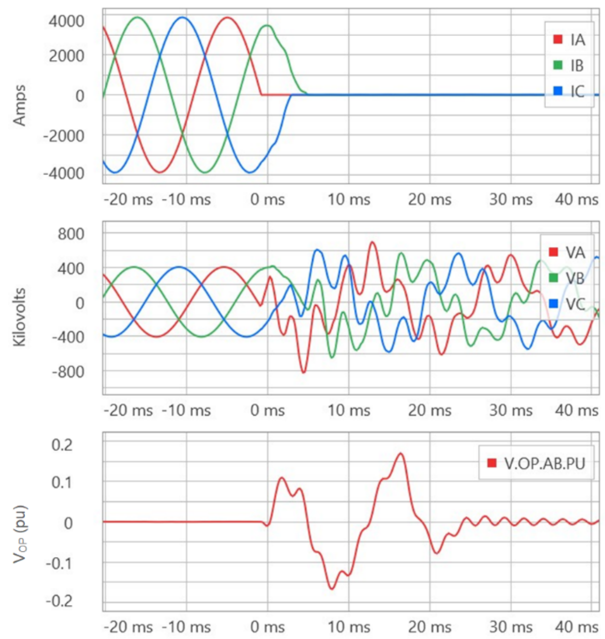

Fig. 4. Sample case of load rejection: relay currents, voltages, and the per-unit TD21 operating signal (AB loop).

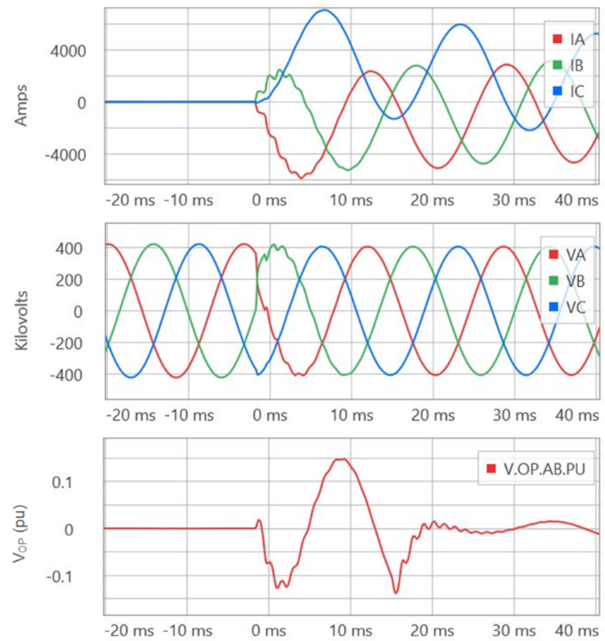

Fig. 5. Sample case of load pickup: relay currents, voltages, and the per-unit TD21 operating signal (AB loop).

TD21 loadability is concerned not with the amount of load, but with the amount of sudden change in load, i.e., load switching. Any change in the line current causes a change in the voltage drop between the relay and the TD21 reach point, and as a result, it causes a change in the TD21 reach-point voltage (TD21 operating signal in (1)). The element remains secure as long as the operating signal is safely below the restraining signal, which we analyze next.

5 TD21 Loadability Analysis

Assume the line is not loaded or is lightly loaded before a large amount of generation or load is switched on, causing the line load current to rise abruptly, as illustrated in Fig. 5. With reference to Fig. 6, assume the local and remote sources (E_L and E_R) have nominal voltage magnitudes (V_{NOM}) and are shifted in phase by $\Delta\Theta$. Assume the line impedance is Z_L and the local and remote system SIRs are SIR_L and SIR_R, respectively.

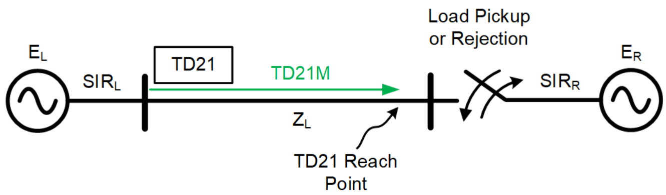

Fig. 6. Equivalent network diagram for load switching.

Before the breaker closes, the line is not loaded and the TD21 reach-point voltage equals the local system voltage, E_L. Refer to Fig. 7 and observe that the voltage difference between the two systems is:

$$\Delta V = 2 \cdot V_{NOM} \cdot \sin\left(\frac{\Delta\Theta}{2}\right) \tag{4}$$

When the breaker closes and connects the local and remote systems, the voltage difference (4) drives the current in the protected line, while the system and line impedances limit the current:

$$I = 2 \cdot \frac{V_{NOM}}{Z_L \cdot (SIR_L + 1 + SIR_R)} \cdot \sin\left(\frac{\Delta\Theta}{2}\right) \tag{5}$$

The current (5) causes a voltage drop between the local system and the TD21 reach point that is proportional to the sum of the local system impedance and the impedance between the relay and the TD21 reach point. Because the preswitching voltage at the reach point is E_L, the change in voltage at the reach point (i.e., the TD21 operating signal, V_{OP}) equals the voltage drop:

$$V_{OP} = I \cdot Z_L \cdot (SIR_L + TD21M) \tag{6}$$

Substituting (5) into (6), we obtain:

$$V_{OP} = 2 \cdot V_{NOM} \cdot \sin\left(\frac{\Delta\Theta}{2}\right) \cdot \frac{SIR_L + TD21M}{SIR_L + 1 + SIR_R} \tag{7}$$

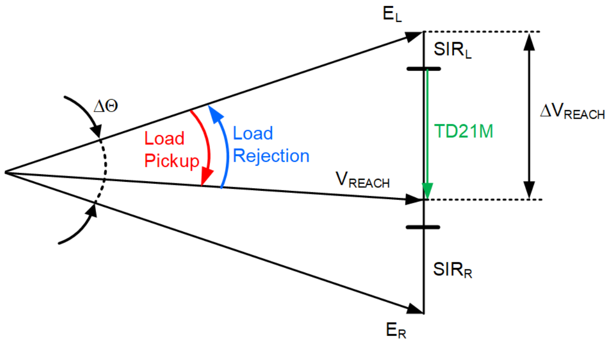

Fig. 7. Voltage diagram for load switching.

As shown in Fig. 7, the change in voltage at the TD21 reach point is a fraction of the voltage difference between the two sources. The fraction is the ratio between SIR_L + TD21M and $SIR_L + 1 + SIR_R$. The greater the system SIR_L, the larger the TD21 operating signal.

The TD21 restraining signal (V_{RT}) is never less than a fraction, H, of the nominal voltage (minimum restraining level in Fig. 3). Implementation [3] uses H = 0.50 if the line is not series compensated and H = 1 if the line is series compensated:

$$V_{RT} > H \cdot V_{NOM} \tag{8}$$

Comparing (7) with the minimum restraining signal (8), we obtain the general TD21 security condition:

$$TD21M < \frac{H}{2} \cdot \frac{SIR_L + 1 + SIR_R}{\sin\left(\frac{\Delta\Theta}{2}\right)} - SIR_L \tag{9}$$

The TD21 element is applicable to systems with a low SIR. As explained in Section 2.3, implementation [3] effectively inhibits the TD21 element when SIR_L is greater than about 2.5.

Fig. 8 plots (9) and clamps the TD21 reach at 90 percent of the line impedance to reflect the reach setting range in implementation [3].

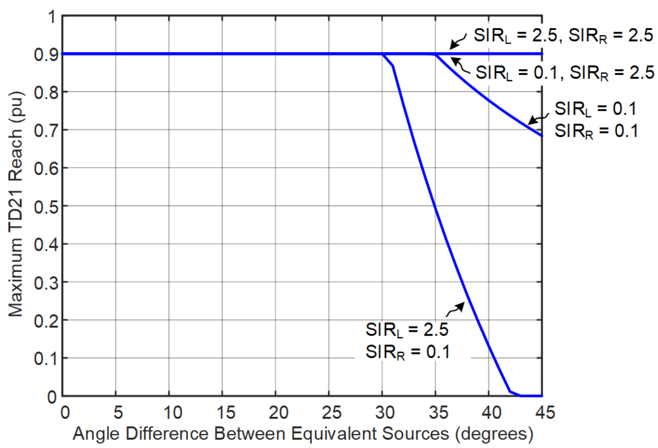

Fig. 8. Maximum TD21 reach as a function of the system voltage difference angle during load pickup for selected values of the SIR (H = 0.5).

Consider several examples to better understand the impact of the SIRs.

Case 1. Strong local system, weaker remote system

Consider $SIR_L = 0.4$, $SIR_R = 1.5$, and $\Delta\Theta = 40$ degrees. Criterion (9) allows the maximum reach of 172 percent of the line length.

Case 2. Relatively weak local system, strong remote system

Consider $SIR_L = 2.5$, $SIR_R = 0.1$, and $\Delta\Theta = 40$ degrees. Criterion (9) allows the maximum reach of only 13 percent.

Case 3. Both systems relatively weak

Consider $SIR_L = 2.5$, $SIR_R = 2.5$, and $\Delta\Theta = 40$ degrees. Criterion (9) allows the maximum reach of 188 percent.

Generally, for a particular value of the angle difference, $\Delta\Theta$, the greater the SIR_L value compared with the value of $1 + SIR_R$, the shorter the TD21 reach. Fig. 9 shows SIR combinations that allow the TD21 reach of 80 percent for various angle differences when switching load. For example, in Case 1, for $\Delta\Theta = 40$ degrees and $SIR_L = 0.4$, the 80 percent TD21 reach is allowed as long as the SIR_R is less than 0.25. In Case 2 ($\Delta\Theta = 40$ degrees and $SIR_L = 2.5$), the 80 percent TD21 reach would be allowed if the SIR_R were greater than 1.

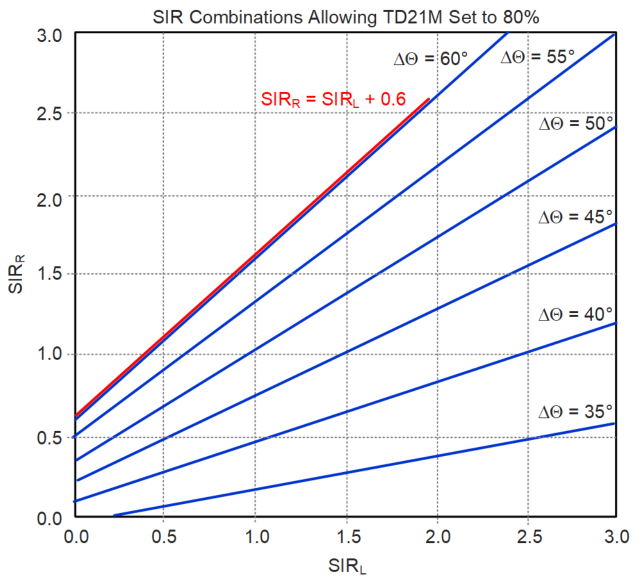

Fig. 9. SIR combinations allowing TD21 reach of 80 percent for various angle differences during load switching.

5.1 *Switching Angle Less Than 30 Degrees*

As shown in Fig. 8 and Fig. 9, the TD21 reach is not constrained if the source angle difference during load switching is less than 30 degrees. To understand and prove this, rewrite the right-hand side of (9) as follows:

$$\frac{H}{2 \cdot \sin\left(\frac{\Delta\Theta}{2}\right)}\left(1 + SIR_R + \left(1 - \frac{2}{H}\sin\left(\frac{\Delta\Theta}{2}\right)\right) SIR_L\right) \quad (10)$$

For $\Delta\Theta$ less than 28.9 degrees (we will round up to 30 degrees for simplicity) and $H = 0.5$, the expression:

$$1 - \frac{2}{H}\sin\left(\frac{\Delta\Theta}{2}\right) \quad (11)$$

which acts as a multiplier for the SIR_L in (10), is positive. Therefore, the SIR_L in (9) does not decrease the allowed TD21 reach but increases it.

If the load-switching angle is less than 30 degrees, the TD21 reach is not constrained and no loadability verification is needed.

5.2 *Load-Switching Angle Greater Than 30 and Less Than 60 Degrees*

Load switching is unlikely when the angle is greater than 60 degrees. If we assume 60 degrees as the worst case, we can use Fig. 9 to obtain a conservative loadability condition for the TD21 setting of 80 percent of the line impedance:

$$SIR_R > SIR_L + 0.6 \quad (12)$$

5.3 *Conservative TD21 Loadability Criterion*

Combining findings from Sections 5.1 and 5.2, we can write the following conservative loadability criterion for the TD21 element assuming the reach of 80 percent:

$$\begin{gathered} \text{TD21M} = 0.8 \text{ pu is allowed if} \\ \Delta\Theta < 30° \text{ or } SIR_R > SIR_L + 0.6 \end{gathered} \quad (13)$$

6 TD21 and Load Pickup

We can use synchronism-check settings to obtain the limit of the maximum voltage angle difference between the two equivalent systems prior to load pickup. When switching generation or load near the remote line terminal, the equivalent system voltages can differ by as much as the synchronism-check phase angle setting for the breaker that performed the switching, but not by more.

Obtain the $\Delta\Theta_{SYNC}$ angle as the maximum synchronism-check phase angle setting among all breakers in the immediate vicinity of the remote line terminal, i.e., breakers connected to the remote bus and breakers at the remote ends of any line or transformer connected to the remote bus. To verify the TD21 reach setting, use (9), Fig. 9, or (13) with $\Delta\Theta = \Delta\Theta_{SYNC}$.

7 TD21 and Load Rejection

When the line load current is interrupted by an external breaker, the reach-point voltage changes from the pre-event voltage at the reach point to the voltage of the local source. As shown in Fig. 7, this angle change is identical and opposite in direction to the change when picking up load. Therefore, (9) applies to both load pickup and load rejection and can be used with the following angle:

$$\Delta\Theta = MAX(\Delta\Theta_{SYNC}, \Delta\Theta_{LOAD}) \quad (14)$$

Note that $\Delta\Theta_{LOAD}$ is the angle between equivalent systems. The angle across the protected line ($\Delta\Theta_{LINE}$) is a fraction proportional to the SIR values. If you know the maximum load angle across the line, you can approximate the angle between the systems as follows:

$$\Delta\Theta_{\mathrm{LOAD}} \cong \Delta\Theta_{\mathrm{LINE}} \cdot (\mathrm{SIR_L} + 1 + \mathrm{SIR_R}) \quad (15)$$

and use it in (14) and (9).

8 TD21 Load-Switching Verification

Load-switching requirements are technically outside of the standard loadability requirements, such as NERC PRC-023 [6]. However, it is a logical extension of the standard to include scenarios where the load may be abruptly applied or removed.

The TD21 element operates in just a few milliseconds. Breaker pole scatter when switching the load may create a temporary unbalance and a momentary zero-sequence current. This momentary current may allow the ground TD21 element to operate even though there is no standing zero-sequence unbalance. Therefore, the load-switching criteria apply to both the phase (TD21P) and ground (TD21G) reach settings of the TD21 element.

8.1 General Procedure

Follow this procedure to verify that the TD21 reach is secure or to calculate the maximum secure reach for the TD21 element:

STEP 1. Obtain synchronism-check phase angle settings for all breakers in the immediate vicinity of the remote terminal of the protected line, i.e., the remote terminal breaker and breakers of any line or transformer connected to the remote terminal. Identify the greatest synchronism-check phase angle setting, $\Delta\Theta_{\mathrm{SYNC}}$. If the load angle is greater than the synchronism-check angle, select the greater of $\Delta\Theta_{\mathrm{SYNC}}$ and $\Delta\Theta_{\mathrm{LOAD}}$ according to (14).

STEP 2. Verify that both the TD21P and TD21G settings satisfy (9). Use H = 0.5 for implementation [3] applied to noncompensated lines. Use H = 1 for applications to series-compensated lines. Consider a margin of about 15 percent of the line impedance (0.15 pu) to account for system overvoltage, source voltage magnitude difference, breaker pole scatter, and transients.

STEP 3. In the unlikely situation that Step 2 cannot be satisfied, lower the TD21 reach.

8.2 Procedure for TD21 Reach Setting of 80 Percent or Less

Follow Step 1 and use criterion (13). The 80 percent TD21 setting is allowed if the phase angle is less than 30 degrees or if the phase angle is less than 60 degrees and the system $\mathrm{SIR_L}$ is less than the system $\mathrm{SIR_R}$ with a 0.6 margin.

8.3 Procedure for Series-Compensated Lines

In applications to series-compensated lines, implementation [3] uses H = 1 with margin. An analysis of (9) tells us that the TD21 reach is not constrained for angles as great as 60 degrees, regardless of the SIR values.

9 Conclusions

This document provides information and criteria for evaluating compliance of the TD21 element against typical line loadability requirements (such as NERC PRC-023 [6]) and stable power-swing requirements (such as NERC PRC-026 [7]).

The document explains that the TD21 element is inherently secure and dependable under static load and slow load variations, including stable power swings, and is secure during fast load variations, such as unstable power swings.

The document introduces TD21 load-switching criteria. We recommend verifying that the TD21 reach setting does not exceed a secure value based on the synchronism-check phase angle settings for breakers in the vicinity of the remote line terminal.

The recommended load-switching criterion for the TD21 element is not overly restrictive unless the local system is relatively weak, the remote system is strong, and very wide synchronism-check angle settings are used.

If the maximum synchronism-check phase angle setting is 30 degrees or less or if the $\mathrm{SIR_L}$ is less than the $\mathrm{SIR_R}$ with a 0.6 margin, the TD21 reach can be set to 80 percent without loadability constraints.

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