Challenges in NERC PRC-026 Compliance Evaluation for a Complex Multi-Terminal Transmission Line

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***Abstract*— This paper presents the complexities and challenges involved in the implementation of the NERC PRC-026-1 reliability standard for power systems with complex topologies such as multi-terminal lines and lines with several tap points tied to parallel lines at the low voltage side of the tapped transformers. The standard methodology for compliance evaluation is based on a simple transmission line topology with two terminals. This methodology is extensively detailed in the PRC-026 standard Application Guidelines for two-terminal lines. However, limited guidance is provided for cases with more than two sources, such as transmission lines with more than two terminals or transmission lines with load tap transformers connected to sources of current from parallel lines. This paper explores the additional challenges associated with adapting multi-terminal and multi-source transmission lines to the calculation methodologies outlined in the PRC-026 standard and Application Guidelines for two-terminal lines.**

I. Introduction

PRC-026-1 is a NERC reliability standard that addresses the operation of protective devices during stable power swings. This standard requires applicable entities to ensure that load-responsive protective relays would not trip in response to stable power swings during non-fault conditions. To meet the standard's requirements, transmission and generation owners are required to identify BES elements that are applicable to PRC-026-1, evaluate the protection according to a criteria based on system impedance and conditions, and develop and implement Corrective Action Plans for protection that does not meet the evaluation requirements.

The evaluation aspect of this standard involves the comparison of protective functions sensitive to power swing characteristics, specifically phase distance and overcurrent protection elements, against criteria calculated from system impedance and specified operating conditions. An Application Guideline [1] is included with the PRC-026-1 standard documentation that provides detailed calculations and examples on the evaluation methodology for basic two-terminal lines. However, while two-terminal lines are very well covered in the Application Guideline, only limited consideration is given to more complex line configurations that may have more than two terminals or sources.

Due to the standard having only recently gone into effect, limited guidance or documentation is available for the practical execution of a PRC-026-1 compliance study, particularly for cases of more complex line configurations. An introduction to the power swings and their effect on protection is provided in [2] and technical considerations and process for generation applications with respect to the standard are discussed in [3]. This scarcity of information may pose difficulties to applicable entities that are required to evaluate multi-terminal and multi-source lines against the PRC-026-1 standard.

This paper explores the additional challenges and considerations associated with a practical compliance evaluation and establishment of evaluation methodology for one such entity. This utility, location within the NPCC region, has many lines of multi-terminal and multi-source configuration and heavily utilizes communications-assisted protection schemes on its BES system. In addition to addressing the technical questions in adapting the NERC-provided methodologies to more complex lines, this paper also considers the practical considerations of implementing PRC-026-1 evaluation into a repeatable process to assist utility engineers in aspects of compliance as well as relay settings development and modification.

II. PRC-026-1 Requirements and Evaluation

The PRC-026-1 standard is comprised of the following four requirements:

- Requirement R1 determines the applicability of BES element lines, generators, and transformers according to a list of provided criteria.
- Requirement R2 evaluates the load-responsive protective elements associated with each applicable line, generator, and transformer against the criteria provided in the standard.
- Requirement R3 involves the development of a Corrective Action Plan to address the cases that did not meet evaluation criteria in R2.
- Requirement R4 covers the implementation of the Corrective Action Plan.

This paper will focus on Requirement R2 for the practical aspects of performing an evaluation study for a large utility with complex line configurations.

A. Evaluation Process

Once the applicable lines to the PRC-026-1 standard have been identified, the process for evaluating PRC-026-1 compliance consists of the following steps:

- Definition of line boundaries and identification of the terminals where protection is located
- Identification of applicable protection and settings
- Calculation of the criteria to be used in the evaluation
- Evaluation of protection according to the criteria
- Documentation and reporting of results

The PRC-026-1 evaluation considers the protection on the line with respect to a defined criteria. The evaluation of a line is more clearly stated as the evaluation of settings at each terminal where applicable protection is present. The definition of a line involves identifying each terminal for which the evaluation is required, as well as the boundaries of the line itself, particularly where the line ends (such as load tap transformers or radial ends). Although the two-terminal lines cited in the standard have clear boundaries, the multi-terminal lines discussed later in this paper require consideration beyond two ends of the line.

The protection functions that are applicable to the PRC-026-1 standard are those that could trip on load current instantaneously or with a time delay of less than 15 cycles. For line protection, the following functions are generally considered:

- Phase distance, including those used in telecommunication protection schemes such as DCB, DCUB, POTT, and PUTT
- Phase overcurrent
- Out-of-step tripping

For the protection functions cited above, the PRC-026-1 standard provides exclusions when these functions are used in certain protective schemes. During the identification of applicable protection, each protection element should be considered if they meet these exclusion criteria. The cases most relevant to typical line protections that are not applicable to the standard are the following:

- Relay elements that trip with a delay of 15 cycles or longer; this can potentially remove Zone 2 functions from evaluation unless they are used in communications-assisted schemes
- Relay elements supervised by power swing blocking
- Relay elements associated with switch-onto-fault schemes
- Relay elements only enabled during loss of communications, and overcurrent elements only enabled during loss of potential conditions

The criteria used for evaluation is based on the line and system configurations from the point of view of the terminal under evaluation, as well as system conditions and assumptions specified in the PRC-026-1 standard. Two separate criteria are utilized for evaluation:

- Distance elements are evaluated against a criteria boundary calculated from system impedances and conditions. The resulting boundary shape is referred to as the unstable power swing region. To meet PRC-026-1 requirements, the distance trip characteristic must be wholly contained within this region.
- Overcurrent elements are evaluated against a current limit calculated from system impedances and conditions. To meet PRC-026-1 requirements, the pickup of the overcurrent element used for tripping must be larger than this calculated criteria current limit.

B. Two-Terminal Form for Criteria Calculation

The PRC-026-1 standard Application Guideline provides detailed calculations and examples outlining the methodology for evaluation of a simple two-terminal line. Central to the calculation of the distance and overcurrent criteria used for evaluation is the two-terminal representation of the line under study shown in Fig. 1. This form includes the following elements to consider:

- Sending-end source impedance (Z_S), representing the entirety of the system on the sending side (local to the protection under study) of the line.
- Receiving-end source impedance (Z_R), representing the entirety of the system on the receiving side (remote to the protection under study) of the line.
- Line impedance (Z_L), representing the impedance between the sending-end and receiving-end.
- Parallel transfer impedance (Z_{TH}), representing the impedance of all other possible paths between the sending-end and receiving-end.
- Sending-end source voltage (E_S) and receiving-end source voltage (E_R) represent potential voltage conditions on each end of the line and will be used with the limits specified in the standard to calculate the criteria for distance and overcurrent evaluation.

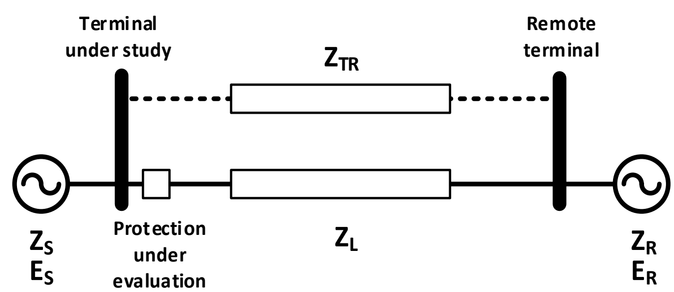

Fig. 1. Two-terminal form for PRC-026-1 evaluation

The sending-end source impedance, receiving-end source impedance, and potentially the parallel transfer impedance can be obtained through the two methodologies cited in the Application Guideline:

- Software Reduction is a function in short-circuit software applications that can reduce a system to user-specified elements [4]. For use in the PRC-026-1 evaluation, the buses representing the sending and receiving ends of the line would be retained, with the rest of system reduced to equivalent sources at each end and a parallel transfer impedance representing all other impedance paths between the end buses. The use of this method is shown in Fig. 2.

- Alternatively, the standard allows the engineer to open the breakers on both ends of the line and apply three-phase bolted faults to determine the Thevenin equivalent of the system at the sending end and receiving end. While simple in concept, this method produces source impedance values that are typically lower than the Software Reduction method, resulting in smaller evaluation criteria that may be more difficult to comply with PRC-026-1 requirements. The use of this method is shown in Fig. 3.

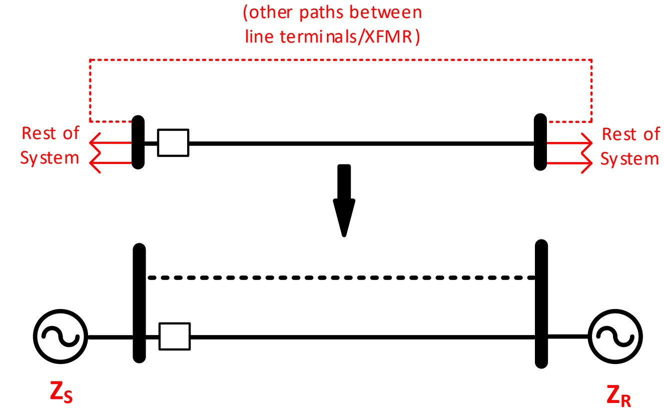

Fig. 2. Software reduction method

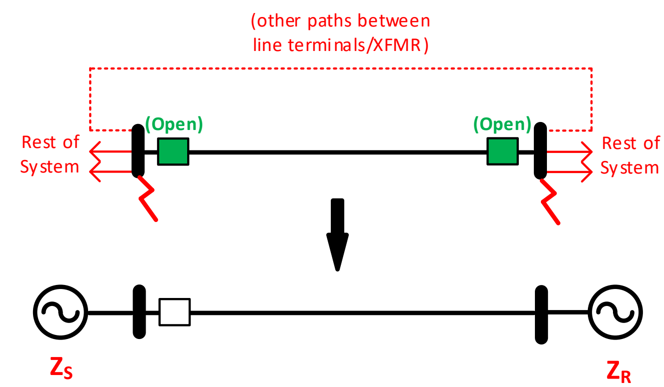

Fig. 3. Open-Breaker-Thevenin method

The calculation of evaluation criteria for both distance and overcurrent elements is based on the resulting two-terminal form. The total system impedance, Z_{sys}, represents the summation of the sending-end source impedance, receiving-end source impedance, and the line impedance between the two. If parallel transfer impedance is ignored, the total system impedance is calculated according to (1).

$$Z_{sys} = Z_S + Z_L + Z_R \tag{1}$$

Assuming the parallel transfer impedance is ignored, the current measured by the relay, I_L, is calculated according to (2).

$$I_L = \frac{E_S - E_R}{Z_{sys}} \tag{2}$$

Where:

E_S = sending-end voltage

E_R = receiving-end voltage

For the calculation of evaluation criteria, the sending-end and receiving-end voltage magnitudes and relative angles are varied from the upper and lower limits specified in the PRC-026-1 standard (voltage ratios of 0.7 through 1.43 and separation angle of 120 degrees).

C. Criteria Calculation for Distance Elements

The criteria for distance elements is based on the unstable power swing region which is comprised of three shapes:

- A lower loss-of-synchronism circle based on a ratio of the sending-end to receiving-end voltages of 0.7 (Shape 1 in Fig. 4)
- An upper loss-of-synchronism circle based on a ratio of the sending-end to receiving-end voltages of 1.43 (Shape 2 in Fig. 4)
- A lens that connects the endpoints of the total system impedance bounded by varying the sending-end and receiving-end voltages from 0.7 to 1.43 per unit, while maintaining a constant system separation angle of 120 degrees across the total system impedance (Shape 3 in Fig. 4)

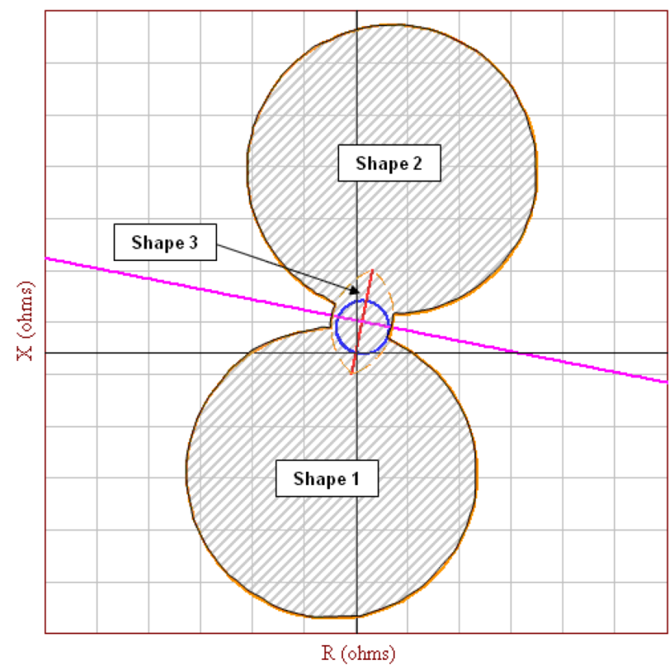

Fig. 4. Unstable power swing region for PRC-026-1 evaluation of distance elements [1]

The points on the lens shape are calculated by varying the sending-end and receiving-end voltages and angles according to the values specified in the standard, as expressed in (3) and (4).

$$Z_{lens} = \frac{E_S - Z_S I_L}{I_L} \tag{3}$$

$$Z_{lens} = \frac{V_{LL}^{\angle\theta} N_S - Z_S \left[\frac{V_{LL}^{\angle\theta} N_S - V_{LL}^{\angle 0} N_R}{Z_S + Z_L + Z_R} \right]}{\left[\frac{V_{LL}^{\angle\theta} N_S - V_{LL}^{\angle 0} N_R}{Z_S + Z_L + Z_R} \right]} \quad (4)$$

Where:

V_{LL} = Line-to-line voltage

N_S = Magnitude of sending-end voltage

N_R = Magnitude of receiving-end voltage

Θ = Separation angle (120 degrees)

Z_S and Z_R= Sending and receiving-end impedance

Z_L = Line impedance

The variations on the voltage magnitudes and angles for sending and receiving ends are listed in TABLE I. Their corresponding locations on the lens shape of the unstable power swing region are shown in Fig. 5.

TABLE I. VOLTAGE MAGNITUDE AND ANGLE VARIATIONS TO CALCULATE LENS SHAPE

Point	N_S	N_R	Θ (deg)
A	1.0	0.7	-120
A to B	1.0	0.7 to 1.0	-120
B	1.0	1.0	-120
B to C	1.0 to 0.7	1.0	-120
C	0.7	1.0	-120
D	1.0	0.7	120
D to E	1.0	0.7 to 1.0	120
E	1.0	1.0	120
E to F	1.0 to 0.7	1.0	120
F	0.7	1.0	120

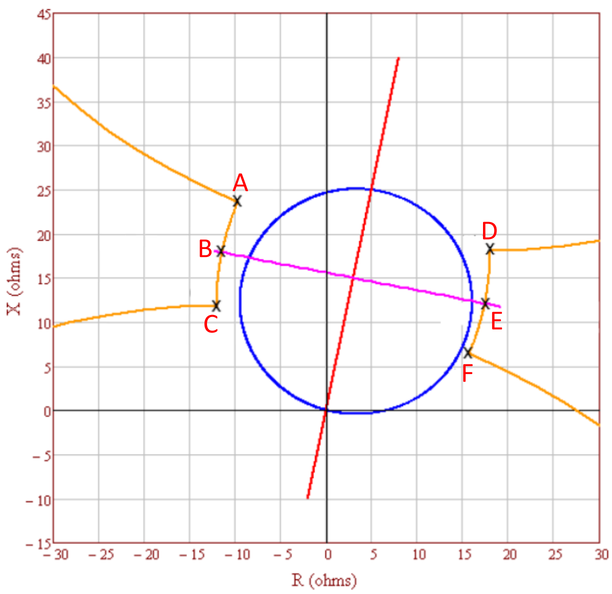

Fig. 5. The lens shape of the unstable power swing region

The calculation for the upper and lower circles are based on a three step process:

- Calculation of the R + jX coordinates of the center circle
- Calculation of the radius of the circle
- Determination of the starting and ending angle of the circle; this is defined as the intersection of the circle with the lens characteristic calculated previously
- Calculation of the R+jX coordinates of the circle, forming the upper and lower loss-of-synchronism portions of the unstable power swing region

The center coordinates, radius, and R+jX coordinates of the upper circle can be calculated through (5), (6), and (7) respectively.

$$R_{cUpper} + jX_{cUpper} = Z_L + Z_R \frac{[Z_S + Z_L + Z_R]}{\left(\frac{1}{N_S}\right)^2 - 1} \quad (5)$$

$$r_{Upper} = \left| \frac{\left(\frac{1}{N_S}\right)[Z_S + Z_L + Z_R]}{\left(\frac{1}{N_S}\right)^2 - 1} \right| \quad (6)$$

$$\begin{aligned} R_{Upper} &= [r_{Upper} \cos\alpha + R_{cUpper}] \\ jX_{Upper} &= [r_{Upper} \sin\alpha + X_{cUpper}] \end{aligned} \quad (7)$$

Where:

α = angle to be varied from α_{start} to α_{end}, defined as the angles corresponding to the intersection points of the circle with the lens

Similarly, center coordinates, radius, and R+jX coordinates of the lower circle can be calculated through (8), (9), and (10) respectively.

$$R_{cLower} + jX_{cLower} = -Z_S - \frac{N_S^2[Z_S + Z_L + Z_R]}{1 - N_S^2} \quad (8)$$

$$r_{Lower} = \left| \frac{N_S[Z_S + Z_L + Z_R]}{1 - N_S^2} \right| \quad (9)$$

$$\begin{aligned} R_{Lower} &= [r_{Lower} \cos\alpha + R_{cLower}] \\ jX_{Lower} &= [r_{Lower} \sin\alpha + X_{cLower}] \end{aligned} \quad (10)$$

Where:

α = angle to be varied from α_{start} to α_{end}, defined as the angles corresponding to the intersection points of the circle with the lens

A more complete explanation of these calculations as well as their derivations is available in the PRC-026-1 Application Guideline [1].

D. Criteria Calculation for Overcurrent Elements

The calculation of the criteria current limit for overcurrent elements is also based on the two-terminal form shown in Fig. 1, and utilizes the formula expressed in (2) as its basis, repeated in (11) in expanded form.

$$I_{criteria} = \frac{N}{\sqrt{3}}\left[\frac{V_{LL}^{\angle\theta} - V_{LL}^{\angle 0}}{Z_S + Z_L + Z_R}\right] \quad (11)$$

Where:

N = Voltage magnitude of sending-end and receiving-end sources (1.05 as per PRC-026-1 standard)

Θ = Separation angle (120 degrees)

III. Study Background

This PRC-026-1 evaluation study was performed for a large utility in the NPCC region that has over 19,000 miles of transmission lines and serves over 1.3 million distribution customers. This compliance study offered a unique opportunity to apply the requirements and evaluation methodologies provided by NERC for the PRC-026-1 standard due to the utility's system configuration, protection philosophy, and own internal requirements. This study not only went beyond a straightforward evaluation of PRC-026-1 requirements, but also served to influence the utility's processes for compliance and protection settings.

A. System Configuration

The line configurations involved in this compliance evaluation were typically of greater complexity than the two-terminal lines covered in the Application Guideline. The majority of lines applicable to the PRC-026-1 standard featured multiple terminals, each with their own protection schemes. Since the Application Guideline provides only a limited example for a three-terminal line, these configurations required further consideration in their evaluation. An example of a typical multi-terminal line is shown in Fig. 6.

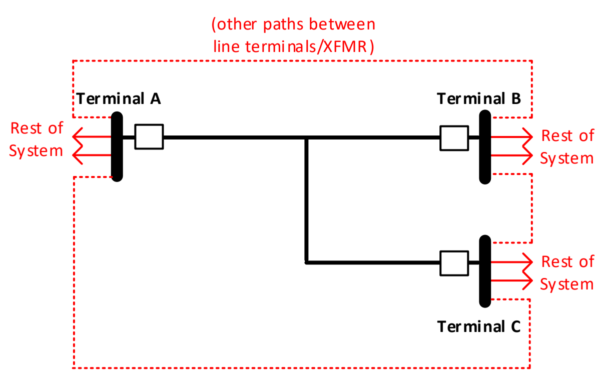

Fig. 6. Example of a multi-terminal line

In addition to multiple terminals, line configurations commonly featured tapped generation and/or load, each with a source of voltage. A typical configuration was for a line to feature load tap transformers to a lower voltage that in turn connect to other BES lines on the system. The treatment of these load tap transformers with voltage source or generators were not addressed in the Application Guideline, and also required further consideration in their evaluation. An example of a typical case of load tap transformer and tapped generation is shown in Fig. 7.

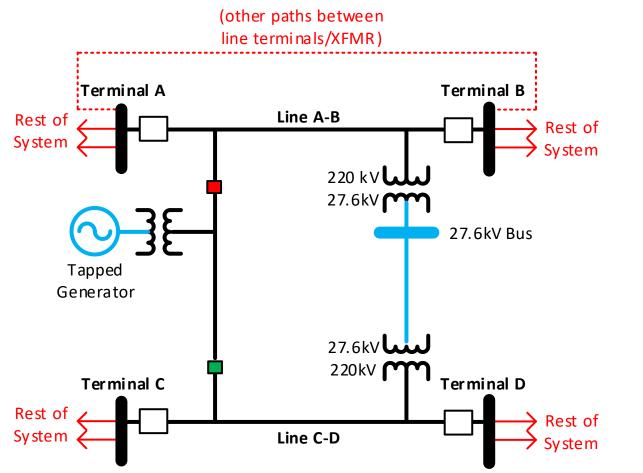

Fig. 7. Example of a load tap transformer connecting to multiple BES lines

Finally, numerous lines within the study scope featured both of the aforementioned features, with one particular line configuration featuring three terminals and seven load tap transformers.

B. Protection

The utility's protection on BES lines heavily utilize telecommunication protection schemes such as DCB and POTT, which are initiated by Zone 2 phase distance elements. This does make Zone 2 distance protection applicable to PRC-026 evaluation, which have greater potential than Zone 1 functions to breach the unstable power swing region used as the evaluation criteria.

With consideration for the Zone 2 greater potential to not meet compliance requirements, the already-conservative assumptions in the standard, and the utility's protection philosophy bias towards dependability rather than security, this study was conducted using the less conservative methodology allowed for the calculation of evaluation criteria.

C. Scope of Compliance Evaluation

Beyond the actual execution of this study, considerations for the establishment of internal processes for future PRC-026-1 compliance studies as well as the influence on relay settings development process were required. This utility had over 175 lines applicable to the PRC-026-1 standard, each of which may feature three or more terminals that require evaluation. Furthermore, due to the high number of lines applicable to the standard, production engineers are required to perform a compliance check against the PRC-026-1 requirements when issuing new or revised relay settings.

This high number of cases and the calculation-intensive nature of the evaluation can place a burden on compliance and production engineers if done manually, as well as introduce potential for human error in the calculations and evaluation. To address these concerns, particularly for the compliance check required of production engineers, the utility also required a repeatable process for the evaluation of this standard. The practical implementation of the evaluation process in software scripts was an additional consideration when performing this study.

IV. Methodology for Multi-Terminal Line Evaluation

As discussed in Section II, the PRC-026-1 standard document includes an Application Guideline that provides detailed calculations and examples on the process and methodology for evaluating PRC-026-1 requirements. However, this Application Guideline focuses on the two-terminal line configuration with voltage sources only at the ends of the line. Very limited guidance is provided for line configurations of more than two terminals, as is the case for the majority of applicable lines in this study. This section discusses the adaption of the NERC-provided methodology to accommodate the line configurations involved in this compliance evaluation.

To demonstrate the concepts associated with evaluation for multi-terminal lines, the line shown in Fig. 8 is presented as a typical configuration addressed in this study. This example line features three terminals as well as load tap transformers with source. Although not fully shown in Fig. 8, an extensive network of parallel paths connect all terminals of the line, as well as the two load tap transformers.

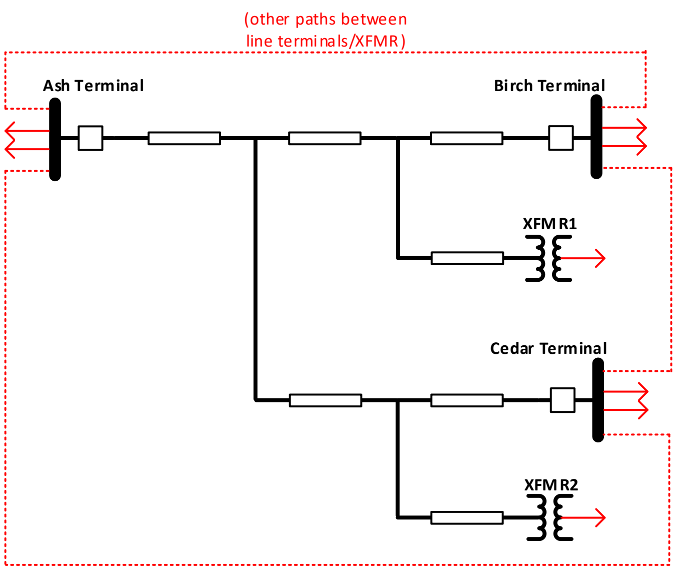

Fig. 8. Example multi-terminal line addressed in this study

A. *Three-Terminal Line Example*

The example for a three-terminal line provided in the PRC-026-1 Application Guideline involves a two-stage process for calculation of the evaluation criteria:

- The first stage obtains the sending-end and receiving-end source impedances for all ends of the line. For the three-terminal line in the example, the sending-end source impedance is behind the protection under study and the two receiving-end source impedances represent the remote ends of the line. This stage of the process is shown in Fig. 9.
- The second stage reduces the three-terminal line to an equivalent two-terminal form through progressive series and parallel equivalent calculations. This results in a two-terminal form where the receiving-end of the line is defined as the location where the two line branches split. The impedance Z_{eq} is used in place of Z_R to indicate that this newly calculated "receiving-end source impedance" is an equivalent of the rest of the line and system beyond. This stage of the process is shown in Fig. 10.

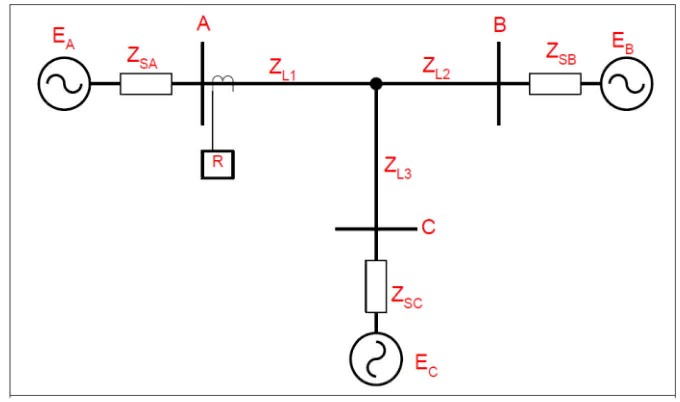

Fig. 9. Obtaining receiving-end impedances for three-terminal line [1]

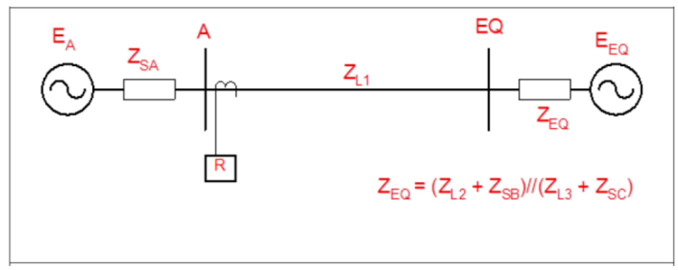

Fig. 10. Line reduction of three-terminal line to equivalent two-terminal form [1]

After obtaining this equivalent two-terminal form, the calculations for the unstable power swing region used as evaluation criteria for distance elements and the criteria limit used for overcurrent elements are performed in the same manner as for the two-terminal line configuration.

The considerations associated with obtaining this two-terminal equivalent representation form the basis of the challenges in the evaluation of multi-terminal lines for PRC-026-1.

B. *Sending-End and Receiving-End Sources*

As in the provided example, each terminal of the line that has a voltage source requires an equivalent receiving-end source and impedance. The example multi-terminal line with sending-end and multiple receiving-end source impedances is shown in Fig. 11.

One additional aspect of consideration for the multi-terminal lines involved in this study is the presence of the load tap transformers that may be connected to multiple lines. Although the Application Guideline does not address these transformers, the presence of voltage sources behind these units indicates they must be treated as additional remote ends of the line for the purposes of PRC-026-1 evaluation. It is recommended that the receiving-end source impedances for these load tap transformers be calculated at the high-voltage side of the transformer, including the impedance of the transformer itself in the equivalent impedance. It should be noted that line ends that do not have a voltage source do not need to be considered in this evaluation.

As indicated in Fig. 11, these load tap transformers would each be represented by a receiving-end source impedance in the calculation of the two-terminal form.

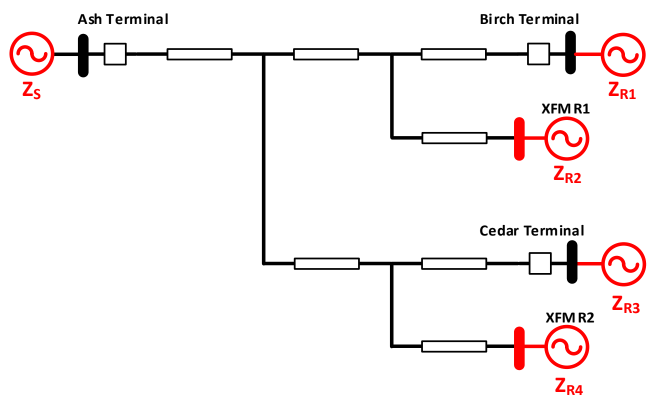

Fig. 11. Example multi-terminal line with sending-end and receiving-end source impedances

As in the two-terminal line configuration case, the sending-end and receiving-end source impedances can be obtained through one of the two methodologies provided in the Application Guideline. The Software Reduction approach is the preferred methodology because it provides the less conservative criteria for evaluation. For this particular multi-terminal line under consideration, the differences in resulting source impedances between the two methodologies are shown in TABLE II.

TABLE II. SYSTEM SOURCE IMPEDANCE DIFFERENCE

Terminal	Software Reduction	Open-Breaker-Thevenin
Z_S (Ω)	6.04	4.67
Z_{R1} (Ω)	4.31	3.61
Z_{R2} (Ω)	306.61	152.06
Z_{R3} (Ω)	1212.53	61.53
Z_{R4} (Ω)	3170.98	61.53

It can be seen that the methodology used to determine source impedances can have a significant effect on resulting values. The large differences for the receiving-end impedances close to the Cedar Terminal are due to the configuration of the system past the boundaries of the example line. The load tap transformer XFMR2 is connected to a parallel line, which also connects Ash to Birch. Since the Software Reduction removes parallel transfer impedances, the Z_{R4} impedance is comprised solely of the generators. In comparison, the Open-Breaker-Thevenin methodology simply applies a three-phase fault at the Z_{R4} location and retains the parallel connections to the other terminals.

C. *Line Reduction*

Once the sending-end and receiving-end source impedances are obtained, the multi-terminal line is reduced to a two-terminal equivalent through a progression of series and parallel equivalent calculations. The example in the Application Guideline reduces the line to the point where the two branches split. For the multi-terminal line, this is taken as the *first* location where any line branch with a receiving-end source impedance splits off from the others.

For the multi-terminal line example, this point is shown in Fig. 12. Everything downstream of this point, including the multiple receiving-end source impedances and the system beyond, would be combined into the equivalent source impedance Z_{eq}. The line reduction arithmetic itself is straightforward, consisting of basic parallel and series equivalent calculations.

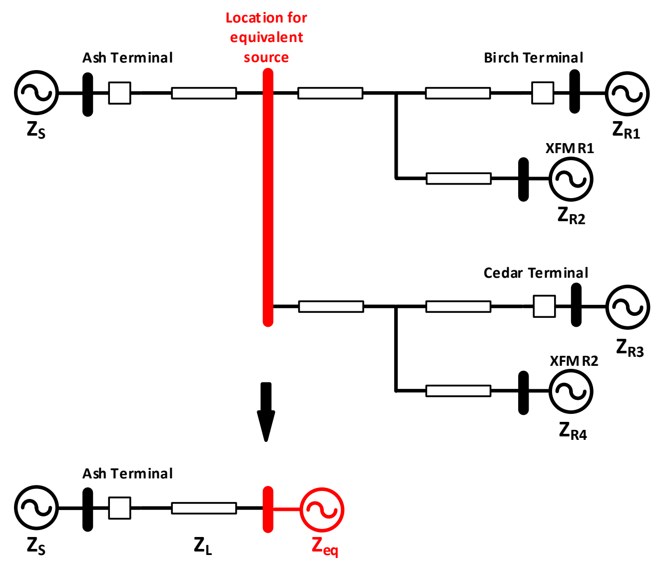

Fig. 12. Multi-terminal line equivalent location

V. IMPLEMENTATION FOR MULTI-TERMINAL LINE EVALUATION

This section discusses the challenge of practical implementation of the methodology to obtain the equivalent two-terminal form of a multi-terminal line. In particular, the utility requirements for compliance and software scripting are considered.

A. *Line Reduction Calculation*

The series and parallel equivalent calculations to reduce the line to two-terminal form is the primary burden of consideration for the evaluation of this study as well as the implementation in software scripting. While the calculations themselves are simple, the number of calculations required to be performed can become a significant burden for engineers. In the example multi-terminal line, the equivalent two-terminal form for Ash Terminal is obtained through the calculations shown in Fig. 13.

This calculation requirement is compounded by PRC-026-1 evaluation being conducted on a per-terminal basis, with each terminal requiring its own equivalent two-terminal form, and the majority of lines in this study potentially having three or more terminals. Finally, the number of applicable lines in this study further increases the effort required in this compliance evaluation.

Separate from this evaluation study itself, the utility requirement of including PRC-026-1 evaluation as part of the settings development process also places this burden on its production engineers, which led to the requirement of software scripting for the evaluation of this compliance standard.

The challenge in software scripting is the potentially changing line configurations associated with each terminal. As shown in Fig. 14, obtaining the equivalent two-terminal form from the Birch Terminal requires a different set of calculations than the Ash Terminal shown in Fig. 13. The ability to reduce lines of any configuration to the required equivalent would require significant development and testing to implement in the available software scripting environments.

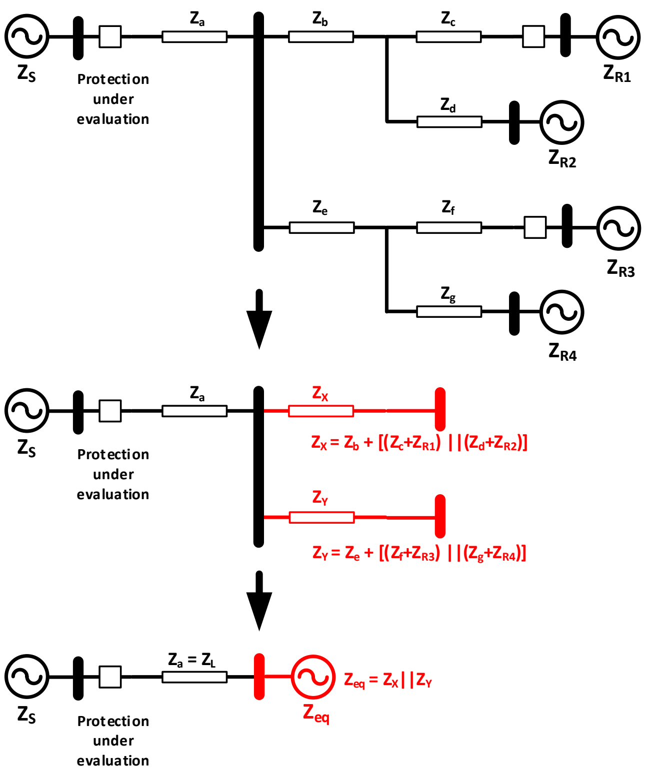

Fig. 13. Line reduction for evaluation at Ash Terminal

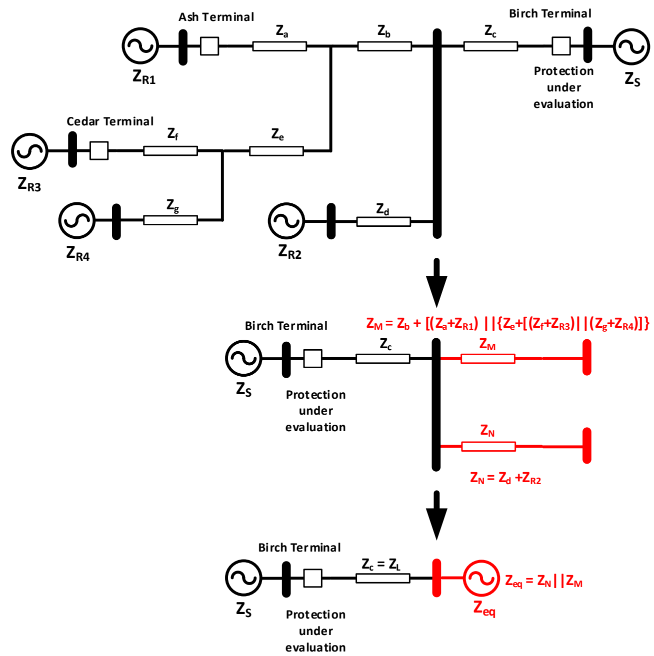

Fig. 14. Line reduction for evaluation at Birch Terminal

B. Reduction Shortcut Consideration

Given that the Unstable Power Swing Region that serves as the criteria boundary for the evaluation is calculated based on the current through the protective devices, it can be argued that a shortcut to calculating the sending-end and receiving-end source impedances could be utilized. Obtaining the Z_S and Z_{eq} values through direct application of software reduction or open-breaker-Thevenin at the targeted equivalent location (the location of first line branch separation), as shown in Fig. 15, may be considered to mitigate the requirement of series and parallel equivalent reductions under different line configurations.

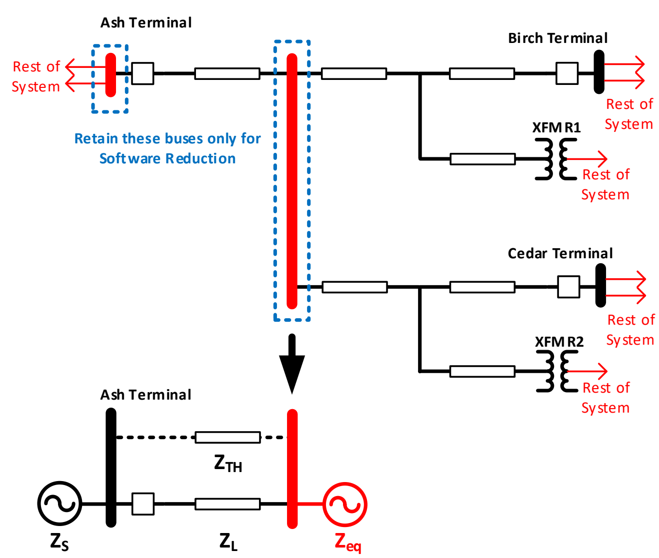

Fig. 15. Direct application of Software Reduction at equivalent bus

However, this considered methodology contradicts the example provided in the Application Guideline, which explicitly splits the process of obtaining the two-terminal equivalent into the two separate steps of reducing to sending-end and receiving-end source impedances followed by line reduction to two-terminal form. Moreover, directly reducing to the equivalent impedance location provides Z_{eq} values that do not match those calculated using the two-step process. The differences in Z_{eq} using the two calculation methodologies for the example line are shown in TABLE III.

TABLE III. DIFFERENCE IN Z_{EQ} USING DIFFERENT CALCULATION METHODOLOGIES

Terminal	Z_{eq} two-step process (Ω)	Z_{eq} direct reduction (Ω)
Ash	2.550 + j33.452	2.557 + j35.570
Birch	3.233 + j44.392	3.809 + j54.671
Cedar	1.890 + j18.200	4.283 + j77.694

The differences in equivalent impedances are attributed to the presence of parallel transfer impedances, as well as how they are addressed in the two methodologies. In the two-step process outlined in the Application Guideline, the parallel transfer impedances are obtained relative to the multiple ends of the line, as shown in Fig. 16.

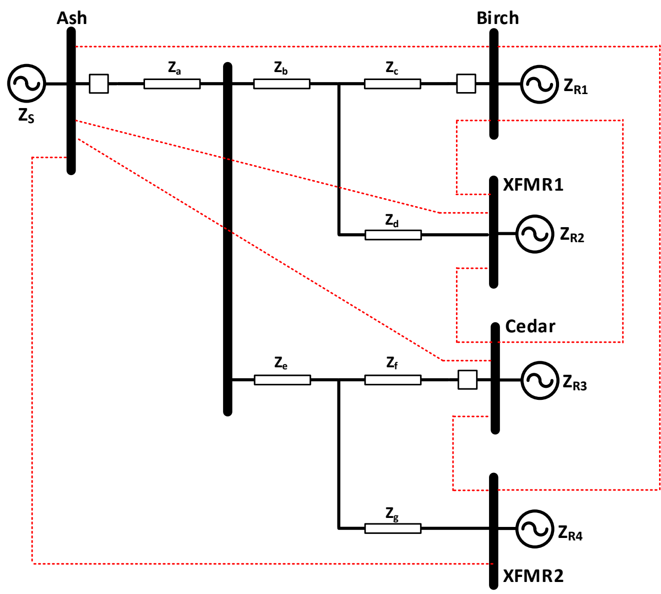

Fig. 16. Parallel transfer impedances relative to the ends of the line

In the direct reduction methodology, the parallel transfer impedances are obtained relative to the equivalent location where the line splits into multiple branches. In this case, portions of the parallel line impedances that were neglected in the two-step methodology are included in the remote equivalent Z_{eq}, resulting in differing impedances.

Since the direct reduction methodology contradicts the example provided in the Application Guideline while also producing an unstable power swing region that could potentially be less conservative than that intended by NERC, this shortcut does not meet the requirements for compliance and cannot be used to mitigate the calculation burden of determining the equivalent impedance.

C. Two-Stage Software Reduction

In the considered shortcut of direct reduction to the Z_{eq} location, the inclusion of parallel transfer impedances in the short circuit reduction resulted in different equivalent impedances when compared to the NERC-provided example methodology. If these parallel transfer impedances had not been present, the two methodologies would have produced the same equivalent impedances.

This consideration for the effect of parallel transfer impedances on reduction functions enabled the development of the methodology utilized for this PRC-026-1 study. The eventual implementation consists of a two-stage process using the software reduction function:

- The first stage performs a software reduction of the system around the line under study, obtaining the sending-end and receiving end source impedances and the parallel transfer impedances.
- The second stage, as shown in Fig. 17, removes the parallel transfer impedances resulting from the first stage and performs a second software reduction to the equivalent impedance location. The removal of the parallel transfer impedance eliminates their effect on the final system equivalent impedances, resulting in the desired Z_{eq} values.

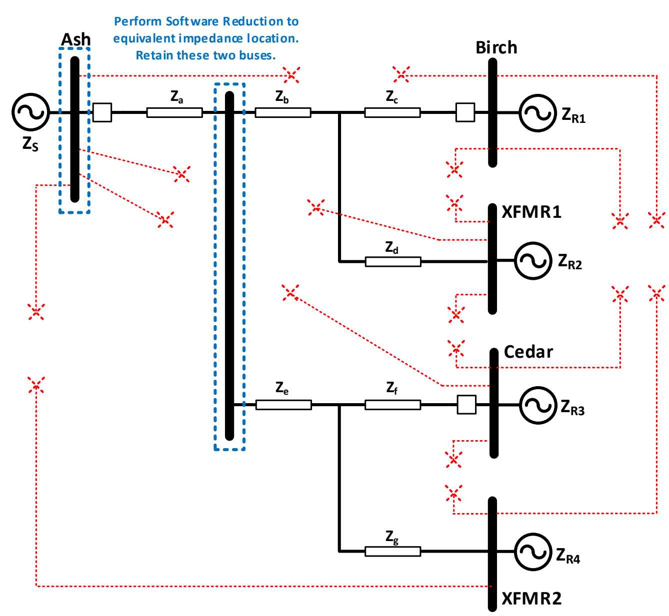

Fig. 17. Second stage of the process removes parallel transfer impedances and performs Software Reduction to the equivalent impedance location

This methodology provides identical Z_S and Z_{eq} values when compared to the process outlined in the Application Guideline and is independent of the actual line configuration, enabling simple implementation in software scripting.

VI. Conclusion

The evaluation of PRC-026-1 compliance for multi-terminal and/or multi-source line configurations bring a number of additional considerations when compared to the well-documented two-terminal lines covered in the standard's Application Guideline. Complex line configurations primarily affect the calculation of the evaluation criteria, requiring a two stage process of obtaining source impedances followed by line reduction to a familiar two terminal form. Since protection is considered on a per-terminal basis, the calculation-intensive nature of PRC-026-1 evaluation can become a burden to protection and compliance engineers, particularly if internal processes require a compliance check when issuing new or modified protection settings.

From a practical implementation viewpoint, a repeatable process utilizing software scripting can be developed to mitigate the calculation burden on engineers. The need for complex algorithms to enable line reduction for different line configurations can be avoided through leveraging existing software functions to implement the two-step reduction methodology presented in this paper. In addition to addressing the application of PRC-026-1 calculation methodologies to more complex line configurations, the outcome of this work has also established a repeatable process to assist utility engineers with evaluation against the PRC-026-1 standard for compliance purposes as well as internal processes.

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Biographies

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