Protective Relaying for Railway Feeders

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***Abstract*—Two types of electrical distribution systems are common in railway systems. These are the 1x25 kV and 2x25 kV systems that are essentially single-phase and two-phase distribution systems, respectively. The purpose of this paper is to describe these systems and the challenges associated with the protection of the feeders. The electrical characteristics of the feeders and their relevance to the protection schemes used are described. There are certain operating restrictions and modes that require special considerations.**

It is common for protective relaying systems for railway feeders to use distance relaying principles. The operating principles are similar to the better-known three-phase distance elements; however, the reach settings and characteristics are different. Moreover, in the 2x25 kV system, the impedance measurement is greatly affected by the presence of balancing autotransformers along the system length. The apparent impedance measured is not a linear function of the distance, which affects the reach settings and fault location algorithms.

Railway feeders are operated in parallel, and reclosing functions are expected. The reclosing sequence is coordinated with additional control and, although the continuity of service is important, restoration speed is not necessarily the objective. The objective is to determine the exact fault location for a permanent fault. Overcurrent backup is normally used, along with synchronism-check functions and a check for incorrect phase coupling, which could occur due to the way traction substations are fed from the utility three-phase system. The discussion is based on experience obtained from the high-speed electrical railway system in Spain.

I. Introduction

Electrical railway systems are large and common in Europe. Spain is a good example of a country that uses high-speed trains and has outstanding infrastructure. This paper describes the ac railway electrical distribution system and the challenges associated with the protection of feeders, mainly based on the Spanish example. The electrical characteristics of the feeders and their relevance to the protection schemes used are also described.

II. Background

AC railway systems require different considerations than those that apply to traditional three-phase distribution networks. The loads and operating procedures are different. These ac systems are used to provide transportation over long distances [1]. In contrast, metropolitan transportation systems tend to distribute power with dc electricity.

Fig. 1 shows the type of load that the ac railway systems feed [2]. The ac power is fed to the moving load (the traction locomotive) via a mechanical arrangement of a single conductor. This conductor is called catenary, reflecting the curvature that solid conductors take when hanging from two points. The catenary is the point of contact for the moving load to the source of electricity. In the locomotive, there is a single-phase transformer that connects to a brush such that it makes good contact with the rotating axis of the vehicle. The return to ground is through the rails along the path, as shown in Fig. 1.

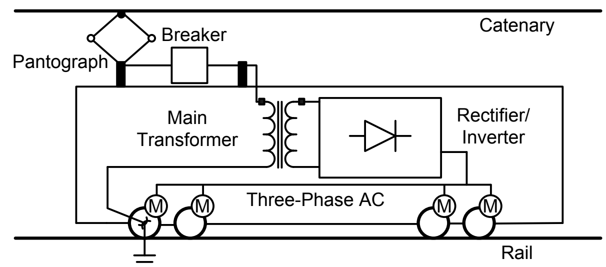

Fig. 1. The Moving Load (the Locomotive) in an Electrical Railway System

The onboard power electronics convert the main single-phase power to three-phase power. Three-phase power is used to feed the electric motors that provide the traction for the locomotive. Additionally, some dc secondary circuits are also fed from it. The power electronics are a vast topic out of the scope of this paper. Suffice it to say that the load is fed from the main transformer in the locomotive, and, for our purposes, the primary winding of the transformer is grounded to the rails. The moving loads that make contact with the catenary and the power electronics are sources of harmonics [3]. The most dominant frequency, however, is the fundamental frequency.

A. 1x25 kV Electrical System

A single-phase electrical system that feeds the loads through the catenary and the rail return is normally referred to as a 1x25 kV system. A single-phase transformer secondary winding is the source of the power. In some installations, the transformer secondary winding is more sophisticated, using a Scott connection [1]. For practical purposes, Fig. 2 is a good illustration of the 1x25 kV system.

This system is simple. It is basically a single-phase system feeding a moving load [4]. The only measurements available are those of the catenary.

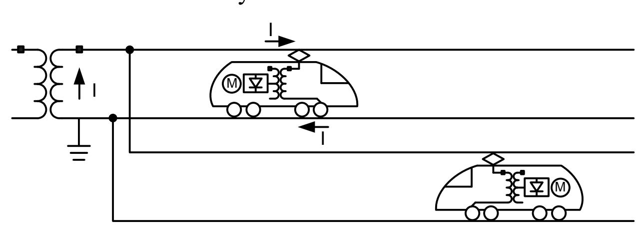

Fig. 2. 1x25 kV Railway System

B. 2x25 kV Electrical System

The 2x25 kV system, shown in Fig. 3, is used in some installations of high-speed railway systems [5]. The secondary winding of a single-phase transformer is tapped in the middle, and a two-phase system is created. The catenary is the positive polarity phase, and the second conductor (negative polarity) is called the feeder. The flow into the loads is still from the catenary to the rails, similar to the 1x25 kV system. Balancing autotransformers are used to distribute the flow in the phases, as shown in Fig. 3 [1] [4] [5]. There is a second methodology used with booster transformers, but it is out of the scope of this paper [1] [4]. The feeder conductor in some installations is used to energize auxiliary devices on the railway system, such as traffic and signaling lights along the route, via distribution transformers.

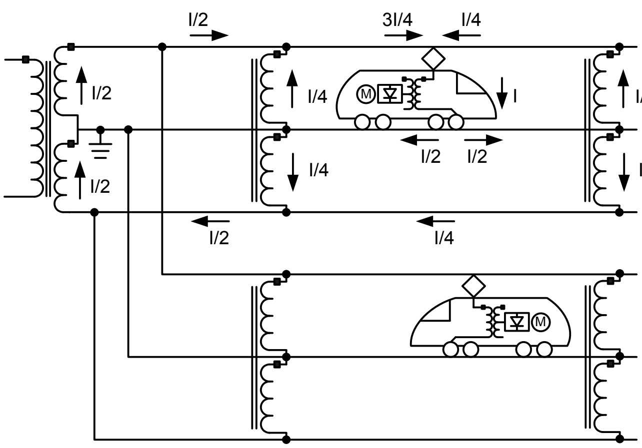

Fig. 3. 2x25 kV Railway System

There are certain criteria that favor the 2x25 kV system over the 1x25 kV system, such as better distribution of currents and less loss overall [5]. In addition, the conductors are generally thinner and the distance between traction substations is greater.

C. Feeding the Loads

AC railway systems get their power from the utility grid. There are substations along the route of the rails that connect to available three-phase power. These substations are known as traction substations, and on average, they are located every 10 to 60 kilometers. The Spanish railway system distributes these traction substations every 30 to 60 kilometers using the 2x25 kV system [5]. A simplified diagram of three traction substations being fed from the electrical grid is shown in Fig. 4. The phasing is different in each, trying to balance the loading in the three-phase network. The traction feeders are therefore not fed from two sources. The source is a single substation, and the power is distributed radially.

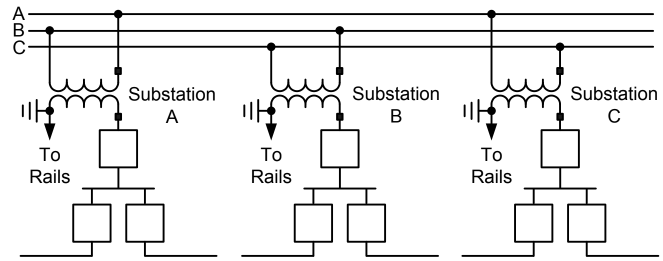

Fig. 4. Distributing Power Along the Railway Trajectory

Fig. 4 shows the distribution of electric power to the moving loads as a 1x25 kV system and a single rail direction. The same layout is true for the 2x25 kV system. The figure is a very simplified illustration of a railway system. Additional disconnect switches for operations are not shown for simplicity.

Fig. 5 shows a 2x25 kV system with dual rail directions. Autotransformer substations (ATSs) are distributed along the route. From the traction substations (Substation A, for example) to the feeder disconnect switch, sections are defined as shown in Fig. 5. These sections can be merged if there is a traction substation that is out of service, as shown in Fig. 5 by Substation B.

In modern installations, a fiber-optic communications network is available that links all of the substations to a control center. Motor-operated disconnect switches and breakers can be remotely controlled via a supervisory control and data acquisition (SCADA) system. All appropriate topology changes and operating modes can be defined remotely by operators and automated control.

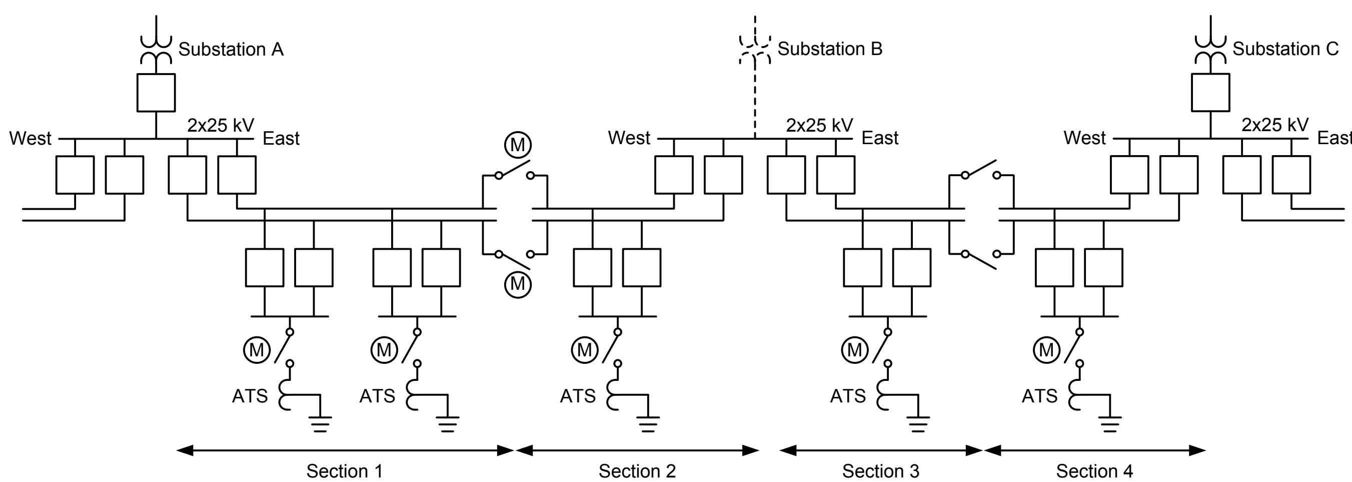

Fig. 5. 2x25 kV and Dual Rail Direction Example

III. Protective Relaying With Distance Elements

It is customary to use a distance protection scheme as the primary protection scheme [4] [6]. The principle of distance protection uses the angle between the voltage and current to determine the location of the fault.

As described previously, electrical railway feeders are radial. Utility radial distribution feeders tend to be protected by definite-time and inverse-time overcurrent elements (50/51). In the case of the railway feeder, the protection philosophy is to use overcurrent elements as backup functions with sufficient time delay to allow the distance elements to operate. Moreover, as opposed to utility distribution feeder protection, there is no time coordination problem because any fault in the feeder should be detected by the protective relays with no time delay.

Distance protection relays evaluate the apparent impedance to the fault and require voltage (V) and current (I) to measure the impedance to the fault (Zapp). The advantages of using distance elements are as follows:

- Distance elements are immune to changes in the source impedance.
- The load regions are clearly defined, and, for faults, distance elements can be set more sensitive than overcurrent elements.
- Instantaneous tripping (no intentional time delay) using distance elements is more secure against transients caused by inrush, train starting, and so on.
- Although not directly related to distance elements, the devices implementing distance algorithms can provide an estimate of the location of the fault. This is useful for rapid service restoration.

In the Spanish railway systems, distance relaying has no intentional time delay. Zone 1 will cover the entire radial feeder, without overreaching the next substation when the section divider switch is closed, as shown in Fig. 6. The figure only shows relays in one direction, but the concepts extend to the other relays.

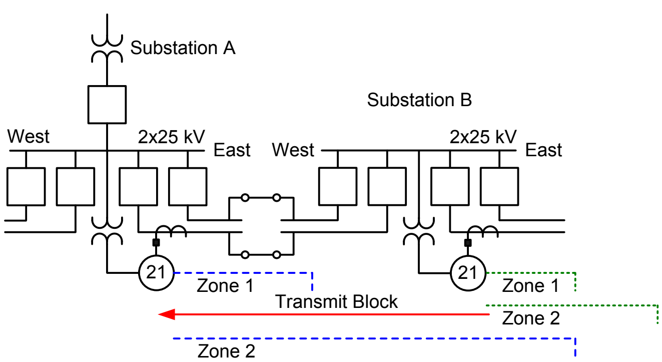

Fig. 6. Impedance Zones

Zone 2 covers up to the Zone 1 of the next protection device in the same direction, as shown in Fig. 6. There is no time delay except for the coordination time needed to ensure that a blocking signal coming from the downstream Zone 2 arrives with ample time. The blocking signal is a pulse that releases Zone 2 after around 250 milliseconds and effectively acts as a backup scheme as well. The blocking signal is sent via IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messaging, taking advantage of the existing fiber infrastructure.

A. *1x25 kV Distance Elements*

There is a single voltage and a single current to measure in a single-phase system. Moreover, there is a single type of fault possible: the catenary-to-ground fault. This makes the implementation of distance elements straightforward in the 1x25 kV system.

$$Z_{\text{catenary-ground}} = \frac{V_{\text{catenary}}}{I_{\text{catenary}}} \tag{1}$$

Equation (1) is the measurement of the only impedance possible. For this system, a single distance plane can describe the element characteristics.

B. *2x25 kV Distance Elements*

There are two conductors and a return path for this system. There are three possible fault types: catenary-to-feeder, catenary-to-ground, and feeder-to-ground. Theoretically, there are three impedance planes to be implemented and measured in a complete distance scheme. As for any electrical power system, the phase-to-ground faults (catenary-to-ground and feeder-to-ground faults) are the most common. About 92 percent of the faults are ground faults [5].

There are several important considerations for this system that are discussed in the next few subsections.

C. *Adapting the Single-Phase Measurement to the 2x25 kV System*

Because of the single measurement of impedance provided by 1x25 kV protective relays, it is not uncommon to use these devices as a solution for the 2x25 kV system. There is, however, a compromise when applying this scheme. For different fault types in the same location, the measured impedance will be different. The idea is to cover (with a single measurement) all possible impedance values, as shown in Fig. 7.

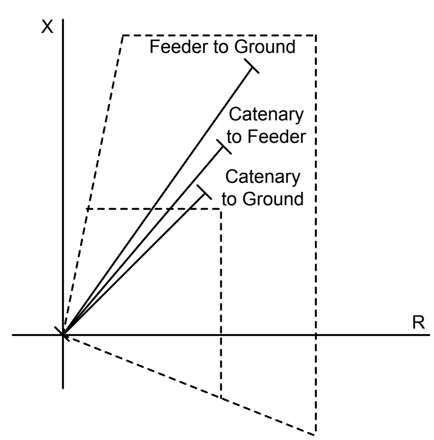

Fig. 7. Single Impedance Measurement

Fig. 7 illustrates the fact that the conductors used for the catenary and feeder are different. The apparent impedance loci for the different fault types are not equal, as shown in the figure. The catenary conductor tends to have a lower impedance value than the feeder conductor. The angle, however, is very similar.

Using a single impedance measurement requires that the meaningful measurement of voltages and currents needs to be properly chosen. Due to the influence of the balancing autotransformers (see Fig. 3) in the impedance measurement (to be described later), the single impedance measurement preferred is:

$$Z = \frac{V_{catenary} - V_{feeder}}{I_{catenary} - I_{feeder}} \tag{2}$$

There are other impedance measurements possible. In any case, when applying this methodology, a thorough short-circuit and apparent impedance study needs to be performed. Two zones of distance protection are generally used.

D. Developing a Complete Distance Protection Scheme for the 2x25 kV System

There are three possible fault types, requiring different impedance measurements. It is theoretically correct to use three impedance measurements to cover these and provide a definite reach in each case.

It is interesting to note that the development of distance-measuring elements for three-phase systems follows the theory of symmetrical components [7] [8]. This theory is extensible to *N*-phase systems. A system of *N* phases can be decomposed into a set of *N* – 1 balanced components and a set of *N* equal vectors (zero sequence). Fortunately, in the 2x25 kV system, *N* = 2 and the problem is simpler than the standard three-phase systems.

1) Two-Phase System

The split winding of a traction transformer can be viewed as the source of a two-phase system. Measuring the two phase currents (IA and IB) and the two phase voltages (VA and VB), it can be deduced from Fig. 8 that there are two possible components. These are the steady-state, balanced set of components that we call positive-sequence components (relating them to the analogous components for three-phase systems) and the zero-sequence set of components. There are no more components possible because *N* = 2. The positive-sequence set is balanced and is related to load flow.

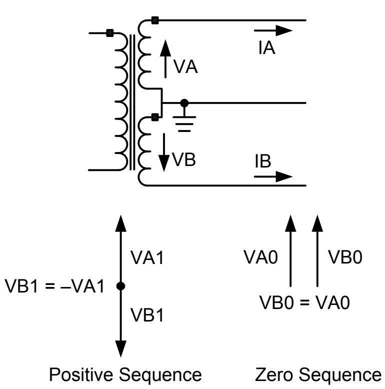

Fig. 8. Symmetrical Components in a Two-Phase System

The phase currents (IA and IB) can be expressed as the sum of their components (with Phase A as the reference):

$$\begin{bmatrix} IA \\ IB \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} I0 \\ I1 \end{bmatrix} \tag{3}$$

where:

I0 is the zero-sequence component.

I1 is the positive-sequence component.

Solving for the inverse in (3):

$$\begin{bmatrix} I0 \\ I1 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} IA \\ IB \end{bmatrix} \tag{4}$$

2) Sequence Network Equivalents

The benefit of symmetrical components is that they make the analysis of a system with several phases a simpler single-phase circuit analysis. Using the results in (3) and (4), it is possible to derive sequence network connections for the different types of faults.

For a phase-to-phase fault, the boundary conditions are:

$$VfA = VfB \tag{5}$$

$$IA + IB = 0 \tag{6}$$

It follows that:

$$\begin{bmatrix} I0 \\ I1 \end{bmatrix} = \begin{bmatrix} 0 \\ IA \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} V0 \\ V1 \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1}{2}(VA - VB) \end{bmatrix} = \begin{bmatrix} 0 \\ Z1\,IA \end{bmatrix} \tag{8}$$

It follows that for a phase-to-phase fault, the positive-sequence network is the only one present. The equivalent network is shown in Fig. 9.

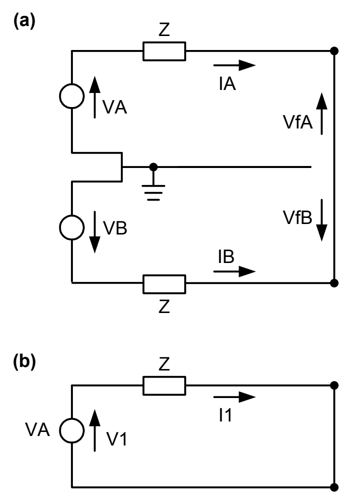

Fig. 9. Phase-to-Phase Fault (a) and Equivalent Sequence Network (b)

For a phase-to-ground fault, the boundary conditions are:

$$VfA = 0 \tag{9}$$

$$IA = If \tag{10}$$

It follows that:

$$\begin{bmatrix} I0 \\ I1 \end{bmatrix} = \begin{bmatrix} \frac{IA}{2} \\ \frac{IA}{2} \end{bmatrix} \quad (11)$$

$$Vf0 + Vf1 = 0 \quad (12)$$

The equivalent sequence network is shown in Fig. 10.

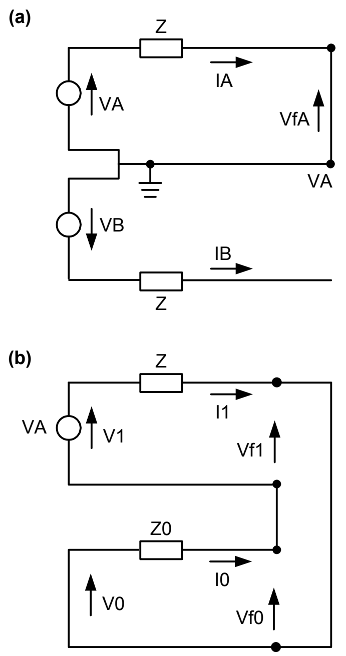

Fig. 10. Phase-to-Ground Fault (a) and Equivalent Sequence Network (b)

3) *Fault Loop Impedances*

To detect faults with distance elements, it is necessary to measure fault loop impedances. These fault loops allow for the plotting of the measurement on the apparent impedance (R-X) plane. The impedance measured is the positive-sequence impedance of the line (ZL1).

For a phase-to-phase fault, Fig. 11 illustrates the sequence network connection and the evaluation of ZL1.

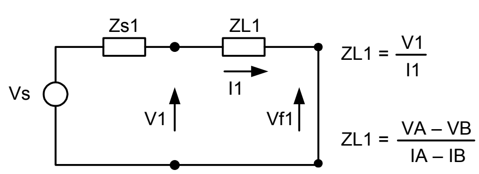

Fig. 11. Phase-to-Phase Fault Loop Impedance

For a phase-to-ground fault, Fig. 12 illustrates the measurement of ZL1. K0 is the zero-sequence compensation factor:

$$K0 = \frac{ZL0 - ZL1}{2\ ZL1} \quad (13)$$

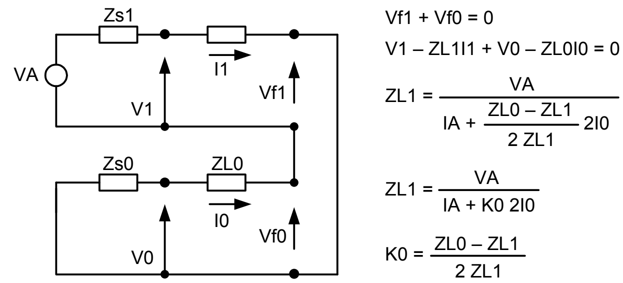

Fig. 12. Phase-to-Ground Fault Loop Impedance

From the derivation of the equations in Fig. 11 and Fig. 12, it follows that for a complete scheme, the following fault loop measurements are required:

$$Z_{catenary\text{-}feeder} = \frac{V_{catenary} - V_{feeder}}{I_{catenary} - I_{feeder}} \quad (14)$$

$$Z_{catenary\text{-}ground} = \frac{V_{catenary}}{I_{catenary} + K0\ 2I0} \quad (15)$$

$$Z_{feeder\text{-}ground} = \frac{V_{feeder}}{I_{feeder} + K0\ 2I0} \quad (16)$$

4) *Autotransformers in the Network*

The balancing autotransformers are distributed along the feeder route to balance the load in the catenary and feeder conductors [1] [5]. Fig. 13a and Fig. 13b illustrate the response of the autotransformers to the flow of positive- and zero-sequence currents, respectively. In Fig. 13, *np* denotes the number of turns in the primary winding, *ns* denotes the number of turns in the secondary winding, and *ns* = *np*.

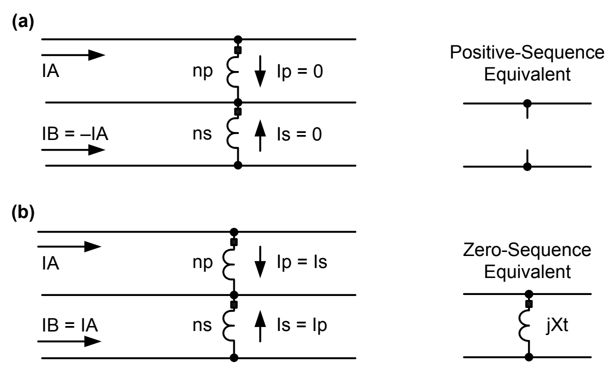

Fig. 13. Positive-Sequence (a) and Zero-Sequence (b) Autotransformer Equivalent Sequence Impedances

The autotransformers are zero-sequence filters. They only allow the flow of zero-sequence currents, and they are an open circuit to the flow of positive-sequence currents. For balanced conditions (such as a phase-to-phase fault), they are not part of the fault and are effectively not present in the network.

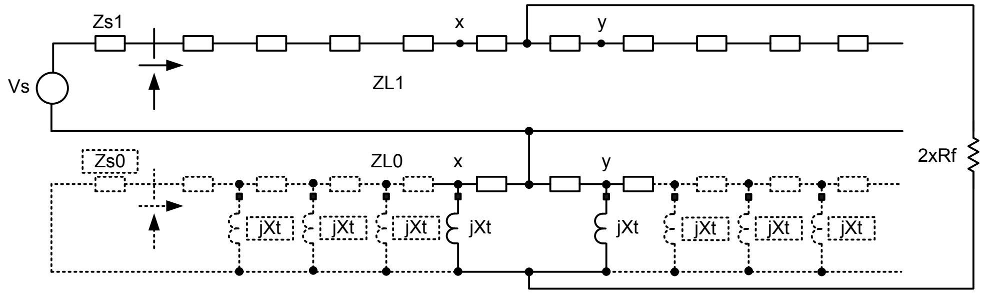

Fig. 14. Sequence Network for a Catenary-to-Ground Fault or Load Flow

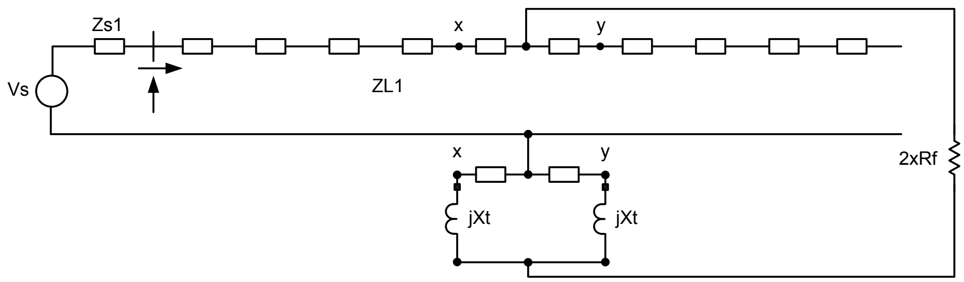

Fig. 15. Practical Sequence Network Equivalent for a Catenary-to-Ground Fault

For a ground fault or load flow (the locomotive is an unbalanced load from catenary to ground), the situation can be visualized as shown in Fig. 14.

The section defined by the two autotransformers where the fault is located (between x and y) will allow the flow of zero-sequence currents. However, because of the low impedance magnitude of the autotransformers, there is very little flow of zero-sequence currents outside the section. For practical purposes, the effective circuit diagram is as shown in Fig. 15.

At the relay location, the voltages and currents are all positive sequence, and a very small zero-sequence current is measured. If a symmetrical network and a phase-to-ground fault are assumed, the apparent positive-sequence impedance measured at the relay location is shown in Fig. 16. The autotransformers along the trajectory of the line make the impedance measurement nonlinear. Only at the ATSs is the impedance proper. This is a consideration when setting distance relays in railway feeders [4] [5].

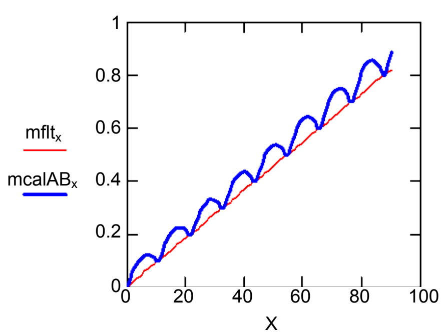

Fig. 16. Positive-Sequence Impedance Variation Due to Autotransformers

5) *Unsymmetrical Conductors*

An additional consideration is the fact that in the 2x25 kV electrical railway system, the catenary conductor (which includes a mechanical support conductor as well) is a different type than the feeder conductor. The catenary conductor is required to make mechanical contact with the pantograph, making its requirements different from those of the feeder conductor, which is not subject to any mechanical contact with the locomotives. The conductor impedances are different, and because of this, there is a large unbalance created and zero-sequence components are created under load.

This is another fact that makes the analysis of 2x25 kV electrical railway systems more complex than analyzing a conventional symmetrical system. The 2x25 kV electrical system is not symmetrical. The analysis with symmetrical components, however, allows the understanding of the behavior of this type of system (as discussed previously).

6) *Radial Network*

The railway feeders are traditionally operated in a radial condition. This has to do mainly with the phasing of the traction substation with respect to the next traction substation. It is not possible to loop feeders. Through the use of disconnect switches, however, any section of the railway system can be energized from a different source, as shown in Fig. 5. Most of the time, there are no trains in the trajectory and only auxiliary load in the feeders.

7) *Parallel Operation*

It is very common in railway systems to have two sets of tracks to allow trains to travel in opposite directions. Fig. 17 shows the electrical system under this operating condition. The two feeders are effectively in parallel, and there is a single autotransformer for both ways in the ATSs.

It is interesting to note that having both feeders in parallel makes the protective relays nonselective, and a fault in either of the feeders will operate both protective relays and open both feeders at a time. The sharing of the autotransformers demands that the two are operated in parallel. With the reclosing scheme (to be described) and an automation scheme, the faulted feeder can be identified.

Fig. 18 shows the influence that the parallel impedances have on a catenary-to-ground fault. The zero-sequence path remains basically the same (because the autotransformer impedances are very low). Fig. 18 also illustrates the fact that for a fault, the current measured will be the same in both feeder relays (with each relay measuring in a railway track). Each railway feeder will be measuring half of the fault current.

The loss of both tracks (in each direction) is acceptable, and because of the parallel feeders, it is not possible to discriminate which is the faulted feeder.

8) Complete Distance Protection Scheme

The 2x25 kV balancing autotransformers and the parallel operation of the feeders make it very hard for the traditional protective relaying practices to be followed. A complete distance protection scheme, however, can follow (14), (15), and (16) with a single adjustment. Having two different types of conductors for the catenary and the feeder requires an adjustment for the impedance measurement for ground faults.

There are two equivalent zero-sequence impedances for the catenary and the feeder conductors:

$$Z0_{catenary} = Z_{catenary} + 2\,Z_{return} \tag{17}$$

$$Z0_{feeder} = Z_{feeder} + 2\,Z_{return} \tag{18}$$

where:

$Z_{catenary}$ is the catenary conductor impedance.

Z_{return} is the return path impedance (rails and ground).

Z_{feeder} is the feeder conductor impedance.

This implies that there are two different K0 factors defined in (13). The impedance measurement equations are:

$$Z_{catenary\text{-}ground} = \frac{V_{catenary}}{I_{catenary} + K0_{catenary}\; 2I0} \tag{19}$$

$$Z_{feeder\text{-}ground} = \frac{V_{feeder}}{I_{feeder} + K0_{feeder}\; 2I0} \tag{20}$$

Equations (19) and (20), together with (14), provide complete coverage for the types of faults possible in the 2x25 kV system.

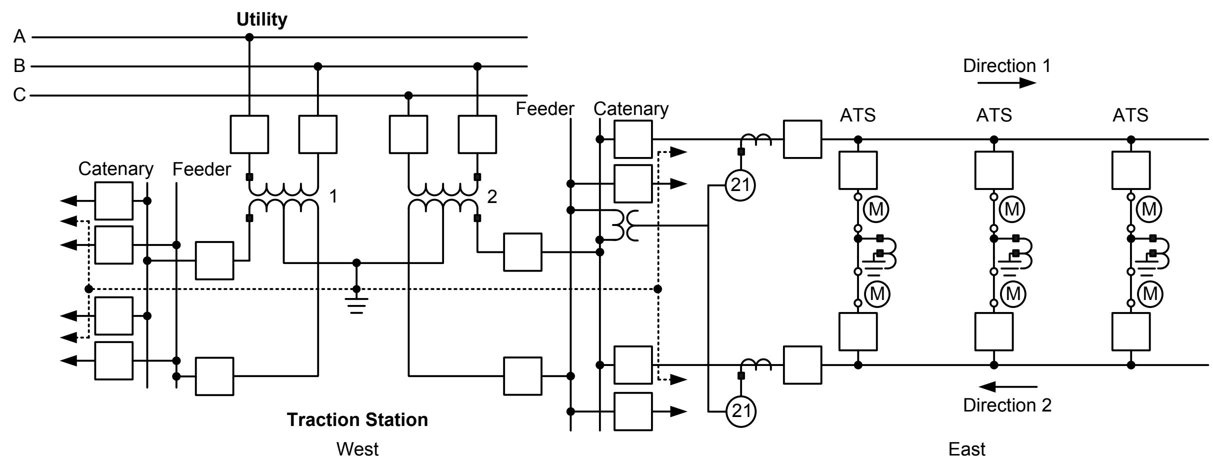

Fig. 17. Parallel Operation of Electrical Railway Feeders

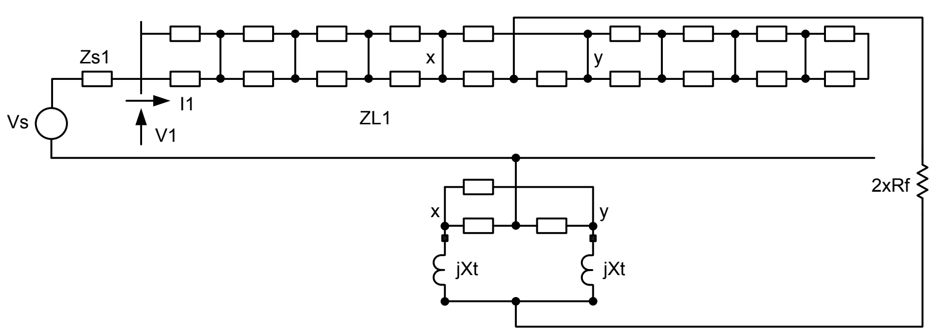

Fig. 18. Sequence Network Equivalent for a Catenary-to-Ground Fault

The individual results of the three equations are compared on the particular impedance plane with R-X characteristics, such as the one shown in Fig. 19.

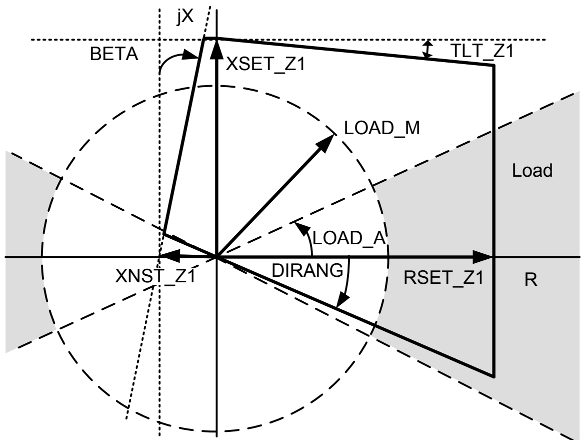

Fig. 19. R-X Characteristic

A set of straight lines defines the operating characteristic on the R-X plane. The load-encroachment area stands out in Fig. 19 as the shaded area.

While the characteristic shown in Fig. 19 is very generic, when applied, some users choose to set it as shown in Fig. 20.

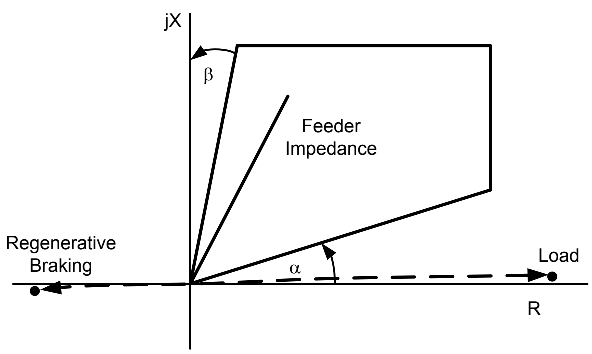

Fig. 20. Application Example

Fig. 20 is not a classical application of a distance element for a utility environment. However, the two angles shown in the figure provide additional security.

Modern locomotives generate power when braking, which is called regenerative braking. This power will show in the third quadrant of the plane. The angle α, shown in Fig. 20, prevents the distance element from operating for the transition from the load to the regenerative braking point. It is an angle set at around 15 to 20 degrees.

When a locomotive starts, the apparent impedance measured at the relay location is highly inductive due to the autotransformers. The angle β, shown in Fig. 20, provides additional security when energizing the feeder. This angle is set within 5 to 15 degrees.

IV. Backup Functions

A. Overcurrent Backup

In the protection scheme associated with railway feeders, overcurrent protection is a backup function to the main distance protection scheme. Both definite-time and inverse-time overcurrent protection is provided (50/51). The idea is to fully allow the operation of the distance protection scheme before the overcurrent elements operate.

The overcurrent elements are applied to both the catenary and feeder conductors. Short-circuit studies are performed and are not much different from those for distribution feeder protection. The appropriate case scenario is used to make sure that the overcurrent protection does not overreach the adjacent substation when it is in the bypass mode, as shown in Fig. 5, and that the 50/51 elements are set above the maximum railway load allowed. The short-circuit study considers the maximum number of trains allowed at a time and the auxiliary load connected to either the catenary or the feeder. This function is time-delayed to around 300 milliseconds to allow a Zone 2 operation and the opening of the breaker.

The inverse-time overcurrent function (51) is set to coordinate with the substation transformer overcurrent protection, and its pickup is set above the maximum load.

The operation of the 50/51 elements is not used to start reclosing; it is a backup protective relaying function.

B. Reclosing Function

The reclosing function in an electrical railway system is applied for two reasons. The first is to allow transient faults to clear and get the system back to normal after a successful reclosing cycle. The second, specifically for the 2x25 kV system, is to estimate the fault location when the reclosing cycle is unsuccessful, denoting a permanent fault.

After the protective relays have issued a trip to the circuit breaker (distance elements only), a reclose initiation signal starts the reclosing cycle. The open breaker interval is in the order of 5 seconds, allowing for a transient fault to disappear.

If the breaker is closed to a permanent fault, the protective relays will open the breaker again, and an automation scheme is enabled. The scheme sends an open command to the motorized disconnect switches in the autotransformer locations shown in Fig. 17. The command effectively decouples the two paralleled feeders so that it is now possible to identify which is the faulted feeder. The automation scheme needs to wait and verify that the autotransformers are disconnected before the breaker is closed again. This automation sequence takes in the order of 30 to 40 seconds. If the automation controller does not get confirmation of the opening of all of the autotransformers within the allowed time, the sequence is aborted.

With the described automated action, the autotransformers are not in the circuit anymore and the feeders are radial. With radial feeders, it is now possible to estimate the location of the fault when the breaker is closed again. Most likely, the second closing is to a permanent fault again. With the autotransformer disconnected and the feeders decoupled, the system is configured for a better fault location estimation (as will be explained in a later section).

C. Synchronism Check

The check for synchronism at both sides of the breaker is only required when manually closing the breaker and when the breaker is in an intermediate substation with no source, such as Substation B in Fig. 5. There are a number of switches in the network to operate, and it may be the case that under some valid operating condition, the voltage in the traction substation bus and the line voltage are different.

D. Harmonic Restraint

Harmonic restraint is often required for additional security during locomotive startup and, what is most important, when reclosing the feeder. The balancing autotransformers are in line in the first reclosing cycle. Each of these balancing transformers is about 10 MVA in size. The inrush current is significant when energizing the feeder with the autotransformers in line. The harmonic restraint units supervise distance elements.

E. Wrong Phase Coupling

The simplified diagram in Fig. 4 illustrates the different phasing combinations along the trajectory of a railway system. There are several disconnect switches in the installation for operational purposes, allowing the operators to feed the loads from different locations. It may happen that operators and/or interlocks fail.

Fig. 21 shows the situation and the phasors of the voltages and currents that the protection device would be measuring. The current is lagging the line angle by the difference between the two source-voltages (VAB – VCA), but the protective relay is using the local source voltage (VAB). The relay current is lagging the relay voltage by angle α (shown in the phasor diagram), which will be in the range of 130 to 180 degrees, depending on the feeder impedance angle.

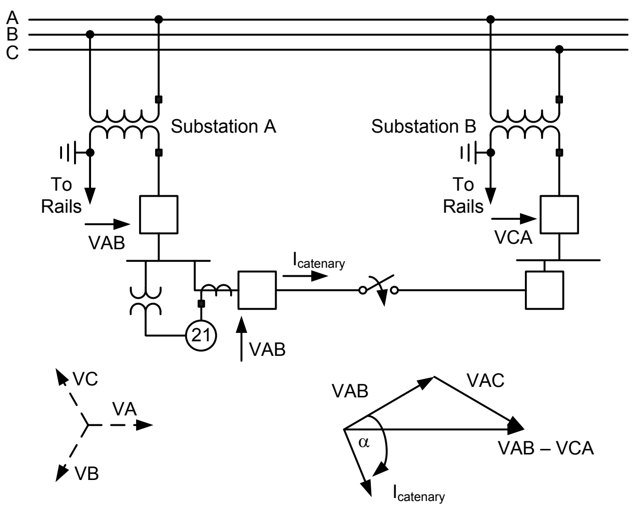

Fig. 21. Wrong Phase Coupling

The impedance measured under the described conditions will fall in the second quadrant, as shown in Fig. 22. This is an area that trips the unit if the impedance plots in the area.

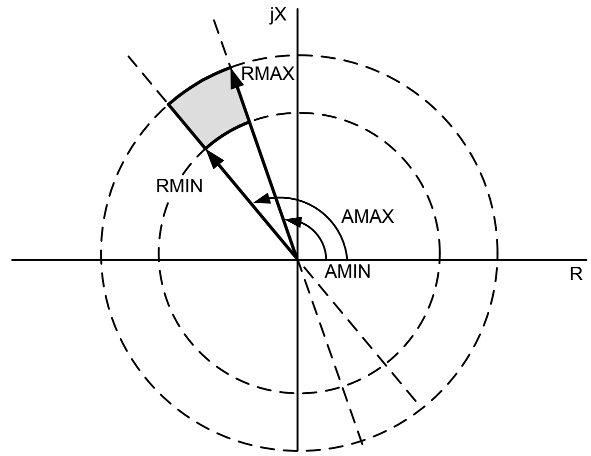

Fig. 22. Wrong Phase Coupling Impedance Area on the ZAB Plane

F. Traditional Railway System Fault Location

For the 2x25 kV system, the parallel operation of feeders and the presence of the balancing autotransformers are a problem when using traditional fault location techniques. The purpose of disconnecting the autotransformers and decoupling the feeders is to allow the proper measurement for accurately estimating a fault location for a permanent fault. Once the feeder is in a radial state, fault location estimation can be performed with accuracy. Moreover, the faulted feeder can be easily identified, and what is also important is that the faulted conductor can be identified.

The fault location can be estimated with the Takagi algorithm [9]. The idea behind the algorithm is to eliminate the effect that the fault resistance (Rf) has in the estimation of the fault location. If *m* is the per-unit fault location in the feeder, the following equation relates the measurements by the relay (V_{Relay}, I_{Relay}), the impedance of the line (ZL), fault current (If), and fault resistance:

$$V_{Relay} = m\ ZL\ I_{Relay} + Rf\ If \quad (21)$$

The fault resistance and the fault current (If) cannot be measured by the protective relay, and they are unknowns. However, if a quantity (such as Is, a current) that is in phase with If could be found, then the following equation for *m* is true:

$$m = \frac{\text{Im}\left\{V_{Relay}\ Is^*\right\}}{\text{Im}\left\{ZL\ I_{Relay}\ Is^*\right\}} \quad (22)$$

In three-phase systems, Is = I2, the negative-sequence current. Because of the homogeneity of the negative-sequence impedances, I2 is very similar in phase with If, and the product ($If\ Is^*$) is all real [10].

In the two electrical railway systems described, the 1x25 kV and the 2x25 kV systems, there is not an equivalent current (like I2) for all the fault types. However, Takagi suggests that the incremental current defined in (22) is in phase with the fault current [9].

$$\Delta I = I_{Relay} - I_{Prefault} \quad (23)$$

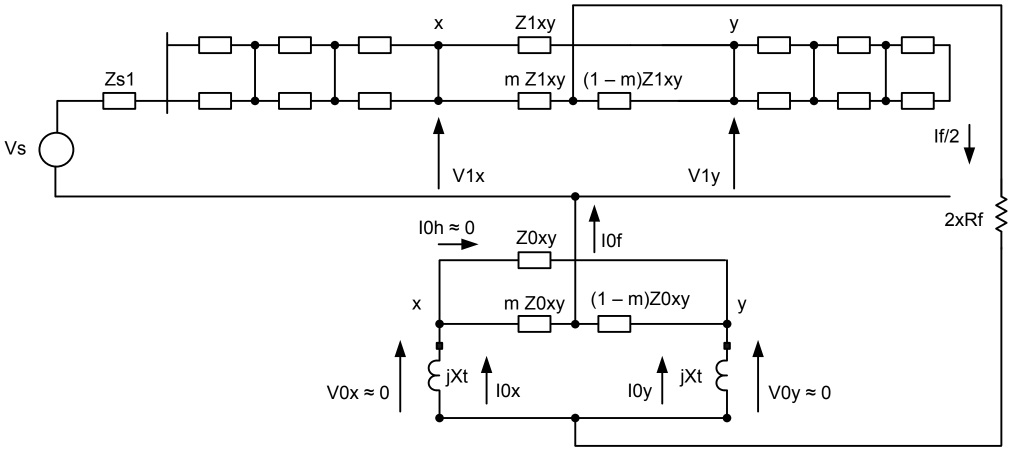

Fig. 23. Measurements Available at the ATSs

For the 2x25 kV system, fault location equations for the three possible fault types are:

$$m_{\text{catenary-feeder}} = \frac{\operatorname{Im}\left\{(V_{\text{catenary}} - V_{\text{feeder}})\,\Delta I1^*\right\}}{\operatorname{Im}\left\{ZL\,(I_{\text{catenary}} - I_{\text{feeder}})\,\Delta I1^*\right\}} \tag{24}$$

$$m_{\text{catenary-ground}} = \frac{\operatorname{Im}\left\{V_{\text{catenary}}\,\Delta I1^*\right\}}{\operatorname{Im}\left\{ZL\,(I_{\text{catenary}} + K0_{\text{catenary}}\,2I0)\,\Delta I1^*\right\}} \tag{25}$$

$$m_{\text{feeder-ground}} = \frac{\operatorname{Im}\left\{V_{\text{feeder}}\,\Delta I1^*\right\}}{\operatorname{Im}\left\{ZL\,(I_{\text{feeder}} + K0_{\text{feeder}}\,2I0)\,\Delta I1^*\right\}} \tag{26}$$

where:

$\Delta I1 = I1 - I1_{\text{Prefault}}$.

G. *Advanced Railway System Fault Location*

The presence of the autotransformers and the periodic paralleling of the railway sections at the ATSs in the 2x25 kV system make it difficult to apply traditional fault location equations, such as the Takagi methodology. As explained in a previous section, in the last reclosing shot, the autotransformers and the paralleling of the two railway feeders are taken out of the circuit (running the two parallel railway paths). This automatic sequence prepares the feeders for the fault location equations (24), (25), and (26). There is only one valid fault location estimate if the fault is permanent. If the fault is transient, it is difficult to estimate the fault location.

Taking advantage of the communications infrastructure available in modern installations, a methodology is proposed using the protective relays for the autotransformers in the ATSs. It covers only ground faults, which are the majority of the faults (92 percent). These protection devices are measuring both the catenary and feeder voltages, the current flowing through the autotransformer, and the ground return.

Fig. 23 shows the equivalent sequence network for a ground fault between the ATS at Point *x* and the ATS at Point *y*. There is a known section impedance (Zxy) between these two substations, and the fault is located at *m* per unit from the *x* substation.

It is practical and very much appropriate to assume that Z0xy is much greater than Xt. The autotransformer impedance is very small compared with the section impedance, which is 30 to 60 kilometers long. This difference indicates that the zero-sequence voltages measured at the ATS locations *x* and *y* are negligible (V0 = 0). With negligible zero-sequence voltages in *x* and *y*, the zero-sequence current in the healthy feeder is zero (I0h = 0). The total zero-sequence current (I0f) divides between two known impedances: m Z0xy and (1 – m)Z0xy. It is a current divider problem.

Solving for the total zero-sequence current:

$$I0f = I0x\,\frac{Z0xy}{(1-m)Z0xy} = I0y\,\frac{Z0xy}{(m)Z0xy} \tag{27}$$

Equation (27) is suggesting correctly that the phase angles of the currents are equal. The expression for *m* is:

$$m = \frac{|I0y|}{|I0x| + |I0y|} \tag{28}$$

Equation (28) is the per-unit fault location in the section from ATS *x* to ATS *y*. To complete the fault location evaluation that is useful for the operator, the two ATSs have to be selected by the following:

- Measuring I0 above a threshold.
- Identifying a ΔI0 and a ΔV1.

The measurements can be sent to the appropriate central location or simply exchanged between the two protective devices, as shown in Fig. 24.

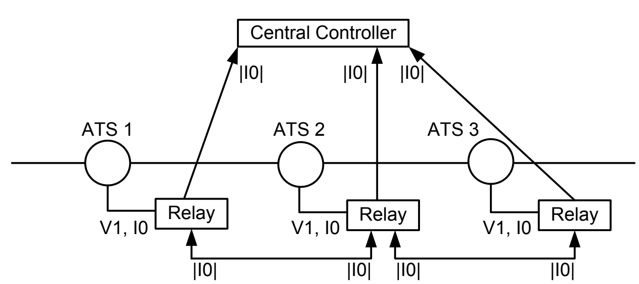

Fig. 24. Possible Architectures for |I0| Exchange for Fault Location

Fault location is an algorithm that allows plenty of time for evaluation. It is not protecting equipment, and it is evaluated only after a fault. The protective relay at the traction substation issues the trip command and can publish a freeze measurements command to all the autotransformer protective relays. With frozen measurements (practically at the same time), and because (28) does not require the measurements to be fully synchronized, the fault location can be evaluated. The messaging can be implemented with available control protocols. IEC 61850 GOOSE messaging is appropriate for this type of scheme because it allows for binary (freeze measurements command) for analog data exchange (|I0| measurement).

V. Conclusion

This paper provides an overview of the problems and solutions pertaining to protective relaying for railway systems. Two systems are used and are described as 1x25 kV and 2x25 kV.

The 1x25 kV system is electrically a single-phase supply, and protective relaying can only use the catenary voltage and current for the protection functions.

The 2x25 kV system presents a more complex problem due to the two phases involved, catenary and feeder. Autotransformers are used to balance the load along the way, and in the majority of the high-speed railway systems, the two traffic directions run in parallel. The feeders are paralleled at the autotransformer locations.

Distance protection is the primary instantaneous tripping function used. It is easier to apply compared with other protective relaying functions, such as overcurrent protection, and it is not dependent on load flow magnitudes. Overcurrent protection is the backup and is time-delayed to allow the distance scheme to operate first.

In the 2x25 kV system, the reclosing sequence is coordinated with an automation scheme that takes the autotransformers out of service for fault location purposes.

An advanced fault location scheme allows fault location estimates for transient faults.

VI. References

[1] Y. Oura, Y. Mochinaga, and H. Nagasawa, "Railway Electric Power Feeding Systems," *Japan Railway & Transport Review*, Vol. 16, June 1998, pp. 48–58.

[2] "Electric Locomotive Glossary," *Railway Technical Web Pages*, June 2014. Available: http://www.railway-technical.com/elec-loco-bloc.shtml.

[3] A. J. Petersen and M. Meyer, "Handling Large Railway Supply Systems – A Challenge for System Modelling and a Need to Guarantee Rail Vehicle's System Compatibility," proceedings of the 8th International Conference on Harmonics and Quality of Power, Athens, Greece, October 1998.

[4] Alstom Grid, *Network Protection & Automation Guide: Protective Relays, Measurement & Control*, Third Edition. Alstom Grid, Paris, France, 2011.

[5] E. Pilo de la Fuente, "Diseño óptimo de la electrificación de ferrocarriles de alta velocidad," doctoral dissertation, Departamento de Electrotecnia y Sistemas, Universidad Pontificia Comillas de Madrid, Spain, 2003.

[6] T. Sezi and F. E. Menter, "Protection Scheme for a New AC Railway Traction Power System," *IEEE Transmission and Distribution Conference*, Vol. 1, April 1999, pp. 388–393.

[7] F. Calero, "Distance Elements: Linking Theory With Testing," proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA, October 2008.

[8] C. F. Wagner and R. D. Evans, *Symmetrical Components: As Applied to the Analysis of Unbalanced Electrical Circuits*. Robert E. Krieger Publishing, Malabar, Florida, 1982.

[9] T. Takagi, Y. Yamakoshi, M. Yamaura, R. Kondow, and T. Matsushima, "Development of a New Type Fault Locator Using the One-Terminal Voltage and Current Data," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-101, Issue 8, August 1982, pp. 2892–2898.

[10] F. Calero, "Rebirth of Negative-Sequence Quantities in Protective Relaying With Microprocessor-Based Relays," proceedings of the 30th Annual Western Protective Relay Conference, Spokane, WA, October 2003.

VII. Biographies

Francisco Javier Martínez Novo received his Computer Engineering Degree in 2005 from the Universidad de León. He completed a B.S. degree in Industrial Engineering with an Electrical Engineering concentration in 2008 from the Universidad de León and the Engineering College of Copenhagen, Denmark. In 2009, Mr. Martínez joined Sistemas de Computación y Automática General S.A. (SICA) and is presently a senior automation and protection systems engineer.

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Fernando Calero received his B.S.E.E. in 1986 from the University of Kansas, his M.S.E.E. in 1987 from the University of Illinois (Urbana-Champaign), and his M.S.E.P.E. in 1989 from the Rensselaer Polytechnic Institute. From 1990 to 1996, he worked in Coral Springs, Florida, for the ABB relay division in support, training, testing, and design of protective relays. Between 1997 and 2000, he worked for Itec Engineering, Florida Power and Light, and Siemens. In 2000, Mr. Calero joined Schweitzer Engineering Laboratories, Inc. and is presently a senior automation systems engineer.

Isaac Arroyo received his B.S. in electrical industrial engineering in 1997 from the Universidad Rovira y Virgili of Tarragona, Spain, his M.S. in industrial engineering from the Universidad Europea de Madrid, his M.B.A. from the ADM Business School of Madrid, and his H.S.E. Master from the EAGE school at the Universidad de Oviedo, Spain. He developed his career mainly at chemical firms such as BASF Española and Dow Chemical as a site electrical operations and maintenance leader, engineering firms such as Técnicas Reunidas and Fúor as an electrical project leader of national and international projects in chemical, and petrochemical and power plants projects, and at Ferrovial in industrial business as an electrical sites manager since 1996. In 2011, Mr. Arroyo joined Schweitzer Engineering Laboratories, Inc. and is presently the business manager in Spain.

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